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FLAVOUR-CHANGING RADIATIVE TOP QUARK DECAY

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The flavour-changing radiative decay of the t quark has been considered at one loop level in a nonlinear R_ξ gauge within the standard model and beyond. The electroweak penguin diagrams involving one insertion of the W boson and/or scalar particle have been considered, and we have also calculated the contribution arising from those diagrams using the fourth generation CKM matrix elements.

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1. Introduction

Top quark has now come into existence [1]. The top quark mass is approximately lying in the range 160 GeV to 180 GeV as measured by CDF and DØ [2,3]. Transition for heavy quarks flavour-changing neutral process attracts much interest recently. The radiative b quark decay attracts much attention for last few years and the theoretical calculations are more or less synchronized with experimental observations. It has been argued that the experimental data provides more informations about the restrictions on the standard model (SM) [4], and QCD corrections [5,6]. The predictions of the standard model are in conformity with the CLEO data at the 2σ level. The new results opened the scope for investigations in various classes of models, namely; anomalous top-quark couplings [7], anomalous trilinear gauge couplings [8], fourth generation [9], two-Higgs-doublet model [10], three-Higgs-doublet model [11], supersymmetry [12], extended technicolour [13], leptoquarks [14] and left-right symmetric models [15]. The results are found to be sensitive to the theoretical calculations of such decays.

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Unfortunately, no experimental results are available for the radiative t decay modes and related processes; and it is interesting that the top quark mass is larger than that of the W and Z bosons.

The decay $t \to c\gamma$ does not arise at the tree level in the standard model (SM), like any other flavour changing neutral current (FCNC) process. Actually, one-loop W,ϕ exchange diagrams generates this decay at the lowest order in the SM. The decay process is particularly interesting because its rate is of order $G_F^2 \alpha_{\rm QED}$ and all other FCNC processes involving leptons and photons are of the order $G_F^2 \alpha_{\rm QED}^2$. The long-range strong interactions may be expected to play minor role in the exclusive process $T^i \to {\rm X}_c^i\, \gamma$ (yet we are aware that the lifetime of the top quark of the order of 1 GeV which is shorter than the hadronization time [16]).

More generally, the FCNC decays are

$$\mathrm{t} \to \left(\begin{array}{c} \mathrm{g} \\ \mathrm{Z} \\ \gamma \end{array} \right) + \left(\begin{array}{c} u \\ c \end{array} \right).$$

The determination of limits on flavour-changing one-loop rare processes like t$\to$ cγ and tree process like t$\to$ Zc are yet to be analysed. We know that in the FCNC processes in the SM, the leading-order mass-independent term is strongly suppressed by GIM cancellation mechanism [17] due to the unitarity of the Cabbibo-Kobayashi-Maskawa (CKM) matrix [18]. This is experimentally confirmed and this paves the way for investigating the new sources of FCNC. So, the study of virtual effects opened hydraheaded windows on electroweak symmetry breaking and physics beyond SM. The examination of these indirect effects of new physics in higher order processes yields a complementary approach to the search for direct production of new particles at high-energy colliders. The decay angular-distributions offer a direct information on the V–A nature of the Wtb coupling, and we also get information on the relative coupling of longitudinal and transverse W boson to the top quark. We are interested in particular in re-examining previous effective field theory computations of rare weak decays. The rapid decay of the top quark means there is no time for the formation of top mesons or baryons. Accordingly, the spin orientation of the top quark at the moment of its production is reflected, without dilution, in the decay angular-distribution of its decay products. The lepton angular distribution thus may become a tool for probing the structure of the charged-current interactions of top. Recently, the top-quark-production dynamics has been reviewed at the Fermilab Tevatron projecting the current theoretical understanding of the total cross-section and many partial differtial cross-sections and also the effects of extra gluon radiation on the top-quark mass determination [19]. The effect of new physics at production or decay of top quark has been discussed after observing sizable angular correlations between the decay products of the top quark and the anti-top quark in top-quark pair production and decay resulting in large asymmetry in the rate of producing like-spin versus unlike-spin top-quark pairs [20]. Final-state QCD radiative corrections to top production via decaying W reveals that with respect to narrow width approximation, taking into account the widths of particles lowers the cross-section, and QCD correction to $\Gamma_{\rm top}$ enhances it [21]. It may be worth noting that the rare top-quark decays t$\rightarrow$ b W^+ Z and t$\rightarrow$ c W^+ W^- has been studied by Elizabeth Jenkins [22].

