The flavor-changing rare top decays $t \rightarrow cVV$ in topcolor-assisted technicolor theory

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October 22, 2018

Abstract

In the framework of topcolor-assisted technicolor (TC2) theory, we calculate the contributions of the scalars (the neutral top-pion $\pi_t^0$ and the top-Higgs $h_t^0$) to the flavor-changing rare top decays $t \rightarrow cVV (V = W, g, \gamma$ or $Z)$. Our results show that $h_t^0$ can enhance the standard model $B_{SM}^{t \rightarrow cWW}$ by several orders of magnitude for most of the parameter space. The peak of the branching ratio resonance emerges when the top-Higgs mass is between $2m_W$ and $m_t$. The branching ratio $B_r(t \rightarrow cWW)$ can reach $10^{-3}$ in the narrow range.

$^*$This work is supported by the National Natural Science Foundation of China, the Excellent Youth Foundation of Henan Scientific Committee; and Foundation of Henan Educational Committee.

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The large value of the top quark mass offers the possibility that it plays a special role in current particle physics. Indeed, the properties of the top quark could reveal information on flavor physics, electroweak symmetry breaking (EWSB) as well as new physics beyond the standard model (SM)\(^{1}\). One of these consequences is that the flavor-changing rare top decays which are very small due to the GIM-suppressed in the SM can be used to detect new physics. This fact has lead to a lot of theoretical activity involving the rare top decays within some specific models beyond the SM\(^{2}\).

The strong top dynamical symmetry breaking models, such as topcolor-assisted technicolor (TC2) models\(^{3}\) and top see-saw models\(^{4}\), are attractive because they explain the large top quark mass and provide possible dynamical mechanism for breaking electroweak symmetry. Such type of models generally predict light composite scalars with large Yukawa couplings to the third generation. This induces distinct new flavor mixing phenomena which may be tested at both low and high energies \(^{5, 6}\). For example, TC2 theory \(^{3}\) predicts the existence of the top-pions\((\pi^\pm_t, \pi^0_t)\) and the neutral CP-even state, called top-Higgs \(h^0_t\). These new particles are most directly related to the dynamical symmetry breaking mechanism. Thus, studying the possible signatures of these new particles at high energy colliders will be of special interest.

Ref\(^{5}\) has pointed out that the Yukawa couplings of the scalars to charm and bottom quarks can be large due to a significant mixing of the top and charm quarks. Furthermore, the neutral scalars\((\pi^0_t\) and \(h^0_t\)\) can couple to a pair of gauge bosons through the top quark triangle loop in an isospion violating way\(^7\). The main difference between the neutral top-pion \(\pi^0_t\) and top-Higgs \(h^0_t\) is that \(h^0_t\) can couple to gauge boson pairs \(WW\) and \(ZZ\) at tree level, which is similarly to that of the SM Higgs \(H\). Thus, the neutral scalars may have significant contributions to the rare top decays \(t \rightarrow cVV(V = W, g, \gamma\) or \(Z))\)\(t \rightarrow cWW\) (only for \(h^0_t\)), \(t \rightarrow cgg\), \(t \rightarrow c\gamma\gamma\) and \(t \rightarrow cZ\gamma\).

The top quark mass has been measured \(^8\) by reconstructing the decay products of top pairs produced at the Tevatron. The combined measurement from CDF and D0 is \(m_t = 173.4 \pm 5.1\text{GeV}\). This implies that the rare top decay \(t \rightarrow cWW\) is allowed. However, this process is occurring near threshold and is highly phase space suppressed.
Within the SM, the decay channel $t \rightarrow cWW$ is also highly GIM-suppressed ($B_{r}^{SM}(t \rightarrow cWW) \approx 10^{-13}$[9]), which can not be observed in the future high energy colliders. So, studying such rare top decay will be very useful to detect the effects of new physics.

