$t \rightarrow cH^0$ decay in the general two Higgs doublet model

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We study the flavor changing $t \rightarrow cH^0$ decay in the framework of the general two Higgs doublet model, the so called model III. Here, we take the Yukawa couplings complex and switch on the CP violating effects. We predict the branching ratio six orders larger compared to the one calculated in the SM, namely, $BR \sim 10^{-7}$, and observe a measurable CP asymmetry, at the order of $\sim 10^{-2}$.

I. INTRODUCTION

The top quark has attracted great interest since it breaks the $SU(2) \times U(1)$ symmetry maximally and it has rich decay products due to its large mass. The rare decays of the top quark have been studied in the literature in the framework of the standard model (SM) and beyond [1–10]; the one-loop flavor changing transitions $t \rightarrow cg(\gamma, Z)$ in [5,8], and $t \rightarrow cH^0$ in [3,8–10].

In the SM, these decays are suppressed as a result of the Glashow-Iliopoulos-Maiani (GIM) mechanism [11]. The branching ratios (BR) of the decays $t \rightarrow cg(\gamma, Z)$ have been predicted in the SM as 4×10^{-11} (5×10^{-13}, 1.3×10^{-13}) in [3]. $t \rightarrow cH^0$, which can give strong clues about the nature of electroweak symmetry breaking, has been calculated at the order of the magnitude of $10^{-14} - 10^{-13}$ in the SM, in [9]. These are small rates for the measurement, even at the highest luminosity accelerators and therefore, there is a need to analyze these rare decays in new physics beyond the SM.

In the present work, we study the flavor changing $t \rightarrow cH^0$ decay in the framework of the general two Higgs doublet model (model III), where H^0 is the SM Higgs boson. Here, we take the Yukawa couplings complex and switch on the CP violating effects. Since the BR is at the order of $\sim 10^{-13}$ in the SM, we neglect this contribution and calculate the new physics effects in the model III. In the calculations, we take into account the interactions due to the internal mediating charged Higgs boson $H^\pm$ and neglect the ones including internal neutral Higgs bosons, h^0 and A^0 (see the Discussion). The numerical results show that the BR of this process can reach to the values of order 10^{-6}, playing with the free parameters of the model III, respecting the existing experimental restrictions. This prediction is almost seven orders larger compared to the one in the SM and it is a measurable quantity in the accelerators.

Furthermore, we predict the possible CP asymmetry A_{CP} at the order of 10^{-2} for the intermediate values of the CP parameter, due to the complex Yukawa coupling $\xi^D_{N,bb}$ (see Sec. II for its definition). This is purely a new physics effect and the measurement of A_{CP} for the process under consideration may open a new window to go beyond the SM and test the new physics.

The paper is organized as follows: In Sec. II, we present the BR and A_{CP} of the decay $t \rightarrow cH^0$ in the framework of model III. Section III is devoted to discussion and our conclusions.

II. THE FLAVOR CHANGING $t \rightarrow cH^0$ DECAY IN THE FRAMEWORK OF THE GENERAL TWO HIGGS DOUBLET MODEL

The flavor changing transition $t \rightarrow cH^0$ is quite suppressed in the SM due to the GIM mechanism [11]. The extended Higgs sector could bring large contributions to this decay and make CP violation possible, in general. This section is devoted to the calculation of the BR and the CP violating asymmetry of the decay under consideration, in the general two Higgs doublet model, so called model III. In the model III, the flavor changing neutral currents in the tree level are permitted and various new parameters, such as Yukawa couplings, masses of new Higgs bosons, exist.