The decay rate for t $\rightarrow$ cγ, as fixed up by Diaz-Cruz [23], is lying in the range 10^{-5} to 10^{-9}. But recent CDF data [24] have fixed up an upper bound, $BF(\mathrm{t} \rightarrow \mathrm{c}\gamma) + BF(\mathrm{t} \rightarrow \mathrm{u}\gamma) < 2.9\%$, however, no prescription for the lower bound is available.

The calculation of the t $\rightarrow$ cγ decay rate is carried out in a non-linear R_ξ gauge for the SM with three and four generations in Sect. 2 and Sect. 3, respectively, the results and conclusions are given in Sect. 4, and the calculation of the integrals are given in the Appendix.

2. *Calculation of* $\Gamma(\mathrm{t} \rightarrow \mathrm{c}\gamma)$ *in the SM*

We first note that the number of one-loop diagrams for the t $\rightarrow$ cγ decay is reduced as in the nonlinear R_ξ gauge the vertx $A^\mu_\gamma\, W^\pm_\mu\, s^\pm$ vanishes [25], where $s^\pm$ are the unphysical Higgs boson, and so the Feynman rules become simpler. The general calculation of the process $q_{ui} \rightarrow q_{uj}\gamma$ for photon of arbitrary momentum and quarks of arbitrary mass is done following [26], where it was shown that the Ward-Takahashi identities for the electromagnetic vertex remain the standard identities in quantum electrodynamics, and this feature greatly simplifies renornalization of these vertices. As q_{ui}, i.e., the t quark and q_{uj}, i.e., the c quark are both on-mass-shell, we can impose constraints, $p^2 = m_\mathrm{t}^2$ and $p'^{\,2} = (p-q)^2 = m_\mathrm{c}^2$. For real photon emission, also $q^2 = 0$. Thus $2\, p.q = m_\mathrm{t}^2 - m_\mathrm{c}^2$.

The relevant penguin SM amplitude for the t $\rightarrow$ cγ decay is given by

$$\mathcal{A}_{\mathrm{t}\rightarrow\mathrm{c}\gamma} = \tag{1}$$

$$\frac{e\,G_F}{4\sqrt{2}\,\pi^2}\sum_i U_i\,\epsilon^{\mu\dagger}(q,\lambda)\,\bar{u}_c(p',\lambda')\,q^\nu\,\sigma_{\mu\nu}\left(F_2^{(i)R} m_\mathrm{t} P_R + F_2^{(i)L} m_\mathrm{c} P_L\right) u_t(p,\lambda)\,,$$

where $i =$ d, s, b are the internal quarks, $U_i = V^*_{ci}\,V_{ti}$, V_{pq} are the CKM matrix elements, $P_R(P_L)$ are the right-(left) handed helicity projection operators, ϵ is the photon polarization vector, q is the photon momentum, p is the momentum of t quark, p' is the momentum of c quark and $\lambda's$ are the spin elenents. The magnetic transition form factors F_2 are given by [26]:

$$2\,F_2^{(i)R}\,m_\mathrm{t} \;=\; (A_1^{(i)} + A_3^{(i)} + 2\,A_5^{(i)})m_\mathrm{t} - B_3^{(i)} m_\mathrm{c} + B_{12}^{(i)} - 2\,B_{11}^{(i)} \tag{2}$$

and

$$2\,F_2^{(i)L}\,m_\mathrm{c} \;=\; (B_1^{(i)} + B_3^{(i)} + 2\,B_5^{(i)})m_\mathrm{t} - A_3^{(i)} m_\mathrm{c} + A_{12}^{(i)} - 2\,A_{11}^{(i)} \tag{3}$$

where $i =$ d, s, b are internal quarks. As $g^2/(8M_\mathrm{W}^2) = G_F/\sqrt{2}$, taking $\mathbf{a} = \sqrt{-1}/e$, the $A's$ and $B's$, may be defined as follows:

