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Unparticle effects in rare $t \to cgg$ decay

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In this work the flavor-changing, rare $t \to cgg$ decay induced by mediation of scalar and tensor unparticles is studied. Using the standard model result for the branching ratio of the $t \to cgg$ decay, the parameter space of $d_{\mathcal{U}}$ and $\Lambda_{\mathcal{U}}$, where the branching ratio of this decay exceeds the one predicted by the standard model, is obtained. Measurement of the branching ratio larger than 10^{-9} can give valuable information for establishing unparticle physics.

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The impressive and exciting results on the flavor-changing neutral current (FCNC) decays in the B-meson sector that are observed at the B-meson factories *BABAR* [1], BELLE [2,3], and CLEO [4] seem to be in good agreement with the standard model (SM) prediction.

The interest to study FCNC decays in the t-quark sector can be explained by the following reasons: (i) In many models beyond the SM the new physics scale is closer to the t-quark mass, and (ii) many two-body t-quark FCNC decays, like $t \to cV$ ($V = g$, γ, Z) and $t \to cH$ are highly suppressed in the SM due to the Glashow-Iliopoulos-Maiani mechanism, and their branching ratios are of the order 10^{-11}–10^{-14} [5,6]. These branching ratios are practically impossible to measure at the Large Hadron Collider (LHC) [7] or at the International Linear Collider [8]. But many models of new physics predict that the branching ratios of the above-mentioned FCNC decays are much larger compared to that obtained in the SM (see [9] and references therein).

The t-quark three-body FCNC decays like $t \to cWW$, cZZ, bWZ are also discussed in the framework of the SM [10–12] and beyond [13]. It is shown in [10–12] that the rate of higher order three-body FCNC decay $t \to cgg$ exceeds the rate of lower order $t \to cg$ decay. However, the branching ratio of $t \to cgg$ decay predicted by the SM is about $\sim 10^{-9}$, and hence, the detection of this rather small value is quite problematic. In the frame work of the minimal supersymmetric model (MSSM), a larger estimate results from allowing a nonzero flavor violating parameter δ [14]. The dominance of the branching ratio of the $t \to cgg$ over the $t \to cg$ in the MSSM can be attributed to the flavor violation in the down sector via mixing between second and third generations. In this case, up to $(\delta_{\mathcal{D}}^{23})_{LL} < 0.6$ $((\delta_{\mathcal{D}}^{23})_{LR} < 0.75)$, the branching ratio of the $t \to cgg$ decay dominates over the $t \to cg$, and is about $\sim 10^{-9}$. When $(\delta_{\mathcal{D}}^{23})_{LL} > 0.6$ $((\delta_{\mathcal{D}}^{23})_{LR} > 0.75)$, branching ratios of both decays increase and the branching ratio of the $t \to cg$ decay dominates over the $t \to cgg$, which are about 10^{-6} (10^{-7}) and 10^{-7} (10^{-8}), respectively.

As has already been noted, FCNC processes are very sensitive to the new physics effects. One such model is the so-called unparticles recently proposed by Georgi [15]. Phenomenology of unparticle physics is studied extensively in the literature [16,17]. In the present work we study $t \to cgg$ $(t \to c\gamma\gamma)$ decay in the framework of unparticle physics.

For the calculation of the branching ratio of $t \to cgg$ $(t \to c\gamma\gamma)$ decay in unparticle physics, an interaction Lagrangian between SM fields and unparticles is needed. Below $\Lambda_{\mathcal{U}} = 1$ TeV, it has the following form:

$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda_{\mathcal{U}}} O_{\text{SM}} O_{\mathcal{U}}. \tag{1}$$

Obviously, high-dimension operators should be suppressed by the inverse power of $\Lambda_{\mathcal{U}}$. Therefore, we should choose the appropriate operators with the lowest dimension which satisfy the SM gauge symmetry. The effective Lagrangians of scalar and tensor unparticle operators with SM fields are given in [18], and it follows from their expressions that, in unparticle theory, gluons and photons interact with unparticles, and therefore, the flavor violating $t \to cgg$ and $t \to c\gamma\gamma$ decays can take place at tree level in unparticle physics, while they exist at loop level in the SM, and this is the main reason why we consider them in unparticle physics.

