Unparticle effects on top quark rare decays

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In this work we study the flavor changing neutral current (FCNC) decays of the top quark, $t \to c\gamma$ and $t \to cg$, in the framework of the unparticle physics. The Standard Model predictions for the branching ratios of these decays are about $\sim 5 \times 10^{-14}$, and $\sim 1 \times 10^{-12}$, respectively. The parameter space of $\lambda, \Lambda$, and $d$ is obtained by taking into account the SM predictions and the results of the simulation performed by the ATLAS Collaboration for the branching ratios of $t \to c\gamma$ and $t \to cg$ decays.

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I. INTRODUCTION

After the Large Hadron Collider (LHC) has been launched very recently, next decade will be a stage for a better understanding of the nature of the properties of, and the interactions among the elementary particles at TeV scale. On the one hand, LHC is expected to give a perfect understanding of the electroweak symmetry breaking of the Standard Model (SM) which is expressed through the Higgs mechanism. On the other hand, diversity of the new physics scenarios will be sought at the LHC. Having a mass about the electroweak scale and being the heaviest particle in the SM the top quark is one of the beacons of the LHC to shed light on the riddles of the electroweak symmetry breaking, and to explore the new physics effects at TeV scale. Importance of the top quark searches at the LHC has been concisely reviewed by Ref.s [1], [2], and [3].

Since there will be huge amount production ($\sim 80$ million pair, and $\sim 30$ million single, Ref. [2]) of the top quark at the LHC, one can predict that the interest of the top quark studies will be grown. There are two possibilities to seek for the new physics effects through the top quark decays, one is the decays via charged currents and the other is the decays via neutral currents.

In the SM, the top quark mainly decays to a $W^+$ boson and a quark $q$, ($q = d, s, b$ ), Ref. [4]. As a very important remark to explore the several new physics predictions, besides those charge current decays of the top quark there is no tree level decay of the top quark through neutral currents in the SM. New physics searches via the top quark decays have been extensively analysed in the literature (see Refs [2, 3, 6, 7, 8], and references there in).

The flavor changing neutral current (FCNC) decays of the top quark are highly suppressed in the SM (namely, the branching ratios for $t \to qZ$, $q\gamma$, $qg$ are predicted about from $\sim 10^{-15}$ to $\sim 10^{-11}$) due to the Glashow-Iliopoulos-Maiani (GIM) mechanism, eg. Ref.s [6, 7, 9]. Note that recently, simulation performed by the ATLAS Collaboration gives upper bound $\sim 10^{-5}$ on $t \to q\gamma (g)$ decay at 95% C.L., [10, 11]. There are many beyond the SM proposals to predict FCNC decays of the top quark (a good literature is given by Refs [3, 8]). For example in the (minimal, or left-right)supersymmetric standard model scenario, Refs [12, 13, 14], or in the littlest Higgs model scenario, Ref. [15], or in the left-right supersymmetric model, Ref. [8] those ratios are found about $10^{-3} - 10^{-6}$.

One of the most interesting and mind-bending recent new physics scenarios is the unparticle physics which is proposed by Georgi, Ref. [16, 17]. According to unparticle physics proposal given by Georgi, if there is a conformal
symmetry in nature it must be broken at a very high energy scale which is above the current energy scale of the colliders. Considering the idea of Ref. [18], in Ref. [16], the scale invariant sector is presented by a set of the Banks-Zaks operators $O_{BZ}$, and defined at the very high energy scale. Interactions of BZ operators $O_{BZ}$ with the SM operators $O_{SM}$ are expressed by the exchange of particles with a very high energy mass scale $M_k U$ in the following form

$$\frac{1}{M_k^d} O_{BZ} O_{SM}$$

where BZ, and SM operators are defined as $O_{BZ} \in O_{BZ}$ with mass dimension $d_{BZ}$, and $O_{SM} \in O_{SM}$ with mass dimension $d_{SM}$. Low energy effects of the scale invariant $O_{BZ}$ fields imply a dimensional transmutation. Thus, after the dimensional transmutation Eq.(1) is given as

$$\frac{C_U A_{BZ}^{d_{BZ} - d}}{M_k^{d_{BZ}}} O_{BZ} O_{SM}$$

where $d$ is the scaling mass dimension (or anomalous dimension) of the unparticle operator $O_{U}$ (in Ref.[16], $d = d_{U}$), and the constant $C_U$ is a coefficient function.