$$A_1^{(i)} = -\left(4+2\frac{m_i^2}{M_{\rm W}^2}\right) \mathbf{a} Q_{\rm W} \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \, \frac{\alpha_p(1-\alpha_p)}{X_0} \tag{4}$$

$$+\left(4+2\frac{m_i^2}{M_{\rm W}^2}\right) \mathbf{a} Q_i \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \, \frac{\alpha_p^2}{Y_0}$$

$$A_3^{(i)} = 4\,\mathbf{a} Q_{\rm W} \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \, \frac{(\alpha_p\alpha_q+\alpha_p-1)}{X_0} \tag{5}$$

$$+2\,\frac{m_i^2}{M_{\rm W}^2}\,\mathbf{a} Q_{\rm W} \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \, \frac{\alpha_p\alpha_q}{X_0}$$

$$+4\,\mathbf{a} Q_i \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \, \frac{\alpha_p(\alpha_q-1)}{Y_0} + 2\,\frac{m_i^2}{M_{\rm W}^2}\,\mathbf{a} Q_i \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \, \frac{\alpha_p\alpha_q}{Y_0}$$

$$A_5^{(i)} = 4\,\mathbf{a} Q_{\rm W} \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \, \frac{1-\alpha_p}{X_0} \tag{6}$$

$$+(2-\frac{m_i^2}{M_{\rm W}^2})\,\mathbf{a} Q_i \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \, \frac{\alpha_p}{Y_0}$$

$$A_{11}^{(i)} = -\frac{m_i^2}{M_{\rm W}^2}\, m_{\rm c}\, \mathbf{a} Q_i \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \, \frac{1}{Y_0} \tag{7}$$

$$A_{12}^{(i)} = 2\,\frac{m_i^2}{M_{\rm W}^2} m_{\rm c} \left(\mathbf{a} Q_{\rm W} \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \, \frac{\alpha_p}{X_0} - \mathbf{a} Q_i \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \frac{\alpha_p}{Y_0} \right) \tag{8}$$

$$B_1^{(i)} = 2\,\frac{m_t}{M_{\rm W}}\frac{m_c}{M_{\rm W}} \left(\mathbf{a} Q_{\rm W} \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \, - \frac{\alpha_p(1-\alpha_p)}{X_0} + \mathbf{a} Q_i \int_0^1 {\rm d}\alpha_p \int_0^{(1-\alpha_p)} {\rm d}\alpha_q \frac{\alpha_p^2}{Y_0} \right) \tag{9}$$

$$B_3^{(i)} = 2\frac{m_t}{M_\mathrm{W}}\frac{m_c}{M_\mathrm{W}}\left(\mathbf{a}Q_\mathrm{W}\int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q\, \frac{\alpha_p\alpha_q}{X_0} + \mathbf{a}Q_i\int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q\, \frac{\alpha_p\alpha_q}{Y_0}\right) \quad (10)$$

$$B_5^{(i)} = -\frac{m_t}{M_\mathrm{W}}\frac{m_c}{M_\mathrm{W}}\mathbf{a}Q_i\int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q\, \frac{\alpha_p}{Y_0} \quad (11)$$

$$B_{11}^{(i)} = -\frac{m_i^2}{M_\mathrm{W}^2}\frac{m_t}{M_\mathrm{W}}\mathbf{a}Q_i\int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q\, \frac{1}{Y_0} \quad (12)$$

$$B_{12}^{(i)} = 2\,\frac{m_t}{M_\mathrm{W}}\frac{m_i^2}{M_\mathrm{W}^2}\left(\mathbf{a}Q_\mathrm{W}\int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q\, \frac{\alpha_p}{X_0} - \mathbf{a}Q_i\int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q\, \frac{\alpha_p}{Y_0}\right) \quad (13)$$

where m_i is the internal quark mass, $i =$ d, s and b, Q_W is the charge of the internal loop W boson, Q_i is the charge of internal loop quark line, $Q_\mathrm{t} = Q_\mathrm{c} = Q_i - Q_\mathrm{W}$, the extracting the magnitude of the charge of the electron $|e|$, one has then $Q_\mathrm{t} = Q_\mathrm{c} = +\frac{2}{3}|e|$ and $Q_i = -\frac{1}{3}|e|$ and then $Q_\mathrm{W} = -|e|$. X_0 and Y_0 are given by

