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The $t \to c\gamma$ Decay In Universal Extra Dimensions

El Decaimiento de t a $c\gamma$ en Dimensiones Universales Adicionales

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Resumen

Se calcula el cambio de sabor del quark top $t \to c\gamma$ en un modelo con una dimensión extra universal compactificada en el gauge no-lineal R_ξ. La fracción de decaimiento puede ser mayor que la predicha por el Modelo Estándar debido a la dinámica originada en la dimensión extra. Obtenemos que cuando el inverso del radio de compactificación es $1/R = 0{,}5$ TeV, la fracción de decaimiento es del orden de $Br(t \to c\gamma) \simeq 10^{-10}$.

***Palabras Clave*:**Procesos con cambio de sabor, Dimensiones extra, Decaimientos del quark top.

Abstract

The Flavor changing process of the top quark $t \to c\gamma$ is considered in a model with a single universal extra dimension which is compactified and the R_ξ gauge is used. The Branching fraction associated can be bigger that the one predicted in the Standard Model because the dynamic arising from the extra dimension. When the inverse of the compactification radius is $1/R = 0{,}5$ TeV, the branching fraction can get $Br(t \to c\gamma) \simeq 10^{-10}$.

***Keywords*:** Flavor Changing processes, extra dimensions, top quark decays.

1. Introduction

Flavor changing neutral currents (FCNC) are very suppressed in the standard model (SM): there are no tree level contributions and at one loop level the charged currents operate with the Glashow-Iliopoulos-Maiani (GIM) mechanism. The branching ratio for top quark FCNC decays into charm quarks are of the order of 10^{-11} for $t \to cg$ and 10^{-13} for $t \to c\gamma, (Z)$ in the framework of the SM [1,2]. This suppression can be traced back to the loop amplitudes: they are controlled by down-type quarks, mainly by the bottom quark, resulting in a m_b^4/M_W^4 factor which can be compared to the enhancement factor that appears in the $b \to s\gamma$ process where the top quark mass m_t is involved instead of m_b in this factor. This fourth power mass ratio is generated by the GIM mechanism and is responsible for the suppression beyond naive expectations based on dimensional analysis, power counting and Cabibbo-Kobayashi-Maskawa (CKM)-matrix elements involved.

2. Development

New physics effects have also been introduced in models with large extra dimensions (ED) [3]. In recent years, these models have been a major source of inspiration for beyond the SM physics in the ongoing research. Scenarios where all the SM fields, fermions as well as bosons, propagate in the bulk are known as ünniversal extra dimensions”[4,5]. In these theories the number of KK-modes is conserved at each elementary vertex and the coupling of any excited KK-mode to two zero modes is prohibited. Then the constraints on the size of the extra dimensions obtained from the SM precision measurements are less stringent than in the case where there is no conservation of the KK particles (non universal extra dimensions).

In five dimensions, let $x = 0, 1, 2, 3$ be the normal coordinates and $x^4 = y$ the fifth one. The fifth extra dimension is compactified on the orbifold S^1/Z_2 orbifold of size R which is the compatification radius. We consider a generalization of the SM where the fermions, the gauge bosons and the Higgs doublet propagate in the five dimensions. The Lagrangian L is

$$L = \int d^4x\, dy\, (\mathcal{L}_A + \mathcal{L}_H + \mathcal{L}_F + \mathcal{L}_Y) \qquad (1)$$

with

$$\begin{aligned}
\mathcal{L}_A &= -\frac{1}{4} W^{MNa} W^a_{MN} - \frac{1}{4} B^{MN} B_{MN}, \\
\mathcal{L}_H &= (D_M \Phi)^\dagger D^M \Phi - V(\Phi), \\
\mathcal{L}_F &= \left[\overline{Q}(i\Gamma^M D_M) Q + \overline{U}(i\Gamma^M D_M) U + \overline{D}(i\Gamma^M D_M) D \right], \\
\mathcal{L}_Y &= -\overline{Q} \widetilde{Y}_u \Phi^c U - \overline{Q} \widetilde{Y}_d \Phi D + h.c.
\end{aligned} \qquad (2)$$

Where the numbers $M, N = 0, 1, 2, 3, 5$ denote the five dimensional Lorentz indexes, W^a_{MN} is the strength field tensor for the $SU(2)_L$ electroweak gauge group and B_{MN} is that one of the $U(1)_Y$ group. The covariant derivative is defined as $D_M \equiv \partial_M - i\widetilde{g} W^a_M T^a - i\widetilde{g}\,' B_M Y$, where $\widetilde{g}$ and $\widetilde{g}\,'$ are the five dimensional gauge couplings constants for the groups $SU(2)_L$ and $U(1)_Y$ respectively, and T^a and Y are the corresponding generators. The standard Higgs field is denoted by $\Phi(x, y)$ and $\widetilde{Y}_{u,d}$ are the Yukawa matrices in the five dimensional theory responsible for the mixing of different families whose indices were suppressed in the notation for simplicity.

The low energy theory will only have zero modes for fields that are even under Z_2 symmetry: this is the case for the Higgs doublet that we choose to be even under this symmetry in order to have a standard zero mode Higgs field. Then we introduce the Fourier expansions of the fields and it is by integrating the fifth y component in Eq. (1) that we obtain the usual interaction terms and the KK spectrum for ED models. We are interested in the third family of quarks and $Q_t^{(n)}$ and $Q_b^{(n)}$ are the upper and lower parts of the doublet Q. There is a mixing between the mass and gauge eigenstates of the KK top quarks ($Q_t^{(n)}$ and $U_t^{(n)}$) where the mixing angle is given by $\tan(2\alpha_t^n) = m_t/m_n$ with $m_n = n/R$.