The $t \rightarrow cH^0$ process is controlled by the Yukawa interaction and in the model III, it reads as

$$\mathcal{L}_Y = \eta^U_{ij} \bar{Q}_{iL} \tilde{\phi}_1 U_{jR} + \eta^D_{ij} \bar{Q}_{iL} \phi_1 D_{jR} + \xi^{U\dagger}_{ij} \bar{Q}_{iL} \tilde{\phi}_2 U_{jR} + \xi^D_{ij} \bar{Q}_{iL} \phi_2 D_{jR} + \text{H.c.}, \tag{1}$$

where L and R denote chiral projections $L(R) = 1/2(1 \mp \gamma_5)$, ϕ_i for $i = 1,2$, are the two scalar doublets, $\bar{Q}_{iL}$ are left handed quark doublets, $U_{jR}(D_{jR})$ are right handed up (down) quark singlets, with family indices i, j. The Yukawa matrices $\eta^{U,D}_{ij}$ and $\xi^{U,D}_{ij}$ have in general complex entries. It is possible to collect SM particles in the first doublet and new particles in the second one by choosing the parametrization for ϕ_1 and ϕ_2 as

$$\phi_1 = \frac{1}{\sqrt{2}} \left[\begin{pmatrix} 0 \\ v + H^0 \end{pmatrix} + \begin{pmatrix} \sqrt{2}\chi^+ \\ i\chi^0 \end{pmatrix} \right], \quad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}H^+ \\ H_1 + iH_2 \end{pmatrix}, \tag{2}$$

with the vacuum expectation values,

$$\langle \phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle \phi_2 \rangle = 0. \tag{3}$$

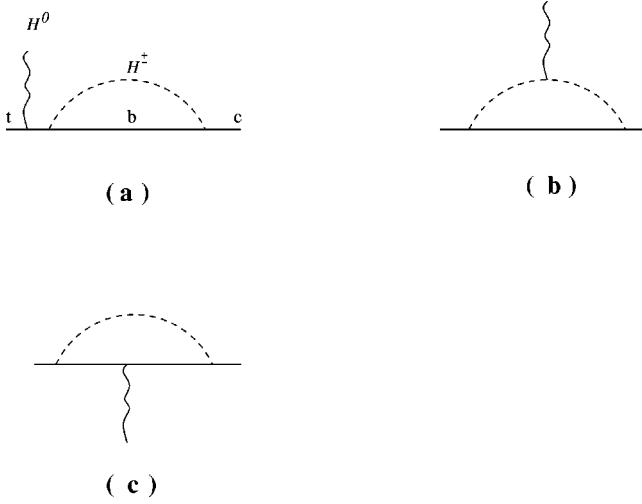*Email address: eiltan@heraklit.physics.metu.edu.tr

FIG. 1. One loop diagrams contribute to the decay $t \rightarrow cH^0$ due to internal charged Higgs boson. Wavy line represents the H^0 field and dashed line the $H^{\pm}$ field.

Here, H_1 and H_2 are the mass eigenstates h^0 and A^0 respectively since no mixing occurs between two CP-even neutral bosons H^0 and h^0 at tree level, for our choice.

The flavor changing (FC) interaction can be obtained as

$$\mathcal{L}_{Y,FC} = \xi_{ij}^{U\dagger} \bar{Q}_{iL} \tilde{\phi}_2 U_{jR} + \xi_{ij}^D \bar{Q}_{iL} \phi_2 D_{jR} + \text{H.c.}, \quad (4)$$

where the couplings $\xi^{U,D}$ for the FC charged interactions are

$$\xi_{ch}^U = \xi_N^U V_{CKM},$$

$$\xi_{ch}^D = V_{CKM} \xi_N^D. \quad (5)$$

and $\xi_N^{U,D}$ is defined by the expression

$$\xi_N^{U(D)} = (V_{R(L)}^{U(D)})^{-1} \xi^{U,(D)} V_{L(R)}^{U(D)}. \quad (6)$$

Here the index "N" in $\xi_N^{U,D}$ denotes the word "neutral."