$$X_0 = \{M_\mathrm{W}^2(1-\alpha_p) + m_i^2\,\alpha_p + m_\mathrm{t}^2\alpha_p(\alpha_p - 1) + (m_\mathrm{t}^2 - m_\mathrm{c}^2)\alpha_p\alpha_q\}/\, M_\mathrm{W}^2\,,$$

and

$$Y_0 = \{M_\mathrm{W}^2\,\alpha_p + m_i^2\,(1-\alpha_p) + m_\mathrm{t}^2\alpha_p(\alpha_p - 1) + (m_\mathrm{t}^2 - m_\mathrm{c}^2)\alpha_p\alpha_q\}/\, M_\mathrm{W}^2\,.$$

As $m_\mathrm{t}^2 \gg m_\mathrm{c}^2,\ m_\mathrm{c}^2/M_\mathrm{W}^2$ is neglected with respected to $m_\mathrm{t}^2/M_\mathrm{W}^2$, and we rewrite X_0 and Y_0 as

$$X_0 = \frac{m_\mathrm{t}^2}{M_\mathrm{W}^2}\alpha_p\alpha_q + \frac{m_\mathrm{t}^2}{M_\mathrm{W}^2}\alpha_p^2 + \left(\frac{m_i^2}{M_\mathrm{W}^2} - \frac{m_\mathrm{t}^2}{M_\mathrm{W}^2} - 1\right)\alpha_p + 1\,,$$

and

$$Y_0 = \frac{m_\mathrm{t}^2}{M_\mathrm{W}^2}\alpha_p\alpha_q + \frac{m_\mathrm{t}^2}{M_\mathrm{W}^2}\alpha_p^2 + \left(1 - \frac{m_i^2}{M_\mathrm{W}^2} - \frac{m_\mathrm{t}^2}{M_\mathrm{W}^2}\right)\alpha_p + \frac{m_i^2}{M_\mathrm{W}^2}\,.$$

However $i =$b' is taken also in addition for the consideration of the fourth generation.

Neglecting $m_\mathrm{c}^2/M_\mathrm{W}^2$, it is observed that $B_1^{(i)}, B_3^{(i)}, B_5^{(i)}, A_{11}^{(i)}, A_{12}^{(i)}$ are negligibly small, and also $A_3^{(i)}$, therefore, the term $F_2^{(i)L}$ is neglected. Again, as $m_\mathrm{t} \gg m_\mathrm{c}$, one may neglect the final state fermion mass. Thus, from Eqn.(1) the QCD uncorrected decay rate is given by

$$\Gamma(\mathrm{t} \to \mathrm{c}\gamma) \quad = \quad \frac{\alpha\, G_F^2}{128\, \pi^4}\, m_\mathrm{t}^5 \left| \sum_i U_i\; F_2^{(i)R} \right|^2 \tag{14}$$

The calculations of the relevant integrals are given in the Appendix.

3. Calculation including contribution from the fourth generation

Next, the effect of the fourth generation is considered. One has to make the choice of the masses of the fourth generation down-type quark b' and up-type quark t' for the calculation of the CKM [18] matrix that arises in diagonalization from the quark mass matrices. And its calculation will require the constituent quark masses [27].

The fourth generation quark masses are not free parameters, rather they are constrained by the experimental value of the ρ parameter. The ρ parameter, in terms of the transverse part of the W- and Z-boson self-energies at zero momentum transfer, is given by [28],

$$\rho = \frac{1}{1-\Delta\rho}; \qquad \Delta\rho \;=\; \frac{\Pi_{\mathrm{ZZ}}(0)}{M_\mathrm{Z}^2} \;-\; \frac{\Pi_{\mathrm{WW}}(0)}{M_\mathrm{W}^2} \tag{15}$$

