Chromomagnetic and chromoelectric dipole moments in the 4GTHDM

A. Hernández-Juárez and G. Tavares
Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla,
Apartado Postal 1152, Puebla, Pue., México.

A. Moyotl
Departamento de Física, CINVESTAV, Apdo. Postal 14-740, 07000 México, D. F., México.

Abstract. The contributions to the chromomagnetic (CMDM) and chromoelectric (CEDM) dipole moments of the top quark are calculated in framework of the two-Higgs doublet model with a sequential fourth family. We only consider the contributions arising from the neutral scalar bosons $H^0$ and $A^0$, whereas the contribution of the charged scalar will be analyzed elsewhere. For the scalar boson masses we consider the degenerate case, with 200 GeV $\lesssim m_\phi < 500$ GeV, while for the mass of the fourth family up quark we consider the interval 400 GeV $< m_{t_4} < 600$ GeV. It is found that the CMDM and CEDM are specially sensitive when $m_\phi$ is about 600 GeV and can reach the sizes of $|a_t| \sim 10^{-5}$ and $|d_t| \sim 10^{-24}$ e cm, respectively.

1. Introduction

Since its discovery, the top quark has played a special role in the standard model (SM) phenomenology due to its large mass, which is of the same order as the electroweak symmetry breaking scale. Furthermore, it is the only quark that decays semi-weakly, and its Yukawa coupling is almost of the order of the unity. In addition, it has a very short life time, therefore it does not hadronize. At the CERN Large Hadron Collider (LHC), the top quark is produced mainly in pairs through the processes $qq \rightarrow tt$ and $gg \rightarrow tt$, where at $\sqrt{s} = 14$ TeV about 90% of the top quark production arises from gluon-gluon fusion and the remainder from $qq$ annihilation.

In the context of the SM there are many unsolved problems, one of the most interesting is the baryon asymmetry of the universe. According to Sakharov’s criteria, CP violation is a necessary requirement for this phenomena. CP violation is included in the SM via the complex phase of the CKM matrix, which is not enough to explain the baryon asymmetry and so it is worth studying new sources of CP violation arising beyond the SM. A chromoelectric dipole moment (CEDM) violates time-reversal and parity invariance, which due to the CPT theorem is equivalent to CP violation. So a non-zero CEDM would represent a signal of new sources of CP violation. The top quark chromomagnetic dipole moment (CMDM) and CEDM have been studied in several models such as the SM [1], the two-Higgs doublet model (THDM) [2], the minimal supersymmetric standard model (MSSM) [3, 4], technicolor models, 331 models [5] and models with vectorlike multiplets [6].

The top quark anomalous couplings to a gluon pair can be defined via the following
Lagrangian:

\[ L = g_s \bar{T}^a \left( \gamma_\mu + \frac{i}{2m_t} \sigma_{\mu\nu} \left( a_t + id_t \gamma^5 \right) q^\nu \right) T^a G_\mu^a \]  

(1)

where \( a_t \) and \( d_t \) are the CMDM and CEDM respectively, while \( G_\mu^a \) is the gluon field, \( T^a \) are the color generators and \( q \) is the outgoing gluon four-momentum. In the SM the top quark CMDM is induced at one loop level [5], whereas the CEDM appears only at the three-loop level [7] and thus the SM prediction is negligibly small. The most recent bounds to CMDM and CEDM are \(-0.016 < a_t < 0.008 \) and \(|d_t| < 4.8 \times 10^{-16} \text{ e} \cdot \text{cm} \) respectively [8].

In this work we study the CMDM and CEDM of the top quark in the THDM with a sequential fourth family (4GTHDM), which was proposed by Bar Shalom et al. in 2011 [9]. In 2012 with the discovery of a Higgs boson consistent with the SM, these authors revisited their model [10, 11] and constrained the fourth family mass and some parameters of the model. A fourth family was introduced in the past in the SM4 [12]. Unfortunately, this model is not consistent with the Higgs boson production in the LHC [13, 14]. In the 4GTHDM the fourth family interacts only with the heavy scalar bosons, and thus the theoretical prediction for Higgs boson production remains unchanged. The contributions to the magnetic dipole moment have been calculated in [15] and were reviewed in [10], also different decay modes have been studied in [15]. In this work we only consider the neutral scalar boson contributions to the CMDM and CEDM of the top quark, whereas a discussion on the contribution of the charged scalar boson mass will be presented elsewhere.