The SM contribution to the BR of the process $t \rightarrow cH^0$ is negligibly small, which is at the order of the magnitude 10^{-13}. Therefore, we take into account only the new effects beyond the SM. The relevant diagrams are given in Fig. 1. At this stage, we would like to discuss the possibilities not to take into account the tree level contribution to the decay under consideration, in the model III. First, it can be assumed that all the off diagonal neutral Yukawa couplings vanish and therefore the coupling $\xi_{N,tc}^U$ vanishes. Another possibility is to take the mixing between two neutral Higgs bosons H^0 and h^0 is small and the tree level interaction $t - c - H^0$ is negligible. In our case, we consider the gauge and CP invariant Higgs potential which spontaneously breaks $SU(2) \times U(1)$ down to $U(1)$ as

$$V(\phi_1, \phi_2) = c_1(\phi_1^+ \phi_1 - v^2/2)^2 + c_2(\phi_2^+ \phi_2)^2$$
$$+ c_3[(\phi_1^+ \phi_1 - v^2/2) + \phi_2^+ \phi_2]^2$$
$$+ c_4[(\phi_1^+ \phi_1)(\phi_2^+ \phi_2) - (\phi_1^+ \phi_2)(\phi_2^+ \phi_1)]$$
$$+ c_5[\text{Re}(\phi_1^+ \phi_2)]^2 + c_6[\text{Im}(\phi_1^+ \phi_2)]^2 + c_7. \quad (7)$$

Since we assume that only ϕ_1 has vacuum expectation value, no mixing occurs between two neutral Higgs bosons and the tree level interaction vanishes. Furthermore, since we take the c-quark mass zero and the coupling $\xi_{N,tc}^U$ negligible compared to the couplings $\xi_{N,tt}^U$ and $\xi_{N,bb}^D$ (see [12]), the main contribution comes from the diagrams with internal charged Higgs boson and for the matrix element, we get

$$M(t \rightarrow cH^0) = -iV_{cb}V_{tb}^* \frac{g}{64 m_W \pi^2} (F^{(vert)} + F^{(self)})$$
$$\times \bar{c}(1 + \gamma_5)t, \quad (8)$$

where

$$F^{(vert)} = \xi_{N,bb}^D (m_b \xi_{N,tt}^{U*} f_1 + m_t \xi_{N,bb}^{D*} f_2),$$

$$F^{(self)} = m_b \xi_{N,bb}^D \xi_{N,tt}^{U*} f_3, \quad (9)$$

and the functions f_1, f_2, f_3 are defined as

$$f_1 = \int_0^1 dx \int_0^{1-x} dy \left\{ 1 + \frac{z_t(-1+x+y)(y+xzt)}{x + g(x,y)} \right.$$
$$+ \frac{y_W\left(2 - \frac{1}{\cos^2 \theta_W}\right)}{1 - x + g(x,y)} + 2 \ln(x + g(x,y)) \right\},$$

$$f_2 = \int_0^1 dx \int_0^{1-x} dy \frac{y_W(-1+x+y)\left(2 - \frac{1}{\cos^2 \theta_W}\right)}{1 - x + g(x,y)}, \quad (10)$$

$$f_3 = \frac{1 - y_b + y_b \ln y_b}{1 - y_b},$$

with $g(x,y) = (-1 + x + y)(xy_t + yz_t)$. Here $y_t = m_t^2/m_{H^{\pm}}^2$, $z_t = m_{H^0}^2/m_{H^{\pm}}^2$, $y_W = m_W^2/m_{H^{\pm}}^2$ and $y_b = m_b^2/m_{H^{\pm}}^2$. Using Eq. (8), it is straightforward to obtain the decay width as

$$\Gamma(t \rightarrow cH^0) = \frac{1}{32\pi} \frac{y_t - z_t}{m_t y_t} |M|^2. \quad (11)$$