In the present work we follow Georgi's approach [15], namely, Feynman propagators of the unparticle operator $O_{\mathcal{U}}$ are determined from the scale invariance. The scalar and tensor unparticle operators are given as

$$\begin{aligned} \mathcal{D}(q^2) &= \frac{A_{\mathcal{U}}}{2\sin(d_{\mathcal{U}}\pi)}(-q^2)^{d_{\mathcal{U}}-2}, \quad \text{and,} \\ \Delta_{\mu\nu\rho\sigma} &= \mathcal{D}(q^2)\mathcal{P}_{\mu\nu\rho\sigma}, \end{aligned} \tag{2}$$

respectively. The explicit form of $\mathcal{P}_{\mu\nu\rho\sigma}$ due to the scale invariance and in conformal field theory can be found in [18,19] (see also [20]), and the normalization factor $A_{\mathcal{U}}$ can be found in [15], respectively.

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After standard calculation for the matrix element of the $t \to cgg$ decay exchanging the scalar and tensor unparticles, we get, respectively,

$$M_S = T^+_{\mu\nu}\left\{\frac{\lambda^a}{2}\frac{\lambda^b}{2}\right\}\bar{c}[C_S + C_P\gamma_5]t\varepsilon^a_\mu(k_1)\varepsilon^b_\nu(k_2),$$

$$M_T = \left(T^+_{\mu\nu\rho\sigma}\left\{\frac{\lambda^a}{2}\frac{\lambda^b}{2}\right\} + T^-_{\mu\nu\rho\sigma}\left[\frac{\lambda^a}{2}\frac{\lambda^b}{2}\right]\right) \times \mathcal{P}_{\rho_1,\sigma_1,\rho\sigma}\bar{c}\{\lambda^{tc}[\gamma_{\rho_1}(p_c + p_t)_{\sigma_1} + \gamma_{\sigma_1}(p_c + p_t)_{\rho_1} + \lambda'^{tc}[\gamma_{\rho_1}\gamma_5(p_c + p_t)_{\sigma_1} + \gamma_{\sigma_1}\gamma_5(p_c + p_t)_{\rho_1}]\}t\varepsilon^a_\mu\varepsilon^b_\nu, \quad (3)$$

where

$$T^+_{\mu\nu} = \frac{1}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}-1}}\frac{A_{\mathcal{U}}}{\sin(d_{\mathcal{U}}\pi)}\frac{1}{(q^2)^{2-d_{\mathcal{U}}}}\{\lambda_0[k_{1\nu}k_{2\mu} - g_{\mu\nu}(k_1\cdot k_2)] + \lambda_0'\epsilon_{\mu\nu\alpha\beta}k_{1\alpha}k_{2\beta}\},$$

$$T^\pm_{\mu\nu\rho\sigma} = \frac{1}{4\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}}\frac{A_{\mathcal{U}}}{2\sin(d_{\mathcal{U}}\pi)}\frac{1}{(q^2)^{2-d_{\mathcal{U}}}} \times (\lambda_2 K^{S(A)}_{\mu\nu\rho\sigma} + \lambda_2' F^{S(A)}_{\mu\nu\rho\sigma}), \quad (4)$$

where

$$K^{S(A)}_{\mu\nu\rho\sigma} = \tfrac{1}{2}\{(k_1\cdot k_2)g_{\mu\rho}g_{\nu\sigma} + g_{\mu\nu}k_{1\rho}k_{2\sigma} - g_{\nu\sigma} + g_{\mu\nu}k_{1\rho}k_{2\mu} - g_{\mu\rho} + g_{\mu\nu}k_{1\nu}k_{2\sigma} \pm [(k_1\cdot k_2)g_{\mu\nu}g_{\rho\sigma} + g_{\mu\rho}k_{1\nu}k_{2\sigma} - g_{\rho\sigma} + g_{\mu\rho}k_{1\nu}k_{2\mu} - g_{\mu\nu} + g_{\mu\rho}k_{1\rho}k_{2\sigma}]\},$$

$$F^{S(A)}_{\mu\nu\rho\sigma} = \tfrac{1}{2}(k_{1\rho}k_{2\beta}\epsilon_{\mu\nu\beta\sigma} - k_{1\alpha}k_{2\beta}g_{\mu\rho}\epsilon_{\sigma\alpha\beta\nu} \mp k_{1\beta}k_{2\rho}\epsilon_{\mu\nu\beta\sigma} \mp k_{1\beta}k_{2\alpha}g_{\rho\nu}\epsilon_{\sigma\alpha\beta\mu}).$$

The matrix element for the $t \to c\gamma\gamma$ decay can easily be obtained from the $t \to cgg$ decay by making the replacements $\{\lambda^a/2, \lambda^b/2\} \to 1$, $[\lambda^a/2, \lambda^b/2] \to 0$, and omitting color indices in ε^a_μ.