In the SM, the contribution of a fermion isodoublet (u,d) to $\Delta\rho$ read at one-loop order as

$$\Delta\rho_0^{SM} \;=\; \frac{N\, G_F}{8\sqrt{2}\, \pi^2}\, F_0(m_u^2, m_d^2) \tag{16}$$

with the colour factor N, and the function F_0 is given by

$$F_0(x,y) \;=\; x + y \;-\; \frac{2xy}{x-y}\;\ln\frac{x}{y} \tag{17}$$

In the SM, the only relevant contribution is from the top/bottom weak isodoublet. Because $m_\mathrm{t} \gg m_\mathrm{b}$ yields $\Delta\rho_0^{\mathrm{SM}} = (3\, G_F\, m_\mathrm{t}^2)/(8\sqrt{2}\pi^2)$, and since the mass of the top quark is now known to be very high, the fourth generation quark mass doublet is left with the constraint [29] $\rho(\mathrm{t}'-\mathrm{b}') \lesssim 0.002$ by the experimental data. Adopting $m_\mathrm{b} = 4.6$ GeV and $m_\mathrm{t} = 160$ GeV (i.e., $m_\mathrm{t}(\mathrm{pole}) = 169$ GeV) for $\tan\beta = 1.5$, the allowed region is extended up to $m_{\mathrm{b}'}$, $m_{\mathrm{t}'} \lesssim 120 - 125$ GeV, for $\tan\beta = 2.2$ (and higher) larger $m_{\mathrm{t}'}$ values $\lesssim m_\mathrm{t}$ are possible, but only for $m_{\mathrm{b}'} < M_\mathrm{Z}$. The constraint on $m_{\mathrm{b}'}$ depends greatly upon the manner in which it decays. If $m_{\mathrm{b}'}$ has significant mixing with the second or first generation, then b' $\to$ c, u+W (where W may be real or virtual) decay will be dominant; and $m_{b'} > 85$ Gev at 98% C.L. However, if unmixed with lower generations, the b' will decay via FCNC channels: bγ, bg or bZ* for $m_{b'} < M_Z$ and with b'$\to$ bZ becoming dominant for $m_{b'} > M_Z$.

Holdom [30] remarks that the CP violation originating in the right-handed neutrino sector can feed into the quark sector, in an otherwise CP invariant theory; the dominant effects are superweak, and it builds on and extends a previously proposed model of quark masses, based on a new strong flavour interaction above the weak scale and this yields the (t', b') masses close to a TeV. The quarks and charged-lepton masses may be described in terms of operators of the LRLR form and the values of up-type masses as (0.002, .74, 160, 1000) GeV and the down-type masses as (0.005, 0.1, 3, 1000) GeV are expected to be appropriate for masses renormalized at a TeV, and that a fourth family with these dynamical masses can still be consistent with precision electroweak measurements.

Grounau and London [31], however, are of the opinion that there is a model-independent lower bound of 45 GeV on the mass of t' coming from LEP. There are stronger constraints on the $m_{t'}$ of O(100) GeV coming from hadron colliders, but this can be evaded since they depend on how strongly t' couples with b quark. There is an upper bound of 550 GeV on $m_{t'}$ coming from partial-wave unitarity [32]. A heavier t' will lead to a breakdown of perturbation theory.

However the model-independent lower bound of the b' quark mass has been set [33] at 45 GeV. The pairs of values of $(m_{b'},\ m_{t'})$ that may be choosen keeping due importance to $\rho(t' - b') \lesssim 0.002$ are given below (45,110), (45,115), (50,110), (50,115), (50,120), (60,110), (60,115), (60,120), (60,130), and so on.

The calculation is done using Eq. (14) where the sum over i will also be taken for i =b' for considering the effect of the fourth generation. The relevant fourth generation CKM matrix elements $V^*_{cb'} V_{tb'}$ are calculated following [27].

4. Results and conclusion

In the following, the numerical relevance of the different contributions to the t $\to$ cγ decay will be discussed. For the numerical evaluation, the set of parameters used [34] are given below:

$\alpha =$	1/137.0359895	$G_F =$	1.16639×10^{-5} GeV^{-2}
$m_d =$	0.0468 GeV	$m_s =$	0.17 GeV
$m_c =$	1.55 GeV	$m_b =$	4.7 GeV
$M_W =$	(80.33 ± 0.15) GeV	$m_t =$	160, 170, 175, 180 GeV
$\lvert V_{cd}\rvert =$	0.222	$\lvert V_{td}\rvert =$	0.007
$\lvert V_{cs}\rvert =$	0.974	$\lvert V_{ts}\rvert =$	0.044
$\lvert V_{cb}\rvert =$	0.044	$\lvert V_{tb}\rvert =$	0.999

The masses of the light quarks are effective quark masses in the sense that they reproduce the correct hadronic vacuum polarization and have no further physical meaning.

