Study of the Top Quark FCNC

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Abstract

We study the one-loop contribution of the effective flavor changing neutral couplings (FCNC) $tcZ$ to the charm quark electric dipole moment. Using the known limits on the top and charm quarks electric dipole moments, we place limits on these FCNC anomalous couplings.

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1 Introduction

The standard model (SM) is in a very good agreement with present experimental data. Nonetheless, it is believed to leave many questions unanswered, and this belief has resulted in numerous theoretical and experimental attempts to discover a more fundamental underlying theory. Various types of experiments may expose the existence of physics beyond the SM, including the search for direct production of exotic particles at high energy colliders. A complementary approach in hunting for new physics is to examine its indirect effects in higher order processes. Since top quark is far more massive than other SM fermions, its interactions may be quite sensitive to new physics originating at higher scale \[1\]. If there are any deviations from the SM expectations in the properties of the top quark, they may indirectly lead to modifications in the anticipated branching fractions.

In the SM, due to the Glashow-Iliopoulos-Maiani (GIM) mechanism, the top quark Flavor Changing Neutral Current (FCNC) interactions are absent at tree level and are extremely suppressed at loop level. Therefore, the observation of any FCNC top quark process a smoking gun for new physics beyond the SM.

Within the SM framework, FCNC interactions are induced by the $W$ boson charged current Cabbibo-Kobayashi-Maskawa (CKM) transitions involving down-type quarks in the loops which are much lighter than the top quark. In models beyond SM such as minimal supersymmetric standard model (MSSM) or Technicolor theory, although the top quark FCNC interactions are also induced at loop level, they can be greatly enhanced relative to the SM predictions. For example in MSSM, in addition to the $W$ boson loops, there are four kinds of loops contributing to the top quark FCNC interactions. In MSSM, charged Higgs, chargino, gluino and neutralino loops contribute to the top quark FCNC interactions. Theoretical branching ratios of FCNC top quark decays in various models are presented in Table\[1,2,3\]. It is worth mentioning that at the LHC, the branching fraction for top FCNC decay, $BR(t \rightarrow Zq)$, can be measured with the precision of $6.1 \times 10^{-5}$ and $3.1 \times 10^{-4}$ with the integrated luminosity of 100 $fb^{-1}$ and 10 $fb^{-1}$, respectively \[4,5,6\]. There are several studies on the top quark FCNC which some of them can be found in:
Table 1: Theoretical branching ratios of FCNC top quark decays in various models.

| Model       | SM     | MSSM   | Technicolor |
|-------------|--------|--------|-------------|
| $BR(t \to cZ)$ | $\sim 10^{-14}$ | $\sim 10^{-6}$ | $\sim 10^{-4}$ |

In this article, our aim is to constraint the top quark FCNC anomalous couplings, in the process of $t \to Zc$, using effects induced by the electric dipole moment (EDM) of top quark on the one loop induced EDM of the charm quark. In the analysis, we will use the estimated bounds on the EDM’s of top and charm quark to constraint the anomalous couplings.

2 Effective FCNC Lagrangian

One tool that is often used to describe the effects of new physics at an energy scale of $\Lambda$, much higher than the electroweak scale, is the effective Lagrangian method. If the underlying extended theory under consideration only becomes important at a scale $\Lambda$, then it makes sense to expand the Lagrangian in powers of $\Lambda^{-1}$:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^{n_i-4}} O_i$$

where $\mathcal{L}_{SM}$ is the standard model Lagrangian, $O_i$’s are the operators containing only the SM fields, $n_i$ is the dimension of $O_i$ and $c_i$’s are dimensionless parameters [14], [15], [16].

In the top quark sector, the lowest dimension operators that contribute to FCNC with the $Ztc$ vertex can be written as [17]:

$$\mathcal{L}_{eff} = -\frac{g}{2\cos\theta_W} \left[ \kappa_L Z^n \bar{t} \gamma_\mu P_L c + \kappa_R Z^n \bar{t} \gamma_\mu P_R c + h.c. \right]$$

where $g$ is the coupling constant of $SU(2)_L$, $\theta_W$ is the Weinberg mixing angle and $\kappa_{L,R}$ are free parameters determining the strength of these anomalous couplings. Assuming CP invariance $\kappa_{L,R}$ are real. In the above relation, $P_{L,R}$ are the left-handed and right-handed projection operators. The top FCNC anomalous interaction leads to the following
branching fraction for the $t \to Zc$ (in the limit of zero mass of $b, c$ quarks):

$$BR(t \to Zc) \equiv \frac{\Gamma(t \to Zc)}{\Gamma(t \to Wb)} = \frac{(\kappa_L^2 + \kappa_R^2)}{2} \frac{(m_t^2 - m_Z^2)^2 (m_t^2 + 2m_Z^2)}{(m_t^2 - m_W^2)^2 (m_t^2 + 2m_W^2)} \approx 0.5(\kappa_L^2 + \kappa_R^2) \quad (3)$$

Recent upper bound from CDF experiment for branching fraction of $t \to Zq, (q = u, c)$, is 3.7% (with 95% C.L.)\cite{18}. Therefore, one can conclude $\kappa_L^2 + \kappa_R^2 < 0.074$.