Now, we present the calculation at one-loop level of the $t \to c\gamma$ process in the framework of a 5-dimensional universal ED model. We start with a naive calculation comparing the decay widths calculate in the SM and ED model and assuming that in the ED model only the third generation is running in the loop. The one loop SM width for the top quark decay into a charm quark plus a gauge boson can be approximated by

$$\Gamma(t \to cV) \simeq |V_{bc}|^2\, \alpha\, \alpha_{em}^2\, m_t \left(\frac{m_b}{M_W} \right)^4 \left(1 - \frac{m_V^2}{m_t^2} \right)^2 \qquad (3)$$

where for a photon, the neutral gauge boson and a gluon we have $\alpha = \alpha_{em}$ ($V = \gamma, Z$) or $\alpha = \alpha_s$ ($V = g$) respectively. These results can be compared to the ones expected for extra dimensions, where the ratio m_b/M_W is replaced by M_W/m_n. Using these approximations we can naively estimate the ratio,

$$\begin{aligned}
\frac{\Gamma(t \to c\gamma)_{ED}}{\Gamma(t \to c\gamma)_{SM}} &\simeq \left[\frac{\left(\sum_n (M_W/m_n)^2 \right)^2}{(m_b/M_W)^4} \right] \\
&= \frac{\pi^4}{36} \left[\frac{(M_W/(1/R))}{(m_b/M_W)} \right]^4 \simeq 1{,}2 \times 10^2.
\end{aligned} \qquad (4)$$

for $R^{-1} \sim 0{,}5\, TeV$. We have already mentioned that the SM prediction for the branching fraction for the decay $t \to c\gamma$ is of the order $Br(t \to c\gamma) \sim 10^{-12}$. Then, the branching fraction for ED models is $Br(t \to c\gamma)_{ED} \sim 1 \times 10^{-10}$ for $R^{-1} = 0{,}5$ TeV.

The naive result on the $\Gamma(t \to c\gamma)_{ED}$ motivates a complete analysis of the one loop amplitude in extra dimensions. The general transition $q_i \to q_j + \gamma$ for arbitrary quark flavors i, j in a non linear R_ξ gauge was studied in reference [6], where it was found that a reduced number of Feynman diagrams as well as simplified Ward identities greatly facilitates the calculation in this R_ξ gauge. For on-shell quarks and real photons the transition matrix element is given by

$$M_\mu = i\sigma_{\mu\nu} k^\nu (F_2^L m_c P_L + F_2^R m_t P_R), \qquad (5)$$

where k_μ is the photon momentum, $P_{R,L} = (1 \pm \gamma_5)/2$ and the magnetic transition form factors $F_2^{L,R}$. The decay width for this process can be written as

$$\Gamma(t \to c\,\gamma) = \frac{\alpha^3 m_t}{2^9 \pi^2 s_w^4 c_w^4} |\widetilde{F}_2^R|^2 \approx 4{,}8 \times 10^{-7} |\widetilde{F}_2^R|^2. \qquad (6)$$

In order to perform the one loop calculation (see Figure 1), we consider two scenarios. The first one, when the mass of the excited states associated to the quarks from the three low-energy families are quasi-degenerated at tree level, without any kind of radiative corrections to KK masses. In this case, when the excitations coming from the other quarks are taken into account, we notice that the naive expectation of the decay width $\Gamma(t \to c\gamma)$ is suppressed by the factor $(m_b/(n/R))^4$, and then the final result, including the KK states, is smaller than the SM value.

In the second scenario, we consider that the most important contribution to the loop correction comes from the excited KK states associated to the third generation. This is a more realistic scenario because there is a mass hierarchy in the KK states from the different families, such as at low energy. We should mention that in universal extra dimension theories, the fixed points from the orbifold break the translational symmetry of the extra dimension and it is possible to introduce new interactions on the branes. In these new interactions, there are counterterms that cancel the divergences of the radiative corrections, mass terms, and mixing terms from the different family KK modes [7]. It can be shown that the sum over all the excited KK states is equivalent to multiply the results obtained for the first KK excited state by the factor $\pi^2/6$. The sum of all contributions gives,

$$2F_2^R \approx \frac{g^2 e}{18m_n^2} V_{tb} V_{cb}^* \frac{i}{16\pi^2} \left\{ -\frac{5}{2} + 11\frac{m_b^2}{M_W^2} \right\}. \quad (7)$$

and then the numerical value for the decay width is $\Gamma(t \to c\gamma) = 1{,}65 \times 10^{-10}$ for $R^{-1} = 0{,}5$ TeV, and the branching fraction is

$$Br(t \to c\gamma) \equiv \frac{\Gamma(t \to c\gamma)}{\Gamma(t \to Wb)} = 1{,}08 \times 10^{-10}. \quad (8)$$

This result shows a branching ratio above the SM one, two orders of magnitude.

We have computed the decay widths $\Gamma(t \to c\gamma)$ in a universal extra dimension model with a single extra dimension, where we have considered that the most important contribution to the loop correction comes from the excited KK states associated to the third generation. The results show a branching ratio that is above the SM one. The branching ratios for this decay width is of the order of 10^{-10}.

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