2. THDM with a sequential fourth generation

There are many motivations for the study of THDMs. In particular the MSSM scalar sector is composed by two Higgs doublets and axions models also require two Higgs doublets. THDMs have been introduced in order to explain the large top-quark mass through the inequality between the two vacuum expectation values (VEVs) \( v_1 \gg v_2 \). The Higgs sector of these models is composed of two doublet scalar fields \( \Phi_1 \) and \( \Phi_2 \) with VEVs \( v_1 \) and \( v_2 \) respectively. We use the usual definitions \( v \equiv \sqrt{v_1^2 + v_2^2} \) and \( \tan \beta \equiv v_2/v_1 \). The fourth family can be introduced in three different scenarios [9]: (i) \( \Phi_1 \) gives masses only to the fermions of the fourth family and \( \Phi_2 \) generates masses for all other fermions, (ii) \( \Phi_1 \) generates the masses of both the third and fourth families, while \( \Phi_2 \) generates masses for all the other families, (iii) \( \Phi_1 \) is only coupled to fermions with masses at the EW scale. In this work we only consider the case (i), which is compatible with the 125 GeV Higgs [10, 11].

In the 4GTHDM flavor changing neutral currents arise at the tree level and are associated with the heavy scalar bosons. The Yukawa interactions of the neutral scalar bosons are given by:

\[ \mathcal{L}_{\text{FV}} = \frac{g}{2m_W} f_\beta \tilde{T}^i \left[ g_s^\phi + g_p^\phi \gamma_5 \right] \ell_j \phi_i \]  

(2)

where \( \phi = H^0, A^0 \), whereas the coupling constants \( f_\beta, g_s^\phi \) and \( g_p^\phi \) acquire values according to Table 1. The subscripts \( i, j \) refers to the flavor of the quarks, but we are interested in non-diagonal couplings \( (i \neq j) \). On the other hand, since the SM is reproduced in the limit \( \sin(\beta - \alpha) = 1 \), it is convenient to introduce a parameter \( \chi \) defined as \( \chi \equiv \frac{\pi}{2} - (\beta - \alpha) \), where \( \chi = 0 \) corresponds to the SM limit. Then, we expect tiny deviations from the SM, i.e. we take \( \chi \simeq 0 \).
Table 1. Coupling constant $f_\beta^\phi$, $g_s^\phi$ and $g_p^\phi$ for the neutral scalar bosons $H^0$ and $A^0$. $I_q$ is the weak isospin, whereas $\alpha$ and $\beta$ are mixing angles. We use the short-hand notation $s_\alpha \equiv \sin \alpha$, $c_\alpha \equiv \cos \alpha$ and $t_\beta \equiv \tan \beta$. Additionally, $\Sigma_{u,d}^{ij}$ is a complex element of the new mixing $4 \times 4$ matrix in the 4G2HDM.

| $\phi$ | $f_\beta^\phi$ | $g_s^\phi$ | $g_p^\phi$ |
|-------|-------------|------------|------------|
| $H^0$ | $c_\alpha/c_\beta - s_\alpha/s_\beta$ | $m_{t_4} \Sigma_{ij}^q + m_{q_i} \Sigma_{ji}^{q^*}$ | $m_{t_4} \Sigma_{ij}^q - m_{q_j} \Sigma_{ji}^{q^*}$ |
| $A^0$ | $2iI_q(t_\beta + 1/t_\beta)$ | $m_{t_4} \Sigma_{ij}^q - m_{q_j} \Sigma_{ji}^{q^*}$ | $m_{t_4} \Sigma_{ij}^q + m_{q_j} \Sigma_{ji}^{q^*}$ |

Figure 1. One loop contribution to the CMDM and CEDM of the top quark in the 4GTHDM. In the loop circulate the fourth generation up quark $t_4$ and the heavy scalar bosons $\phi = H^0, A^0$.

3. Top quark CMDM and CEDM

The neutral scalar bosons contributions to the CMDM and CEDM arise through the Feynman diagrams of Figure 1, where we have a heavy quark $t_4$ into the loop. We have used Feynman parametrization to solve the loop integrals. The resulting expressions can be written as follows

\[ a_t^\phi = \left( \frac{g}{2m_W} \right)^2 \frac{f_\phi^2}{(4\pi)^2} \int_0^1 dx \left[ g_p^\phi |x - 1 - r_{t_4}|^2 + |g_s^\phi|^2 (x - 1 + r_{t_4}) \right] x^2 \frac{dx}{xr_{t_4}^2 - (x - 1)(x - r_{t_4}^2)} \]  \hfill (3)

\[ d_t^\phi = -\text{Im}(G_s^\phi G_p^{\phi^*}) \left( \frac{g}{2m_W} \right)^2 \frac{m_t^2 f_\phi^2 r_{t_4}}{(4\pi)^2} \int_0^1 dx \frac{x^2 dx}{xr_{t_4}^2 - (x - 1)(x - r_{t_4}^2)} \]  \hfill (4)

where $r_k = m_k/m_t$ and $G_s^{\phi} = g_s^{\phi}/m_t$. Furthermore, we note that $d_t^\phi$ is proportional to $\text{Im}(G_s^\phi G_p^{\phi^*})$, so a complex phase is necessary to obtain a non-zero result.