Interactions between the unparticles and the SM fields have been listed by Ref[19]. Regarding the Georgi’s original point of view many work on the unparticle physics have been done so far, for example Ref[20].

In this work, we study flavor changing neutral current decays $t \rightarrow c\gamma$, and $t \rightarrow cg$ induced by scalar unparticles.

II. $t \rightarrow c\gamma, g$ DECAYS THROUGH UNPARTICLE

The effective interaction between the scalar unparticle and the SM quarks are given as [19]

$$\frac{1}{A^{d - 1}} \bar{f} (\lambda f' + i\gamma_5 \lambda P) f'$$

where $f$ and $f'$ denote different flavor of quarks, with the same electric charge. The scalar unparticle propagator is given as

$$\Delta_{P}(P^2) = \frac{A_d}{2 sin d \pi} (-P^2 - i\epsilon)^{d - 2}$$

where

$$A_d = \frac{16 \pi^{5/2}}{(2\pi)^2d} \frac{\Gamma(d + 1/2)}{\Gamma(d - 1)\Gamma(2d)}$$

![FIG. 1: Feynman diagrams for FCNC decays of the top quark through scalar unparticle.](image)

The Feynman diagrams for the $t \rightarrow cV$ decays through scalar unparticle is depicted in the Figure 1. The matrix element for the $t \rightarrow cV (V = \gamma, g)$ decay in general form can be written as follows

$$M = e^{\mu (a)}(u(p') [i\sigma_{\mu\nu} q'(A_S + A_P \gamma_5) + \gamma_\mu (C + D \gamma_5) + q_\mu (E + F \gamma_5)]u(p)$$
where \( \epsilon^{(a)} \) and \( q_\mu = p_\mu - p'_\mu \) are the polarization, and the momentum vector of the photon (gluon), respectively, and \( A_S, A_P, C, D, E \) and \( F \) are invariant amplitudes. From the gauge invariance we have \( C = D = 0 \). Since the photon (gluon) is on shell, i.e. \( q^2 = 0 \), and the transversality condition \( q_\mu \epsilon^{(a)} = 0 \), leads that the last term in Eq. (6) can safely be omitted. Other words, the \( t \to eV \) decay is described by magnetic moment type transition

\[
M = \epsilon^{(a)\ast} \bar{u}(p') \gamma_{\mu} q^{\nu} (A_S + A_P \gamma_5) u(p) 
\]

(7)

Obviously the contribution of Fig. 1(a), and Fig. 1(b) are proportional to \( \epsilon^{(a)\ast} \bar{u}(p') \gamma_{\mu} u(p) \) or \( \epsilon^{(a)\ast} \bar{u}(p') \gamma_{\mu} \gamma_5 u(p) \), and therefore, can be omitted since they do not contribute to the structure \( \sigma_{\mu\nu} q^{\nu} \). So, only diagram (c) presented in Fig. 1 should be considered. After some calculation for the invariant amplitudes \( A_S \) and \( A_P \) we get

\[
A_S = \frac{A_d g^V}{2\Lambda^{2(d-1)} \sin\pi} \sum_q \frac{1}{(4\pi)^2} \int_0^1 dx \int_0^{1-x} dy (1-x-y)^{1-d} \left[ -m_t y (1-x-y) (\lambda_S^{\lambda t q} + \lambda_P^{\lambda t q}) + m_q (x+y) (\lambda_S^{\lambda t q} - \lambda_P^{\lambda t q}) \right] 
\]

(8)

\[
A_P = \frac{A_d g^V}{2\Lambda^{2(d-1)} \sin\pi} \sum_q \frac{1}{(4\pi)^2} \int_0^1 dx \int_0^{1-x} dy (1-x-y)^{1-d} \left[ -m_t y (1-x-y) (\lambda_S^{\lambda t q} + \lambda_P^{\lambda t q}) - m_q (x+y) (\lambda_S^{\lambda t q} + \lambda_P^{\lambda t q}) \right] 
\]