Now we would like to give the expression for A_{CP} of the above process. Here, we take $\xi_{N,bb}^D$ and $\xi_{N,tt}^U$ complex with the parametrizations

$$\xi_{N,tt}^U = |\xi_{N,tt}^U| e^{i\theta_{tt}},$$

$$\xi_{N,bb}^D = |\xi_{N,bb}^D| e^{i\theta_{tb}}, \tag{12}$$

and assume that the complexity of $\xi_{N,tt}^U$ is small. Using the definition of the CP violating asymmetry A_{CP}

$$A_{CP} = \frac{\Gamma(t \to cH^0) - \Gamma(\bar{t} \to \bar{c}H^0)}{\Gamma(t \to cH^0) + \Gamma(\bar{t} \to \bar{c}H^0)}, \tag{13}$$

we get

$$A_{CP} = |\xi_{N,tt}^U| \sin(\theta_{tb} - \theta_{tt}) \frac{N}{D}, \tag{14}$$

where

$$N = -2 \, \text{Im}(f_1 f_2^* + f_3 f_2),$$

$$D = \frac{m_t}{m_b} y_W |\xi_{N,bb}^D| |f_2|^2 + 2|\xi_{N,tt}^U|$$
$$\times \text{Re}(f_1 f_2^* - f_3 f_2) \cos(\theta_{tb} - \theta_{tt}), \tag{15}$$

and the functions f_1, f_2 and f_3 are given in Eq. (10). Here the symbol $*$ denotes the complex conjugation. As it is shown from Eq. (14), A_{CP} vanishes when two CP violating angles θ_{tb} and θ_{tt} are equal. This is interesting, since A_{CP} can vanish even in the existence of complex phases, in the model III.

III. DISCUSSION

In this section, we study the $\sin \theta_{tb}$, m_{H^0} and $\bar{\xi}_{N,bb}^D$ dependencies of the BR and A_{CP} for the process $t \to cH^0$, in the model III. For the calculation of the BR we take the value of the total decay width $\Gamma_T \sim \Gamma(t \to bW)$ as $\Gamma_T = 1.55$ GeV. Notice that the coupling $\bar{\xi}_{N,bb}^D$ is defined as $\xi_{N,ij}^{U(D)} = \sqrt{(4G_F/\sqrt{2})}\bar{\xi}_{N,ij}^{U(D)}$.

The process $t \to cH^0$ exists also in the SM and model II (or I) version of the 2HDM. In both models this process appears at least at loop level. In the SM model internal mediating $W^\pm$ bosons are responsible for this decay and its BR is very small, at the order of the magnitude of 10^{-13}. In the model II, additional contribution comes from the charged Higgs boson $H^\pm$ and can be enhanced compared to the SM result by playing with the free parameter $\tan \beta$, respecting the experimental measurements. However, no A_{CP} occurs in the model II (I) and also in the SM. This forces one to go into the model III, with complex and possibly large Yukawa couplings.

Model III contains a large number of free parameters such as Yukawa couplings, $\bar{\xi}_{N,ij}^{U(D)}$, the masses of new Higgs bosons, $H^\pm$, h^0 and A^0, and they should be restricted by using experimental measurements. At this stage we summarize these restrictions.

We neglect all the Yukawa couplings except $\bar{\xi}_{N,tt}^U$ and $\bar{\xi}_{N,bb}^D$ since they are negligible due to their light flavor con-

tents, by our assumption. Notice that we also neglect the off diagonal coupling $\bar{\xi}_{N,tc}^U$, since it is smaller compared to $\bar{\xi}_{N,tt}^U$ (see [12]). Therefore, the new neutral Higgs bosons do not have any contribution to the BR of the decay under consideration.

We take $\bar{\xi}_{N,tt}^U$ and $\bar{\xi}_{N,bb}^D$ complex and respect the constraint for the angle θ_{tt} and θ_{bb}, due to the experimental upper limit of neutron electric dipole moment, $d_n < 10^{-25}$ e cm, which leads to $(1/m_t m_b)\text{Im}(\bar{\xi}_{N,tt}^U \bar{\xi}_{N,bb}^{*D}) < 1.0$ for $M_{H^\pm} \approx 200$ GeV [13].