4. Analysis

To simplify the analysis we will assume degenerate masses for the neutral scalar bosons, and we will consider the interval $200 \text{ GeV} < m_\phi < 500 \text{ GeV}$. Furthermore, from the analysis of the $\tau \to \mu \gamma$ decay [15], assuming that it is also valid for quarks, we have taken $|\Sigma_{34}| = |\Sigma_{43}| \sim 10^{-3/2}$. We will also take $\tan(\beta) \sim O(1)$, which is in accordance with the most recent bounds from experimental data. Finally, in Ref. [11], the mass of the fourth family up quark has been constrained to $400 \text{ GeV} < m_{t_4} < 600 \text{ GeV}$. In this scenario, the lightest scalar boson $h$ is consistent with the 125 GeV Higgs boson signals measured at the LHC. Thus, in the following
In this analysis we will use this interval. In Figure 1 we show the behavior of the CMDM (left plot) and the CEDM (right plot) as functions of the scalar boson mass $m_\phi$ for $m_{t_4} = 400 \text{ GeV}$. Additionally we have used $\tan \beta = 5$ and $\chi = 0.1$. We show the partial contributions of the $H^0$ (dotted line) and $A^0$ (dashed line) scalar bosons as well as the total contribution (solid line). As for the CEDM, the contributions of both the $H^0$ and $A^0$ scalar bosons have the same order of magnitude but opposite signs, therefore the sum of both contributions is of the order $|d_t| \sim 10^{-24} \text{ e cm}$. As far as the CMDM is concerned, the total contribution is $|a_t| \simeq 10^{-5}$ for $m_\phi = 200 \text{ GeV}$, and $|a_t| \simeq 10^{-6}$ for $m_\phi = 500 \text{ GeV}$.

In Figure 3 we show the behavior of the total contribution to the top quark CDMD and CEDM for $m_{t_4} = 400 \text{ GeV}$ (dashed line), 500 GeV (solid line) and 600 GeV (dotted line). In general we have maximal contributions for a heavier $t_4$ quark, however, for a relative light scalar boson mass, the difference between the distinct contributions is negligible. For the CMDM we have $|a_t| \simeq 1.25 \times 10^{-5}$ for $m_\phi = 200 \text{ GeV}$ and $|a_t| \simeq 8.2 \times 10^{-6}$ for $m_\phi = 600 \text{ GeV}$ when $m_{t_4} = 600 \text{ GeV}$, whereas $|a_t| \simeq 6.4 \times 10^{-6}$ for $m_{t_4} = 400 \text{ GeV}$. On the other hand, for the CEDM we have $|d_t| \simeq (1.4 - 1.5) \times 10^{-24} \text{ e cm}$ for $m_\phi = 200 \text{ GeV}$ and $|d_t| \simeq 1.18 \times 10^{-24} \text{ e cm}$ for $m_\phi = 600 \text{ GeV}$ when $m_{t_4} = 600 \text{ GeV}$, whereas $|d_t| \simeq 9.2 \times 10^{-25} \text{ e cm}$ for $m_{t_4} = 400 \text{ GeV}$.

![Figure 2](image-url)  
**Figure 2.** The CMDM (left plot) and CEDM (right plot) as functions of scalar mass $m_\phi$. We have used $m_{t_4} = 400 \text{ GeV}$, $\tan \beta = 5$ and $\chi = 0.1$. We show the partial contributions of $H^0$ (dotted line) and $A^0$ (dashed line) as well as the total contribution (solid line).

![Figure 3](image-url)  
**Figure 3.** The same as in Figure 2, but for the total contribution to the top quark CMDM and CEDM for three distinct values of $m_{t_4}$.
5. Conclusions

We have presented the contributions to both the chromomagnetic and chromoelectric dipole moments of the top quark in the framework of the two-Higgs doublet model with a sequential fourth family. We only discussed the contributions of the neutral scalar bosons. A more comprehensive analysis, including the contribution of the charged scalar boson, will be presented elsewhere. We have found that in general we have maximal contributions for a heavier up quark of the fourth family. We also found that the CMDM and CEDM are sensitive to heavy scalar bosons. In particular, if $m_{t_4} = 600$ GeV $|a_t| \simeq 1.25 \times 10^{-5}$ and $|d_t| \simeq (1.4 - 1.5) \times 10^{-24} e\text{ cm}$ for $m_\phi = 200$ GeV.

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