Now we are ready to calculate the branching ratio of the $t \to cgg$ and $t \to c\gamma\gamma$ decays. In calculation of the branching ratios of these decays there appear infrared and as collinear divergences. The collinear singularity can be avoided by taking into account the mass of the c-quark, and the infrared singularity is eliminated by putting the cutoff factor in the "dangerous" integration limit where singulariries are present (see [21]). Following [22,23], for the polarization sum of the gluons we use $P_{\mu\nu} = \sum_{\lambda=1,2}\varepsilon^*_\mu(k,\lambda)\varepsilon_\nu(k,\lambda) = -g_{\mu\nu} + [(k_{1\mu}k_{2\nu} + k_{1\nu}k_{2\mu})/k_1\cdot k_2]$, which leads to the gauge invariant result for on-shell massless vector mesons.

Using the matrix element for the $t \to cxx$ ($x = g, \gamma$) decay, and performing summation over gluon (photon) polarizations in the rest frame system of the decaying t-quark, we get for the differential decay width

$$d\Gamma = \frac{1}{256 m_t \pi^3}C_X|M_X|^2 dE_c dE_1,$$

where E_c and E_1 are the energies of the c-quark and one of the final gluons (photons), C_X is the color factor whose values for the consired decays can be found in [21].

Having the expression of the differential decay width, we study the sensitivity of the branching ratio on the scaling dimension parameter $d_{\mathcal{U}}$, energy scale $\Lambda_{\mathcal{U}}$, and the coupling constants. In numerical analysis we choose the scaling dimension $d_{\mathcal{U}}$ in the range $1 < d_{\mathcal{U}} < 2$. The main reason for choosing $d_{\mathcal{U}} > 1$ is that in this region the decay rate is free from the nonintegrable singularity [15]. As has already been mentioned, there appear singularities for $d_{\mathcal{U}} > 2$. Therefore, we will consider the above-mentioned restricted domain of $d_{\mathcal{U}}$. In our calculations we introduce the parameter α, which is defined as $\lambda_0' = \alpha\lambda_0$, where we set $\lambda_0 = 1$. The values of the off-diagonal t-c unparticle coupling constants C_S and C_P are chosen in the range 10^{-1}–10^{-3}. A few words about the values of the parameters C_S and C_P are in order. It follows from Eq. (4) that the couplings in the effective Lagrangian are all flavor blind. Therefore, we can use restrictions for these couplings coming from the analysis of the $b \to s\gamma$ and $\mu \to e\gamma$ decays. In view of the study of the unparticle effects on the $b \to s\gamma$ decay in [24], it can be said that the bounds of the couplings C_P and C_S increase with increasing $d_{\mathcal{U}}$. For example, at $d_{\mathcal{U}} = 1.5$, C_P and C_S are both about $\sim 10^{-2}$. Moreover, the analysis of the $\mu \to e\gamma$ decay [25] in unparticle physics also leads to similar restrictions. For these reasons, our choice of the values of C_P and C_S is of the same order of magnitude coming from the analysis of $b \to s\gamma$ and $\mu \to e\gamma$ decays.

For the parameter α we choose three different values $\alpha = 0.1$; 0.5; 1.0. Note that the branching ratio of the $t \to cgg$ decay in the SM is calculated in [9] which predicts $\mathcal{B}(t \to cgg) \simeq 1.02 \times 10^{-9}$, when the cutoff parameter C is taken as $C = 10^{-3}$. Our numerical calculations show that when the cutoff parameter C varies in the range $C = 0.001$–0.1 for a given set of the fixed values of C_P and C_S, no substantial change in the value of the branching ratio is observed, the variation being about 3 times. The above-mentioned value of the branching ratio of the $t \to cgg$ decay in the SM is too small to be observable in the forthcoming LHC experiments. For this reason any experimental observation of the $t \to cgg$ decay will definitely indicate the appearance of the new physics beyond the SM. Therefore, the observability limit of the $t \to cgg$ decay can be assumed to be $\mathcal{B}(t \to cgg) > 10^{-9}$. In this connection there follows the question about the range of values of $d_{\mathcal{U}}$ for which the branching ratio is larger than 10^{-9}, at the value $\Lambda_{\mathcal{U}} = 1$ TeV of the cutoff parameter and at fixed values of the effective couplings C_P and C_S (in the presence of the scalar unparticle operator).