(9)

where \( q = \{ u, c, t \} \), when \( t \) or \( c \) quark running at loop only one of vertices contain flavor changing and another vertex is flavor diagonal. But when \( u \) quark runs at loop both vertices are flavor changing and therefore its contribution to the considered process compared to the \( c \) and \( t \) quark contributions should be very small. For this reason we will neglect \( u \) quark contributions in all next discussions. \( \lambda_S(\lambda_P) \) and \( \Lambda \) are the scalar (pseudo-scalar) couplings and energy scale of unparticles, respectively. The couplings for the vector bosons are defined as \( g^V = Qg_e, g^g = g_s \lambda_a / 2 \).

Taking the square and the average of the amplitude gives

\[
< |M_e|^2 > = \frac{A_d^2 g^V^2 N}{2\Lambda^{2d-4} \sin^2\pi} \left[ |A_S|^2 + |A_P|^2 \right] [(p \cdot q)(p' \cdot q)] 
\]

(10)

where \( N \) is color factor given by \( \frac{2}{3} \) for the \( t \to cg \) and 1 for the \( t \to c\gamma \) decay. Therefore, the FCNC decay width can be written as

\[
\Gamma = \frac{A_d^2 g^V^2 N (|A_S|^2 + |A_P|^2)}{32\pi \Lambda^{2d-4} \sin^2\pi} m_t^3 
\]

(11)

The FCNC top quark decay width \( \Gamma(t \to Vc) \) is calculated in terms of the unparticle coupling to the quarks \( \lambda \), the unparticle scale \( \Lambda \) and the scaling dimension \( d \). In numerical analysis, without loss of generality, for simplicity, we take \( \lambda \equiv \lambda_S^{(t,c)q} = \lambda_P^{(t,c)q} \), and \( m_t = 175 \text{ GeV} \), \( m_c = 1.2 \text{ GeV} \), and \( \alpha = 1/128, \alpha_s = 0.117 \). We consider the total width of the top quark decay as \( \Gamma_{tot} = 1.5 \text{ GeV} \), which is mainly determined by the decay width of \( t \to bW^+ \), Ref. [3].

In Fig. 2 and Fig. 3 we present the branching ratios for \( t \to c\gamma \) and \( t \to cg \) decays with respect to the scaling dimension \( d \) for various values of the coupling \( \lambda \) at \( \Lambda = 1 \text{ TeV} \). In these and the following figures the line (EXP) means the result of the simulations performed by the ATLAS Collaboration where the upper limits of the considered decays are obtained about \( 10^{-5} \) at 95% C.L., Ref. [10]. The SM prediction is represented by the solid horizontal line. From those figures we see that the branching ratio of \( t \to c\gamma \) and \( t \to cg \) decays decreases strongly with increasing \( d \), except \( d = 2 \). It is well known that for scalar unparticles at \( d = 2 \) there is infrared singularity. From the figures it also follows that the branching ratio of \( t \to c\gamma(t \to cg) \) decay becomes smaller than the SM prediction when \( d \leq 1.4 \) at \( \lambda = 10^{-2} \). If the coupling constant is larger than \( 10^{-2} \) then practically at all values of \( d \) in the considered region \( 1 < d < 2 \) branching ratio of \( t \to c\gamma(t \to cg) \) decay in the unparticle theory exceeds the SM one. It should be noted
that the similar analysis for $b \rightarrow s\gamma$, Ref. [21] (and $\mu \rightarrow e\gamma$ decay Ref. [22]) leads to result that the preferable value of the coupling constant is about $\sim 10^{-2} - 10^{-3}$.

In the Figures 4 and 5 we present the dependence of the branching ratios on the parameter $d$ for various values of the energy scale $\Lambda$ at $\lambda = 10^{-2}$. From these figures it follows that for $\Lambda = 1\text{TeV}$ - $\Lambda = 10\text{TeV}$ up to $d = 1.4$ the branching ratio of $t \rightarrow c\gamma$($t \rightarrow cg$) decay exceeds the SM one.
FIG. 4: Branching ratio for $t \rightarrow c\gamma$ decay for $\lambda = 10^{-2}$.