### 3 Estimation of the Constraints

We consider the effective interaction of the quarks with on-shell photons to make prediction of the acceptable range for the FCNC parameters ($\kappa_L, \kappa_R$)\cite{19,20,21}:

$$\mathcal{L}_{\text{eff}} = -i\frac{d_q q \gamma_5 \sigma_{\mu\nu} q F^{\mu\nu}}{2} \quad (4)$$

where $F^{\mu\nu}$ is the electromagnetic field tensor and $d_q$ is the top quark electric dipole moment (EDM) which is a real number by hermiticity. One should note that this is a CP violating term. Therefore, a non-vanishing value for EDM of a fermion is of special interest as it signifies the presence of CP violating interactions.

In the SM, top quark can not have an EDM at least to three-loops. The SM prediction for the top EDM is $10^{-31} - 10^{-32}$ e-cm which is too small to be observable. In contrast, in extensions of SM, such as MSSM, this situation changes sharply and the top quark EDM can arise at the one-loop. In beyond standard model theories the typical top EDM is of order of $10^{-18} - 10^{-20}$ e-cm which is larger than the SM prediction by more than 10 orders of magnitude\cite{20,21}.

The contribution of top quark FCNC introduced by Eq\cite{2} to the on-shell $c\bar{c}\gamma$ coupling is given through the diagram shown in the left side of Fig\cite{1}. Using the effective interactions in Eq\cite{2} Eq\cite{4} and after some algebra the respective one-loop vertex can be written as:

$$\Gamma_{\mu} = -\frac{g^2}{4 \cos^2 \theta_W} \times d_t \times$$

\begin{align*}
&\int \frac{d^4k}{(2\pi)^4} \left[\ldots + (m_t (\kappa_L^2 + \kappa_R^2) (\not{p}_2 - \not{p}_1) - 4\kappa_L \kappa_R (k.(p_1 + p_2) - p_1.p_2 + m_t^2 - m_Z^2)) \gamma_5 \sigma_{\mu\nu} q \not{q}'\right] \\
&\quad \times \frac{(k^2 - m_Z^2)((p_1 - k)^2 - m_t^2)((p_2 - k)^2 - m_t^2)}{(k^2 - m_Z^2)((p_1 - k)^2 - m_t^2)((p_2 - k)^2 - m_t^2)}
\end{align*} \quad (5)
One should note that there are contributions to both magnetic and electric dipole moments of the charm quark which we have kept only the terms contributing to EDM. After evaluating the integral over $k$:

$$d_c = \frac{\alpha}{4\pi \sin^2 \theta_W \cos^2 \theta_W} \times d_t \times \left[ (\kappa_L^2 + \kappa_R^2)f(x_t, x_c) + \kappa_L \kappa_R g(x_t) \right]$$  \hspace{1cm} (6)$$

where

$$f(x_t, x_c) = \frac{\sqrt{x_t x_c}}{2} \times \frac{1 + 3x_t(x_t - 4/3) - 2(2x_t - 1) \log(x_t)}{2(x_t - 1)^3}, \quad g(x_t) = \frac{x_t - \log(x_t) - 1}{x_t - 1}$$  \hspace{1cm} (7)$$

where $x_t = \frac{m_t^2}{m_Z^2}$ and $x_c = \frac{m_c^2}{m_Z^2}$. In obtaining the above relation, we have ignored of the terms proportional to $(m_c^2/m_Z^2)$, which in fact is a negligible quantity.

In [22], the authors have estimated the upper bound of $7 \times 10^{-21}$ on the top and $1 \times 10^{-27}$ on the charm quark electric dipole moments using the experimental bound on neutron electric dipole moment. The combination of these bounds and Eq.[6] leads to the exclusion contour shown in the right side of Fig.[1]. However, in this exclusion contour another parameterizations for top FCNC anomalous coupling has been used which are related to the parameters of Eq.[2] by: $\kappa_{R,L} \equiv g_V \pm g_A$. If we combine our result with that obtained by CDF experiment, which mentioned before, the bounds on $\kappa_{R,L}$ are estimated as: $\kappa_L < 3 \times 10^{-3}$, $\kappa_R < 0.27$. These values are compatible with the ones estimated in the other studies [17]. The obtained upper bound on $\kappa_L$ in [17] is $5 \times 10^{-2}$. Hence, the allowed region for $\kappa_L$ from the present work is one order of magnitude smaller than the one obtained in [17].

4 Conclusion

In this article, within the framework of the effective Lagrangian approach, we performed a calculation of the radiative corrections induced on the charm quark electric dipole moment by the effective FCNC vertex $tcZ$. Using the present upper bounds on the top and charm quark EDM’s, the new limits on the top FCNC anomalous couplings were estimated:
\( \kappa_L < 3 \times 10^{-3} \), \( \kappa_R < 0.27 \). These limits are regular and comparable with the ones obtained in the past studies and the estimated limit on \( \kappa_L \) is slightly better.

**Acknowledgments**

The authors would like to thank A. Khorramian for his supports.

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