We find a constraint region for these free parameters by restricting the Wilson coefficient C_7^{eff}, which is the effective coefficient of the operator $O_7 = (e/16\pi^2)\bar{s}_\alpha \sigma_{\mu\nu}(m_b R + m_s L)b_\alpha \mathcal{F}^{\mu\nu}$ (see [12] and references therein), in the region $0.257 \leq |C_7^{eff}| \leq 0.439$. Here upper and lower limits were calculated using the CLEO measurement [14]

$$BR(B \to X_s \gamma) = (3.15 \pm 0.35 \pm 0.32) \times 10^{-4}. \tag{16}$$

and all possible uncertainties in the calculation of C_7^{eff} [12].

For completeness we present the Wilson coefficient C_7^{eff}. Denoting the contribution for the SM with $C_7^{SM}(m_W)$ and the additional charged Higgs contribution with $C_7^H(m_W)$, we have the initial values

$$C_7^{2HDMH}(m_W) = C_7^{SM}(m_W) + \frac{1}{m_t^2}\left(\bar{\xi}_{N,tt}^{*U} + \bar{\xi}_{N,tc}^{*U}\frac{V_{cs}^*}{V_{ts}^*}\right)$$

$$\times \left(\bar{\xi}_{N,tt}^U + \bar{\xi}_{N,tc}^U \frac{V_{cb}}{V_{tb}}\right) F_1(y_t),$$

$$+ \frac{1}{m_t m_b}\left(\bar{\xi}_{N,tt}^{*U} + \bar{\xi}_{N,tc}^{*U}\frac{V_{cs}^*}{V_{ts}^*}\right)$$

$$\times \left(\bar{\xi}_{N,bb}^D + \bar{\xi}_{N,sb}^D \frac{V_{ts}}{V_{tb}}\right) F_2(y_t). \tag{17}$$
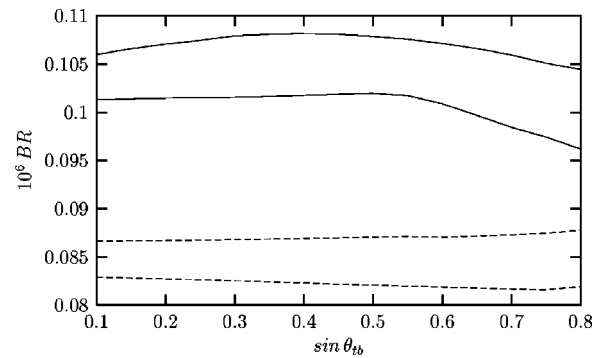
The LO corrected coefficient $C_7^{2HDM}(\mu)$ is given as

FIG. 2. $BR(t \to cH^0)$ as a function of $\sin \theta_{tb}$ for $|\bar{\xi}_{N,bb}^D| = 10m_b$, $m_{H^\pm} = 400$ GeV, $m_{H^0} = 120$ GeV, $\sin \theta_{tt} = 0.1$ in the model III. Here the BR is restricted in the region bounded by solid lines for $C_7^{eff} > 0$ and by dashed lines for $C_7^{eff} < 0$.
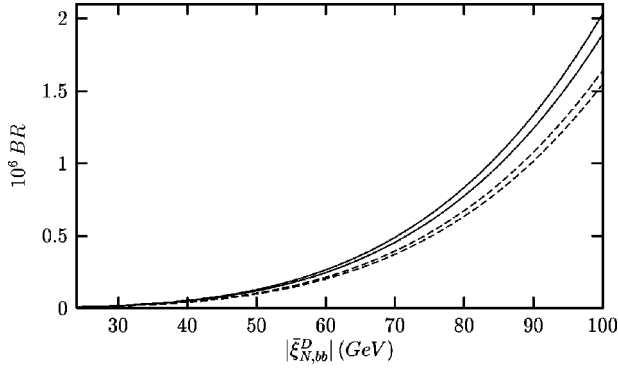
FIG. 3. $BR(t \rightarrow cH^0)$ as a function of $|\bar{\xi}^D_{N,bb}|$ for $\sin\theta_{tt}$ $=0.1$, $\sin\theta_{tb}=0.5$, $m_{H^\pm}=400$ GeV, $m_{H^0}=120$ GeV in the model III. Here the BR is restricted in the region bounded by solid lines for $C_7^{eff}>0$ and by dashed lines for $C_7^{eff}<0$.