During calculation, we encountered singularities except for the integrals of the form

$$\int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q \, \frac{\alpha_p\alpha_q}{X_0} \qquad \text{or} \qquad \int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q \, \frac{\alpha_p\alpha_q}{Y_0} \, .$$

However, we have evaluated the integrals going into the complex domain by indenting the singularities.

It is surprising that the decay width is obtained of the order of 10^{-2} GeV (?) which is above the limit estimated in [23]. The decay width increases with the increase of the top quark mass, as was anticipated.

For the calculation incorporating the effects of the fourth generation, the masses $(m_{\mathrm{b}'}, m_{\mathrm{t}'})$ are taken as (45 GeV, 110 GeV). We are not selective over the issue; the decay width is not very sensitive to other pairs of values given at the end of Sect. 3. The effect of the fourth generation indicates enhancement in the decay width. The results are given in Table 1.

TABLE 1. Widths of t *quark decay* $\Gamma(\mathrm{t} \to \mathrm{c}\gamma)$ *without and with (right column) the fourth generation for various masses of* m_{t}.

m_{t} (GeV)	$\Gamma(\mathrm{t} \to \mathrm{c}\gamma)$ (GeV)	$\Gamma(\mathrm{t} \to \mathrm{c}\gamma)$ (GeV)
160	4.7997×10^{-10}	1.6919×10^{-9}
170	5.5473×10^{-10}	1.9719×10^{-9}
175	5.9555×10^{-10}	2.1246×10^{-9}
180	6.3878×10^{-10}	2.2865×10^{-9}

Using the standard model prediction for the total decay width of the top quark [35,36] as

$$\Gamma^t = \frac{G_F\, m_t^3}{8\,\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}(\frac{2\pi^2}{3} - \frac{5}{2})\right] , \qquad (18)$$

the results of the branching fractions are given in Table 2.

TABLE 2. Values of the total decay width and the branching ratios of $\mathrm{t} \to \mathrm{c}\gamma$ *obtained for the respective top quark masses.*

m_t (GeV)	160	170	175	180
Γ^t (GeV)	1.024	1.275	1.412	1.556
$B(\mathrm{t} \to \mathrm{c}\gamma)$	4.68×10^{-10}	4.34×10^{-10}	4.23×10^{-10}	4.11×10^{-10}
$B(\mathrm{t} \to \mathrm{c}\gamma)$ fourth generation	1.66×10^{-9}	1.54×10^{-9}	1.51×10^{-9}	1.49×10^{-9}

The standard model result is well within the CDF limit [24]. But the branching fraction $B(\mathrm{t} \to \mathrm{c}\gamma)$ decreases with the increase of the value of top quark mass.

It is somewhat surprising that the b quark with mass only 4.7 GeV has the branching ratio for the radiative decay of the order 10^{-4}, while the top quark with a so heavy mass of 180 GeV has the branching ratio so low (of the order 10^{-10}) in the standard model calculation.

Eilam et al. [37] have obtained $B(\mathrm{t} \to \mathrm{c}\gamma) \sim 10^{-12}$ in the SM and with the two Higgs doublet model, by varying the parameters, reached up to $\sim 10^{-8}$ for the branching ratio.

Grzadkowski et al. [38] have obtained $B(\mathrm{t} \to \mathrm{c}\gamma)$ near 0.5×10^{-5} for $m_\mathrm{t} =$ 80 GeV, but with $m_\mathrm{t} = 160$ GeV for $\tan\beta = 0.33$ or even for $\tan\beta = 1.0$, the branching ratio turned out to be of the order slightly less than 10^{-10}.

Luke et al. [39] have studied the process $\mathrm{t} \to \mathrm{c}\gamma$ decay in the SM with an extra scalar doublet and no discrete symmetry preventing tree-level flavour changing neutral current. Their result is $10^{-7} < B(\mathrm{t} \to \mathrm{c}\gamma)/|\xi_{\mathrm{tt}}\bar{\xi}_{\mathrm{tc}}|^2 < 10^{-5}$; and taking the value of $|\xi_{\mathrm{tt}}\bar{\xi}_{\mathrm{tc}}|^2 \sim 10^{-3}$, as prescribed by them, their limit is $10^{-10} < B(\mathrm{t} \to \mathrm{c}\gamma) <$ 10^{-8}.