In this letter, we first calculate the contributions of the top-Higgs $h_{t}^{0}$ to the rare decay channel $t \rightarrow cWW$. We find that the peak of the branching ratio resonance emerges when the top-Higgs mass is between $2m_{W}$ and $m_{t}$. For $m_{h_{t}^{0}} = 165$ GeV, the value of $B_{r}(t \rightarrow cWW)$ is $3 \times 10^{-3}$ for $\varepsilon = 0.01$ and $5.6 \times 10^{-2}$ for $\varepsilon = 0.08$. We further estimate the partial widths of the rare top decays $t \rightarrow cgg$, $t \rightarrow c\gamma\gamma$ and $t \rightarrow cZ\gamma$ contributed by the neutral scalars ($\pi_{t}^{0}$ and $h_{t}^{0}$). The new contributions can enhance the SM partial widths by several orders of magnitude. Even so, it is very difficult to detect the possible signatures of the neutral scalars via these flavor-changing processes.

To solve the phenomenological difficulties of traditional TC theory, TC2 theory[3] was proposed by combing TC interactions with the topcolor interactions for the third generation at the scale of about 1 TeV. In TC2 theory, the TC interactions play a main role in breaking the electroweak symmetry. The ETC interactions give rise to the masses of the ordinary fermions including a very small portion of the top quark mass, namely $\varepsilon m_{t}$ with a model dependent parameter $\varepsilon \ll 1$. The topcolor interactions also make small contributions to the EWSB, and give rise to the main part of the top quark mass, $(1 - \varepsilon)m_{t}$. So, for TC2 theory, there is the following relation:

$$\nu_{\pi}^{2} + F_{t}^{2} = \nu_{w}^{2},$$

where $\nu_{\pi}$ represents the contributions of the TC or other interactions to the EWSB, $F_{t} \approx 50$GeV is decay constant of the scalars predicted by TC2 theory, and $\nu_{w} = \nu/\sqrt{2} \approx 174$GeV. Thus, the majority of the masses of gauge bosons W and Z come from the technifermion condensate.

For TC2 models, the underlying interactions, i.e. topcolor interactions, are non-universal and therefore do not possess a GIM mechanism. When the non-universal interactions are written in the mass eigen-states, it may lead to the flavor changing coupling vertices of the new gauge bosons, such as $Z'tc$, $Z'\mu e$, $Z'\mu\tau$. Thus, the new gauge boson $Z'$
have significant contributions to some lepton flavor changing processes\[10\]. Furthermore, the neutral scalars predicted by this kind of models have the flavor changing scalar coupling vertices. The coupling of the neutral scalars $S$ ( $\pi^0_t$ or $h^0_t$) to the ordinary fermions can be written as\[3, 5\]:

\[
S_{tt} : \frac{im_t}{\sqrt{2}F_t} \sqrt{\nu_w^2 - F_t^2} K_{UR}^{tt}, \quad S_{tc} : \frac{im_t}{\sqrt{2}F_t} \sqrt{\nu_w^2 - F_t^2} K_{UR}^{tc}.
\]

Ref.\[3\] has shown that the value of $K_{UR}^{ij}$ can be taken as:

\[
K_{tt}^{UR} = 1 - \varepsilon, \quad K_{tc}^{UR} \leq \sqrt{2\varepsilon - \varepsilon^2}.
\]

The couplings of the scalars to the bottom quark can be approximately written as:

\[
S_{bb} : \frac{i(m_b - m'_b)}{\sqrt{2}F_t} \sqrt{\nu_w^2 - F_t^2},
\]

where $m'_b$ is the ETC generated part of the bottom-quark mass. According to the idea of TC2 theory, the masses of the first and second generation fermions are also generated by ETC interactions. We have $\varepsilon m_t = \frac{m_t}{m_z} m'_b$. If we take $m_s=0.12\text{GeV}$ and $m_c=1.2\text{GeV}$, then we have $m'_b = 0.1 \times \varepsilon m_t$.

The couplings of the neutral scalars to gauge boson pairs $gg$, $\gamma\gamma$ or $Z\gamma$ via the top quark triangle loop are isospin violating. The general form of the effective $S - V_1 - V_2$ couplings can be written as\[7, 12\]:

\[
\frac{1}{1 + \delta_{V_1 V_2}} \frac{\alpha S_{SV_1 V_2}}{\pi F_t} S_{\epsilon^\mu \alpha \beta} (\partial^\mu V_1^\nu)(\partial^\nu V_2^\beta),
\]

where $V_1^\nu$ and $V_2^\beta$ represent the field operators of the gauge bosons. The anomalous factors $S_{SV_1 V_2}$ are model dependent. They have been given in Refs.[6,12].