$$C_7^{LO,2HDM}(\mu) = \eta^{16/23} C_7^{2HDM}(m_W)$$

$$+ (8/3)(\eta^{14/23} - \eta^{16/23})$$

$$\times C_8^{2HDM}(m_W) + C_2^{2HDM}(m_W) \sum_{i=1}^{8} h_i \eta^{a_i},$$

$$(18)$$

and $\eta = \alpha_s(m_W)/\alpha_s(\mu)$, h_i and a_i are the numbers which appear during the evaluation [15]. The explicit forms of the functions $F_{1(2)}(y)$ are

$$F_1(y) = \frac{y(7 - 5y - 8y^2)}{72(y-1)^3} + \frac{y^2(3y-2)}{12(y-1)^4} \ln y,$$

$$F_2(y) = \frac{y(5y-3)}{12(y-1)^2} + \frac{y(-3y+2)}{6(y-1)^3} \ln y.$$

The discussion given above allows us to obtain a constraint region for the couplings $\bar{\xi}^U_{N,tt}$, $\bar{\xi}^D_{N,bb}$ and the CP violating parameters, $\sin\theta_{tt}$ and $\sin\theta_{tb}$. Here, we assume that the coupling $\bar{\xi}^U_{N,tt}$ has a small imaginary part and we choose
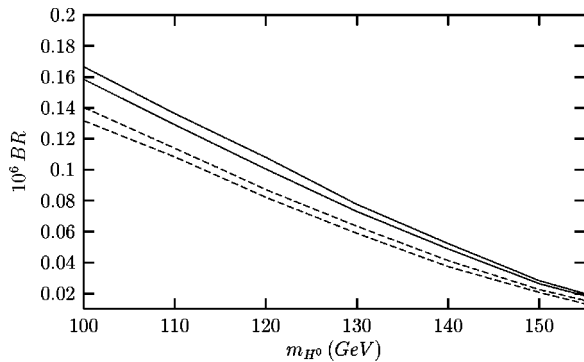

FIG. 4. $BR(t \rightarrow cH^0)$ as a function of m_{H^0} for $|\bar{\xi}^D_{N,bb}|$ $= 10m_b$, $\sin\theta_{tt}=0.1$, $\sin\theta_{tb}=0.5$, $m_{H^\pm}=400$ GeV in the model III. Here the BR is restricted in the region bounded by solid lines for $C_7^{eff}>0$ and by dashed lines for $C_7^{eff}<0$.
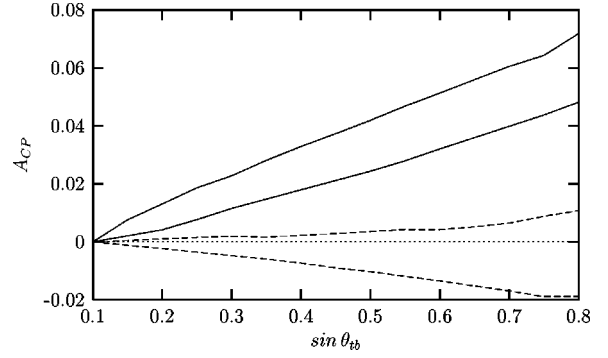

FIG. 5. The same as Fig. 2, but for A_{CP}.

$|r_{tb}| = |\bar{\xi}^U_{N,tt}/\bar{\xi}^D_{N,bb}| < 1$. Notice that, in figures, the BR is restricted in the region between solid (dashed) lines for C_7^{eff} >0 ($C_7^{eff}<0$). Here, there are two possible solutions for C_7^{eff} due to the cases where $|r_{tb}|<1$ and $r_{tb}>1$. In the case of complex Yukawa couplings, only the solutions obeying $|r_{tb}|<1$ exist.