Díaz-Cruz et al. [40] have obtained the decay rate of the order 10^{-12} and with two Higgs doublet model with $m_\mathrm{t} = 150$ GeV, $m_{H^\pm} = 200$ GeV, and $\tan\beta = 0.1$ they obtained the branching ratio of the order 10^{-8}.

Recently, R. Martínez et al. [41] and T. Han et al. [42] obtained the model independent bound $B(\mathrm{t} \to \mathrm{c}\gamma) < 2.2 \times 10^{-3}$ from the CLEO constraints on $B(\mathrm{b} \to \mathrm{s}\gamma)$. This bound should apply, of course, for any model, and the results obtained by us are clearly within the limit.

Thus, it is revealed that since the decay widths are related more with the mass of the decaying particle than with the position of the mass in the hierarchy, the branching fractions, though anticipated, do not necessarily possess the same behaviour. Top decays may be expected to have the potential to surprise.

We see enhancement for the consideration of the fourth generation over the SM value by approximately the factor of 3.5. Future experimental results may indicate how to put constraints on the fourth generation quark masses. It is apprehended that the QCD correction to this decay may yield substantial enhancement.

5. *Appendix*

The expressions X_0 and Y_0 defined in Sect. 2 can, in general, be expressed as

$$P\alpha_p\alpha_q + P\alpha_p^2 + Q\alpha_p + R\,.$$

Then one encounters the following integrals for which α_q integration is performed first, and then α_p integration is performed numerically.

$$I(1) = \int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q \frac{1}{P\alpha_p\alpha_q \, + \, P\alpha_p^2 \, + \, Q\alpha_p \, + \, R} \tag{A.1}$$

$$= \int_0^1 \mathrm{d}\alpha_p \frac{1}{P\alpha_p} \ln\left[\frac{(P+Q)\alpha_p + R}{P\alpha_p^2 + Q\alpha_p + R}\right] ,$$

$$I(2) = \int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q \frac{\alpha_p}{P\alpha_p\alpha_q \, + \, P\alpha_p^2 \, + \, Q\alpha_p \, + \, R} \tag{A.2}$$

$$= \int_0^1 \mathrm{d}\alpha_p \frac{1}{P} \ln\left[\frac{(P+Q)\alpha_p + R}{P\alpha_p^2 + Q\alpha_p + R}\right] ,$$

$$I(3) = \int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q \frac{\alpha_p^2}{P\alpha_p\alpha_q \, + \, P\alpha_p^2 \, + \, Q\alpha_p \, + \, R} \tag{A.3}$$

$$= \int_0^1 \mathrm{d}\alpha_p \frac{\alpha_p}{P} \ln\left[\frac{(P+Q)\alpha_p + R}{P\alpha_p^2 + Q\alpha_p + R}\right] ,$$

$$I(4) = \int_0^1 \mathrm{d}\alpha_p \int_0^{(1-\alpha_p)} \mathrm{d}\alpha_q \frac{\alpha_p\alpha_q}{P\alpha_p\alpha_q \, + \, P\alpha_p^2 \, + \, Q\alpha_p \, + \, R} \tag{A.4}$$

$$= \frac{1}{2\,P} - \frac{1}{P^2} \int_0^1 \mathrm{d}\alpha_p \frac{P\alpha_p^2 + Q\alpha_p + R}{\alpha_p} \ln\left[\frac{(P+Q)\alpha_p + R}{P\alpha_p^2 + Q\alpha_p + R}\right] .$$

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RADIJATIVNI RASPAD TOP KVARKA UZ PROMJENU OKUSA

Razmatra se raspad kvarka t uz promjenu okusa na razini jedne petlje u nelinearnoj R_ξ baždarnosti, unutar standardnog modela i izvan njega. Računaju se elektroslabi pingvinski dijagrami s ubačenim W bozonom i/ili skalarnom česticom, koji nastaju iz njih rabeći CKM matrične elemente četvrte generacije.