The neutral top-pion $\pi_t^0$ can not couple to gauge boson pairs $WW$ and $ZZ$ at tree level. The couplings of the top-Higgs $h_t^0$ to the electroweak gauge bosons at tree level are suppressed by the factor $F_t/\nu_w$ with respect to that of the SM Higgs. For the top-Higgs $h_t^0$, we have

\[
h_t^0 WW : \frac{iF_t}{\nu_w} g m_W g_{\mu\nu}, \quad h_t^0 ZZ : \frac{iF_t}{\nu_w} g m_Z \cos\theta_W g_{\mu\nu}.
\]
From above discussion, we can see that the top-Higgs $h^0_t$ may have significantly contributions to the rare top quark decay channel $t \rightarrow cWW$. The relative amplitude is:

$$ M(t \rightarrow cWW) = \frac{m_t \sqrt{2} F_t^2}{\sqrt{2} F_t \nu_w} K_{UR}^t F_t g m_W F_t \nu_w u(p_c) \gamma_5 u(p_t) \frac{1}{K^2 - m_{h^0_t}^2 + i m_{h^0_t} \Gamma_{\text{total}} \varepsilon_\mu (k_1, \lambda_1) g^{\mu\nu} \varepsilon_\nu (k_2, \lambda_2)}, $$

(7)

where the four momenta $K$ is given by

$$ K = P_t - P_c = k_1 + k_2. $$

(8)

Where $k_i$ is the four momenta of the gauge boson $W$. For $150GeV \leq m_{h^0_t} \leq 350GeV$, the total decay width of the top-Higgs $h^0_t$ can be written as:

$$ \Gamma_{\text{total}} = \Gamma(h^0_t \rightarrow b\bar{b}) + \Gamma(h^0_t \rightarrow gg) + \Gamma(h^0_t \rightarrow \gamma\gamma) + \Gamma(h^0_t \rightarrow Z\gamma) + \Gamma(h^0_t \rightarrow t\bar{c})(for \ m_{h^0_t} \geq m_t + m_c) + \Gamma(h^0_t \rightarrow WW)(for \ m_{h^0_t} \geq 2m_W) + \Gamma(h^0_t \rightarrow ZZ)(for \ m_{h^0_t} \geq 2m_Z). $$

(9)

The branching ratio $B_r(t \rightarrow cWW)$ contributed by the top-Higgs $h^0_t$ is plotted in Fig.1 as a function of the top-Higgs mass $m_{h^0_t}$ for three values of the parameter $\varepsilon$. In Fig.1 we have assumed that the total top width is dominated by the decay channel $t \rightarrow Wb$ and taken $\Gamma(t \rightarrow Wb) = 1.56GeV$[1]. The three-body phase space integral was performed numerically for the parameter values $m_W = 80.4GeV$, $m_t = 175GeV$, $m_c = 1.2GeV$, $\alpha_e = \frac{1}{128}$, $\alpha_s = 0.118$ and $\sin \theta_w = 0.2312$ [13]. From Fig.1 we can see that the peak of the branching ratio $B_r(t \rightarrow cWW)$ resonance emerges when $m_{h^0_t}$ is between $2m_W$ and $m_t$. This is consisted with the results obtained in Ref.[14]. For $m_{h^0_t}=165GeV$, the value of the $B_r(t \rightarrow cWW)$ is $3 \times 10^{-3}$ for $\varepsilon=0.01$ and $5.6 \times 10^{-2}$ for $\varepsilon=0.08$. The $B_r(t \rightarrow cWW)$ decreases rapidly in the regions $m_{h^0_t} < 2m_W$ or $m_{h^0_t} > m_t$. However, for most of the parameter space of the TC2 theory, the branching ratio is several orders of magnitude larger than the $B_{rSM}(t \rightarrow cWW)$. 

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The amplitudes of the rare top decays $t \to cgg$, $t \to c\gamma\gamma$ and $t \to cZ\gamma$ generated by the neutral top-pion $\pi_t^0$ can be written as:

$$M(t \to cVV) = \frac{m_t \sqrt{\nu^2_w - F_t^2}}{\nu_w \sqrt{2} F_t} K_{\nu_W} \frac{\alpha S_{\pi_t^0 V_1 V_2}}{2 \pi F_t}$$

where $\Gamma$ is the total decay widths of the neutral top-pion $\pi_t^0$.