In Fig. 2, we plot the BR with respect to $\sin\theta_{tb}$ for $\sin\theta_{tt}=0.1$, $m_{H^\pm}=400$ GeV, $m_{H^0}=120$ GeV, $\bar{\xi}^D_{N,bb}$ $=10m_b$. As shown in this figure, the BR can reach to the values at the order of the magnitude of 10^{-7} and it is not so much sensitive to the parameter $\sin\theta_{tb}$. Its magnitude is almost 30% larger for $C_7^{eff}>0$ compared to the one for $C_7^{eff}<0$.

Figure 3 represents the BR with respect to $|\bar{\xi}^D_{N,bb}|$ for $\sin\theta_{tt}=0.1$, $\sin\theta_{tb}=0.5$, $m_{H^\pm}=400$ GeV and m_{H^0} $=120$ GeV. This figure shows that the BR is strongly sensitive to the coupling $|\bar{\xi}^D_{N,bb}|$ and it can get the values at the order of 10^{-6} even for $|\bar{\xi}^D_{N,bb}|=20m_b$. This observation is an important clue about the upper limit of the coupling $|\bar{\xi}^D_{N,bb}|$, with the possible future measurement of the BR. For the small coupling $|\bar{\xi}^D_{N,bb}|$, the restricted region for the BR becomes narrow, for both $C_7^{eff}>0$ and $C_7^{eff}<0$.

Finally, we show the m_{H^0} dependence of the BR in Fig. 4 for $\sin\theta_{tt}=0.1$, $\sin\theta_{tb}=0.5$, $m_{H^\pm}=400$ GeV and $|\bar{\xi}^D_{N,bb}|$ $=10m_b$. With the increasing values of m_{H^0}, the BR decreases and the restriction region becomes narrower.

At this stage, we would like to analyze the CP asymmetry A_{CP} of the decay $t \rightarrow cH^0$ and show $\sin\theta_{tb}$ and m_{H^0} depen-
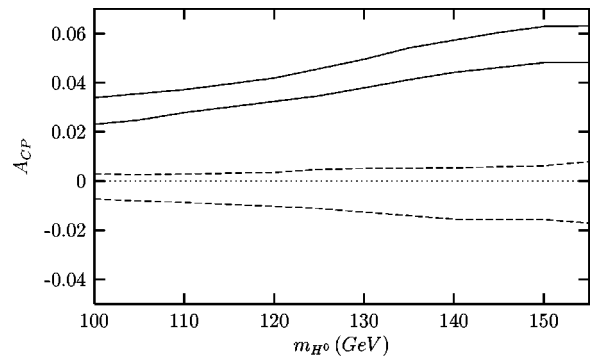

FIG. 6. The same as Fig. 4, but for A_{CP}.

dencies of A_{CP} in Figs. 5 and 6, respectively. A_{CP} is at the order of the magnitude of 10^{-2} for the intermediate values of $\sin \theta_{tb}$ and it can reach to 7×10^{-2} for $C_7^{eff} > 0$. Notice that $\sin \theta_{tt}$ is taken small and A_{CP} vanishes when two CP parameters have the same values, namely $\sin \theta_{tb} = \sin \theta_{tt}$. If A_{CP} is positive (negative), C_7^{eff} can have both signs. However, if it is negative, C_7^{eff} must be negative. This observation is useful in the determination of the sign of C_7^{eff}. The same behavior is observed in Fig. 6 which represents the mass m_{H^0} dependence of A_{CP}. When the Higgs boson mass m_{H^0} increases, an enhancement in A_{CP} is detected, especially for $C_7^{eff} > 0$.

Now we will summarize our results.

The BR of the flavor changing process $t \to cH^0$ is at the order of 10^{-13} in the SM and the extended Higgs sector brings large contributions, at the order of $10^{-7} - 10^{-6}$, which can be measured in the future experiments. This ensures a crucial test for the new physics beyond the SM.