Our numerical analysis predicts that the corresponding branching ratios are larger compared to the SM result,

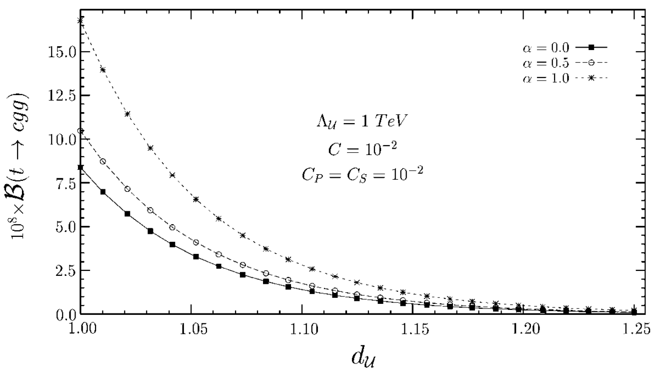

FIG. 1. The dependence of the branching ratio of the $t \to cgg$ decay on $d_{\mathcal{U}}$, at the values $C_P = C_S = 10^{-2}$ of the t-c unparticle coupling constants, at $C = 10^{-2}$ of the cutoff parameter, and at $\Lambda_{\mathcal{U}} = 1$ TeV, when the scalar unparticle is the mediator.

(i) at $C_S = C_P = 10^{-1}$, $d_{\mathcal{U}} < 1.5$ (< 1.53, < 1.55), and when $C = 0.1$ (10^{-2}, 10^{-3});

(ii) at $C_S = C_P = 10^{-2}$, $d_{\mathcal{U}} < 1.2$ (< 1.24, < 1.25), and when $C = 0.1$ (10^{-2}, 10^{-3}).

Note that, except the color factor, the decay rates of the $t \to cgg$ and $t \to c\gamma\gamma$ are identical in the unparticle physics. The branching ratios of both decays are of the same order, which differs from the SM prediction. It should be stressed that, in the SM, the branching ratio of the $t \to c\gamma\gamma$ decay is much smaller compared to the $t \to cgg$ decay, due to the factor α^2/α_S^2 of the coupling constants. As far as the $t \to c\gamma\gamma$ is concerned, we find

(i) at $C_S = C_P = 10^{-1}$, $d_{\mathcal{U}} < 1.4$ (< 1.42, < 1.45), and when $C = 0.1$ (10^{-2}, 10^{-3});

(ii) at $C_S = C_P = 10^{-2}$, $d_{\mathcal{U}} < 1.2$ (< 1.21, < 1.22), and when $C = 0.1$ (10^{-2}, 10^{-3}).

It follows from the above-presented results that the restrictions to the values of $d_{\mathcal{U}}$ in both decays, for which the branching ratio exceeds 10^{-9}, are practically the same.

As an illustration of our analysis, we present in Fig. 1 the dependence of the branching ratio of the $t \to cgg$ decay on $d_{\mathcal{U}}$, at $C_S = C_P = 10^{-2}$, $C = 10^{-2}$, when the scalar unparticle operator is the mediator. From this figure we see that up to $d_{\mathcal{U}} = 1.1$ the perpendicular spin polarization

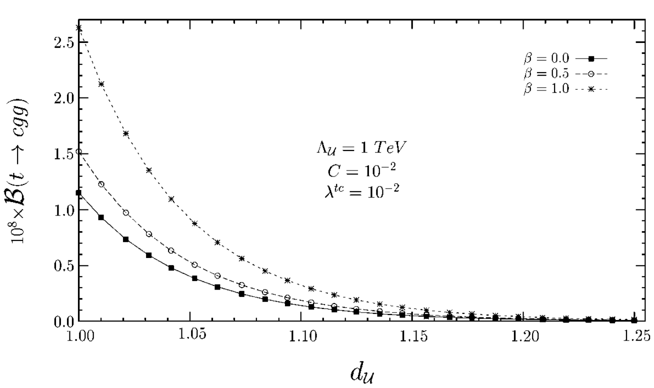

FIG. 2. The same as in Fig. 1, but when the tensor unparticle is the mediator.

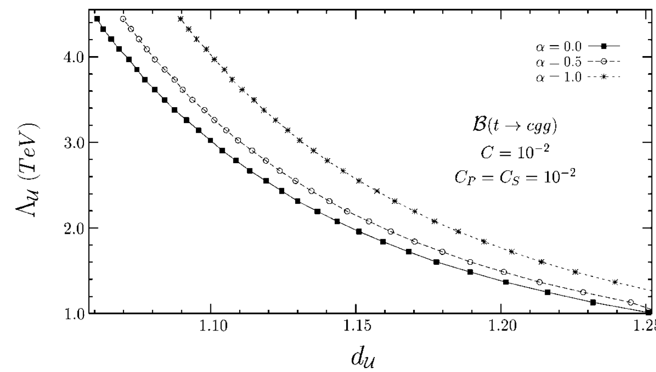

FIG. 3. The parametric plot of the dependence of $\Lambda_{\mathcal{U}}$ on the scaling parameter $d_{\mathcal{U}}$ at $C = 10^{-2}$ and $C_P = C_S = 10^{-2}$, when the branching ratio for the $t \to cgg$ decay $\mathcal{B}(t \to cgg) = 1.2 \times 10^{-9}$, and when the scalar unparticle is the mediator.