The partial decay widths of the rare top decay channels $t \to cVV$ are plotted in Fig.2 as functions of the top-pion mass $m_{\pi_t}$ for $\epsilon = 0.01$. In Fig.2, we have taken the cut that the angle between photons or gluons is larger than $15^\circ$ and the energy of photons or gluons $E_{\gamma(g)} \geq 20 GeV$. From Fig.2 we can see that the partial widths decrease as $m_{\pi_t}$ increasing in most of the parameter space. If we assume that the part of the top quark mass generated by the topcolor interactions makes up 99% of $m_t$, then we have $\Gamma(t \to cgg) \sim 10^{-9} GeV$, $\Gamma(t \to c\gamma\gamma) \sim 10^{-10} GeV$ and $\Gamma(t \to cZ\gamma) \sim 10^{-10} GeV$.

Ref.[15] has discussed the rare top decay channel $t \to cH$ in the SM. Their results show that $B_r(t \to cH) \approx 9 \times 10^{-14}$ for $m_H = 100 GeV$. The dominant decay modes of the SM Higgs boson are $b\bar{b}$, $\tau\bar{\tau}$ and $c\bar{c}$. The branching ratios $B_r^{SM}(H \to VV)$ are very small: $B_r^{SM}(H \to gg) \approx 5 \times 10^{-2}$, $B_r^{SM}(H \to \gamma\gamma) \sim 10^{-3}$ and $B_r^{SM}(H \to Z\gamma) \sim 10^{-4}$[14]. Thus, the $B_r(t \to cVV)$ contributed by the neutral top-pion $\pi_t^0$ is larger than that of the SM by several orders of magnitude.

The contributions of $h_t^0$ to the rare top decays $t \to cVV (V = g, \gamma$ or $Z$) are similar to that of $\pi_t^0$. Certainly, $h_t^0$ can couple to gauge boson pair $WW$ and can give contributions to the rare top decays $t \to c\gamma\gamma$ and $t \to cZ\gamma$ via $W$ loops. This may enhance the branching ratios $B_r(t \to c\gamma\gamma)$ and $B_r(t \to cZ\gamma)$ relative to that of $\pi_t^0$. However, the coupling $h_t^0 WW$ is suppressed with respect to the case of the SM Higgs boson $H$ by a factor $\frac{F_t}{\nu_w}$. Thus the enhancement is very small. We can neglect the contributions of $W$ loops to the rare top decays $t \to c\gamma\gamma$ and $t \to cZ\gamma$. The decay widths of the decays $t \to cVV (V = g, \gamma$ or $Z$) given by the top-Higgs $h_t^0$ approximately equal to that of the neutral top-pion $\pi_t^0$.

To assess the discovery reach of the rare top quark decays in the future high energy colliders, Ref.[17] has roughly estimated the following sensitivities for $100 fb^{-1}$ of integrated
Thus, the effects of $h_t^0$ on the rare top decay $t \rightarrow cWW$ can be detected in the future high energy colliders. If it is not this case, we can conclude that the mass of the top-Higgs $h_t^0$ must be larger than 180GeV.

The scalars predicted by the TC2 theory have large Yukawa couplings to the third family fermions and induce the new flavor changing scalar couplings including the $t - c$ transitions for the neutral scalars. Thus, the neutral scalars have significant contributions to the rare top decay channels $t \rightarrow cVV$. If the mass of the top-Higgs lies in the narrow range $160\,GeV \leq m_{h_t^0} \leq 180\,GeV$, the rare top decay $t \rightarrow cWW$ may be used to detect the signatures of the top-Higgs $h_t^0$. For the neutral top-pion $\pi_t^0$, we have to use other processes to detect its possible signatures.
Figure captions

**Fig.1:** The branching ratio $B_r(t \to cWW)$ as a function of the top-Higgs mass $m_{ht}$ for the parameter $\epsilon = 0.01$ (solid line), 0.05(dotted line) and 0.08(dashed line).

**Fig.2:** The partial decay widths $\Gamma(t \to cVV)$ versus the mass $m_{\pi t}$ for $\epsilon = 0.01$. 
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Fig. 1

Fig. 2