The BR is sensitive to $|\bar{\xi}_{N,bb}^D|$ and its measurement makes it possible to predict an upper limit for this coupling. Furthermore, the measurement of the BR of the decay under consideration can give important information about the mass of Higgs boson H^0.

A_{CP} is at the order of the magnitude of 10^{-2} for the intermediate values of $\sin \theta_{tb}$ and it rises up to the values 7×10^{-2} for $C_7^{eff} > 0$. The measurement of A_{CP} can ensure a hint for the determination of the sign of C_7^{eff}.

Therefore, the experimental investigation of the process $t \to cH^0$ will be effective for understanding the physics beyond the SM.

[1] G. Mahlon and S. Parke, Phys. Lett. B **347**, 394 (1995).

[2] E. Jenkins, Phys. Rev. D **56**, 458 (1997); D. Atwood and M. Sher, Phys. Lett. B **411**, 306 (1997).

[3] G. Eilam, J. L. Hewett, and A. Soni, Phys. Rev. D **44**, 1473 (1991); **59**, 039901(E) (1999).

[4] C. S. Li, R. J. Oakes, and J. M. Yang, Phys. Rev. D **49**, 293 (1994); J. M. Yang and C. S. Li, *ibid.* **49**, 3412 (1994); C. Couture, C. Hamzaoui, and H. König, *ibid.* **52**, 1713 (1995); J. L. Lopez, D. V. Nanopoulos, and R. Rangarajan, *ibid.* **56**, 3100 (1997); G. Couture, M. Frank, and H. König, *ibid.* **56**, 4213 (1997); G. M. de Divitiis, R. Petronzio, and L. Silvestrini, Nucl. Phys. **B504**, 45 (1997).

[5] T. Han, R. D. Peccei, and X. Zhang, Nucl. Phys. **B454**, 527 (1995); T. Han, K. Whisnant, B.-L. Young, and X. Zhang, Phys. Rev. D **55**, 7241 (1997); Phys. Lett. B **385**, 311 (1996); M. Hosch, K. Whisnant, and B.-L. Young, Phys. Rev. D **56**, 5725 (1997); E. Malkawi and T. Tait, *ibid.* **54**, 5758 (1996); T. Tait and C. P. Yuan, *ibid.* **55**, 7300 (1997); T. Han, M. Hosch, K. Whisnant, B.-L. Young, and X. Zhang, *ibid.* **58**, 073008 (1998); F. del Aguila and J. A. Aguilar-Saavedra, Phys. Lett. B **462**, 310 (1999); Nucl. Phys. **B576**, 56 (2000).

[6] W. S. Hou, Phys. Lett. B **296**, 179 (1992); K. Agashe and M. Graesser, Phys. Rev. D **54**, 4445 (1996); M. Hosch, K. Whisnant, and B. L. Young, *ibid.* **56**, 5725 (1997); J. Guasch, hep-ph/9710267.

[7] L. T. Handoko and J. Hashida, Phys. Rev. D **58**, 094008 (1998).

[8] G. Eilam, B. Haeri, and A. Soni, Phys. Rev. D **41**, 875 (1990).

[9] B. Mele, S. Petrarca, and A. Soddu, Phys. Lett. B **435**, 401 (1998).

[10] T. Han, Jing Jiang, and B. Mele, Phys. Lett. B **516**, 337 (2001).

[11] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 875 (1970).

[12] T. M. Aliev and E. Iltan, J. Phys. G **25**, 989 (1999).

[13] D. Bowser-Chao, K. Cheung, and W. Y. Keung, Phys. Rev. D **59**, 115006 (1999).

[14] CLEO Collaboration, S. Chen *et al.*, Phys. Rev. Lett. **87**, 251807 (2001).

[15] A. J. Buras and M. Münz, Phys. Rev. D **52**, 186 (1995).