exceeds the parallel spin polarization for a two-gluon system at $\alpha = 1$. These results are quite interesting since they give valuable information about the scaling parameter $d_{\mathcal{U}}$, as well as information about gluon-gluon unparticle coupling constants.

Before presenting the numerical results on the branching ratio of the $t \to cgg$ decay which takes place via tensor particle exchange, a few remarks about the coupling constant λ^{tc} should be mentioned. In principle, the coupling constant λ^{tc} can be different from the coupling constant $C_{P(S)}$. But, for simplicity, we will assume the universality of the coupling constants, since they are flavor blind. In other words, we will assume that λ^{tc} changes in the region 10^{-1}–10^{-3}, similar to the scalar case. Depicted in Fig. 2 is the dependence of the branching ratio for the $t \to cgg$ decay on $d_{\mathcal{U}}$ at $\Lambda_{\mathcal{U}} = 1$ TeV, when the mediator is the tensor particle. In this figure β is defined as $\beta = \lambda_2'/\lambda_2$, where we set $\lambda_2 = 1$ in the numerical calculations. It follows from this figure that, when the coupling constants of the two-gluon system with perpendicular and parallel spin orientations are equal, the branching ratio of the spin-perpendicular configuration exceeds the spin-parallel configuration of the two-gluon system up to $d_{\mathcal{U}} = 1.15$.

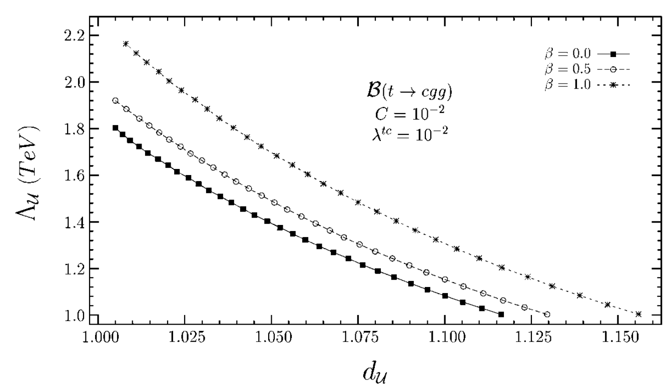

FIG. 4. The same as in Fig. 3, but when the tensor unparticle is the mediator.

Note that all of the above-presented results are obtained at $\Lambda_{\mathcal{U}} = 1$ TeV. In this connection the question of how restrictions on $d_{\mathcal{U}}$ depend on the cutoff parameter $\Lambda_{\mathcal{U}}$ should be considered. In other words, at which parametric region of $d_{\mathcal{U}}$ and $\Lambda_{\mathcal{U}}$ is the branching ratio larger than 10^{-9}? In order to answer this question, we present in Figs. 3 and 4 the parametric plot of the branching ratio with respect to $d_{\mathcal{U}}$ and $\Lambda_{\mathcal{U}}$ which gives $\mathcal{B} = 10^{-9}$, for the $t \to cgg$ decay, at fixed values of $C_S = C_P = \lambda^{tc} = 10^{-2}$ and $C = 10^{-2}$, in the presence of the scalar and tensor operators. The region on the right side of each curve should be excluded, since $\mathcal{B} < 10^{-9}$ in this domain. We perform a similar calculation at the value 10^{-1} of the coupling constants also, and we observe that stringent constraints due to $d_{\mathcal{U}}$ and $\Lambda_{\mathcal{U}}$ are obtained for the $C_P = C_S = \lambda^{tc} = 10^{-2}$ case. The choice of other values of C causes negligibly small changes in the numerical results.

In conclusion, we analyze the rare $t \to cgg$ decay, that can exist at tree level in unparticle physics. Note that these decays can take place only at loop level in the SM. For this reason the branching ratio of these decays in unparticle physics can exceed the ones predicted by the SM. The experimental measurement of the branching ratios larger than 10^{-9} can give valuable information about the existence of the new physics beyond the SM, in particular, about the unparticle physics.

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