In the Figure 4 and 5 we present the dependence of the branching ratios to the coupling parameter $\lambda$ for given values of the parameter $d$. From these figures, one can observe that the branching ratio exceeds the SM prediction if $\lambda > 10^{-2}$.

In the Tables I and II we present numerical values of the branching ratios for $t \rightarrow cg$, and $t \rightarrow c\gamma$, respectively. One can explicitly see that experimental sensitivity is appropriate for only $d < 1.3$ for $\lambda > 1 \times 10^{-1}$, however if the experimental sensitivity can be increased then the unparticle effects can be detected even if the coupling is about $10^{-2}$.

FIG. 5: Branching ratio for $t \rightarrow cg$ decay for $\lambda = 10^{-2}$.
FIG. 6: Branching ratio for $t \rightarrow c\gamma$ decay with $\Lambda = 1$ TeV.

III. CONCLUSIONS

In present work, we study the FCNC rare decays of the top quark $t \rightarrow c\gamma$ and $t \rightarrow cg$ through scalar unparticle. Regarding the latest simulation performed by the ATLAS Collaboration, Ref. [10], the sensitivity to these rare decays of the top quark at %95 C.L. are $Br(t \rightarrow c\gamma) = 2.8 \times 10^{-5}$, and $Br(t \rightarrow cg) = 1.6 \times 10^{-5}$. If there is such a rare decay it will give a window to see the beyond SM physics effects. Using the low energy effective field description of the unparticle physics we show that FCNC decay of the top quark is very good channel to explore for and to put

FIG. 7: Branching ratio for $t \rightarrow cg$ decay with $\Lambda = 1$ TeV.
We want to remark that $t \rightarrow c\gamma$ or $t \rightarrow cg$ are loop level processes both in the SM and in the unparticle physics. However, $t \rightarrow c\gamma\gamma$ or $t \rightarrow cgg$ can take place at tree level in the unparticle physics. The unparticle effects in the rare $t \rightarrow cgg$ decays has been studied in the Ref. $^{23}$. In Table III, we present a comparison our branching ratios $Br(t \rightarrow c\gamma)$, and $Br(t \rightarrow cg)$ with the branching ratios found in the Ref $^{23}$ for various values of the scaling parameter $d$. One could understand this behavior with the observation that the $t \rightarrow c\gamma$ or $t \rightarrow cg$ decays are proportional with $\alpha_{em}$ or $\alpha_s$ but the $t \rightarrow c\gamma\gamma$ or $t \rightarrow cgg$ decays depend on the unparticle coupling $\lambda$ which we take $10^{-2}$, is smaller than $\alpha_s$ but bigger than $\alpha_{em}$. Therefore, the behaviors of the branching ratios of $t \rightarrow c\gamma(g)$, and $t \rightarrow c\gamma\gamma(gg)$ in the SM, and the unparticle physics are different.

Table III: Comparison of the branching ratios $Br(t \rightarrow c\gamma)$, and $Br(t \rightarrow cg)$ with the branching ratios found in the Ref $^{23}$ for various values of the scaling parameter $d$.

| $d$ | $Br$ for $\lambda = 5 \times 10^{-1}$ | $Br$ for $\lambda = 10^{-2}$ |
|-----|-----------------------------------|----------------------------|
| 1.05 | 0.06                              | 0.06                       |
| 1.10 | 0.05                              | 0.05                       |
| 1.15 | 0.05                              | 0.05                       |
| 1.20 | 0.03                              | 0.03                       |

We assume $\Lambda = 1000\text{GeV}$. Here, we assume $\Lambda = 1000\text{GeV}$. According to our results, one could expect to see unparticle effects for $\Lambda = 1 - 10\text{TeV}$ if the coupling is about $\lambda > 10^{-2}$ for $d < 1.3$. This is consistent with the existing results in the literature (see, for example see Refs $^{20, 21, 22, 23}$, and references there in.).
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