Flavor Changing Neutral Currents in a Realistic Composite Technicolor Model

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Abstract

We consider the phenomenology of a composite technicolor model proposed recently by Georgi. Composite technicolor interactions produce four-quark operators in the low energy theory that contribute to flavor changing neutral current processes. While we expect operators of this type to be induced at the compositeness scale by the flavor-symmetry breaking effects of the preon mass matrices, the Georgi model also includes operators from higher scales that are not GIM-suppressed. Since these operators are potentially large, we study their impact on flavor changing neutral currents and CP violation in the neutral $B$, $D$, and $K$ meson systems.

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1 Introduction

Minimal technicolor [1] models present an elegant mechanism for electroweak symmetry breaking, but they do not explain how the fermions acquire their masses. Extended technicolor (ETC) models [2] provide a mechanism for fermion mass generation by means of extended gauge interactions that couple the quarks and leptons to technifermion condensates. Since these interactions mediate flavor changing neutral currents (FCNC), however, it is difficult to construct a realistic ETC model that can generate a large top quark mass without violating the FCNC bounds. Composite technicolor standard models (CTSM) [3] attempt to overcome this problem by introducing three different ETC groups, so that it is possible to maintain a GIM mechanism in the CTSM sector of the theory. The flavor symmetry breaking effects of the preon mass matrices in CTSM models are responsible for generating the fermion masses, while producing FCNC effects at acceptable, and often interesting, levels.

In ref. [4], a composite technicolor model was presented that approximately reproduces the correct phenomenology below 1.5 TeV. In this model, the operators that contribute to flavor changing neutral current processes come not only from the symmetry breaking effects of $M_{\text{preon}}$ at the compositeness scale, $f_2$, but also from operators, produced at a higher scale $f_1$, that are not GIM suppressed. These new operators are of the form

$$\frac{1}{f_1^2}(\overline{\psi_L}_\alpha \gamma^\mu SV_{1L}^\dagger u_L)(\overline{\psi_L}_\alpha \gamma^\mu SV_{1L}^\dagger u_L)$$

(1.1)

for the charge 2/3 quarks, and

$$\frac{1}{f_2^2}(\overline{d_L}_\alpha \gamma^\mu S_{1L}^\dagger V_{1L} d_L)(\overline{d_L}_\alpha \gamma^\mu S_{1L}^\dagger V_{1L} d_L)$$

(1.2)

for the charge −1/3 quarks, where $V$ is the CKM matrix, and $S$ is a matrix that is determined by the detailed dynamics of the model. If we write $V$ in the parameterization of ref. [4]

$$V = \left( \begin{array}{cc} e^{i(\beta-\alpha)}(1 - (1 - c_\phi)u u^\dagger)\Sigma & -s_\phi u \\ e^{i\beta} s_\phi u^\dagger\Sigma & e^{i\alpha} c_\phi \end{array} \right)$$

(1.3)

where $\Sigma$ is a unitary, unimodular 2 × 2 matrix, and $u$ is a two component complex vector, then the matrix $S$ is identical to (1.3) with $\phi$ replaced by an angle $\phi'$, that is determined by the model’s vacuum alignment below the scale $f_2$. We refer the reader to the original literature for technical details. The operators (1.1) and (1.2) alter the results of the standard model box diagram calculation for the $\Delta F = 2$ amplitudes, where $F = B, C,$ or $S$. In this letter, we consider how the totality of CTSM interactions in the model of ref. [4] alters the standard model predictions for flavor mixing and CP violation in the neutral $B, D,$ and $K$ meson systems. Our analysis establishes a definite pattern of deviations from the standard model predictions that may be tested by measurements at future B factories, and by a more precise measurement of $\epsilon'/\epsilon$.

2 B-Meson Physics

The box-diagram contribution to the operator $(\overline{b_L}_\alpha \gamma^\mu d_L d_L)$ in the standard model is given by [6]

$$\frac{G_F^2}{16\pi^2} \left[ (\xi^B_f)_t^2 m_t^2 + \xi^B_c m_c \ln \left( \frac{m_c}{m_t} \right)^2 + (\xi^B_\mu)^2 m_c \right]$$

(2.1)

where

$$\xi^B_q = V_{qd} V^*_{qs}$$

(2.2)

For a top quark mass on the order of 100 GeV, the three terms in (2.1) have magnitudes in the ratio $10^3::10::1$, so we may safely neglect the last two terms in comparison to the first,

$$O^{B=2}_{S.M.} \approx \frac{G_F^2}{16\pi^2} (\xi^B_f)_t^2 m_t^2 (\overline{b_L}_\alpha \gamma^\mu d_L d_L)^2$$

(2.3)

A generic CTSM model contributes to the $\Delta B = 2$ operator by virtue of the flavor-symmetry breaking effects of the preon mass matrices [3, 7]. Treating the preon mass matrices as spurions, we can write down the following operator, consistent with the flavor symmetries of the model

$$\frac{1}{(4\pi)^4 f_2^2} (\overline{d_L}_\alpha \gamma^\mu M_{UL}^\dagger \psi_L)(\overline{d_L}_\alpha \gamma^\mu M_{UL}^\dagger \psi_L)$$

(2.4)

where $M_{UL}$ is the preon mass matrix that is proportional to the mass matrix of the charge 2/3 quarks. The order of magnitude of the coefficient of the operator has been determined by naive dimensional analysis [8], but it’s sign is unknown. From (2.4) we then find [7]

$$O^{B=2}_{1} \approx \frac{G_F^4}{(4\pi)^4} (\xi^B_f)_t^2 m_t^4 \left( \frac{f_2}{v} \right)^6 (\overline{d_L}_\alpha \gamma^\mu d_L d_L)^2$$

(2.5)
where $v$ is the electroweak symmetry breaking scale, and where, as in (2.3), we have only retained the leading terms. The new operator (1.2) gives us an additional contribution

$$\mathcal{O}_{L^2}^{B=2} = -\frac{1}{f_2^4} e^{2i\alpha} (w^*_1)^2 \sin^2(\phi - \phi') (\bar{b}_L \gamma^\mu d_L)^2$$

(2.6)

where, in the notation of (1.3), $w$ is a complex column vector defined by

$$w = \Sigma u$$

(2.7)

From now on we will adopt the parametrization of the CKM matrix in which the largest phases appear in $V_{ub}$ and $V_{td}$. Then we may combine (2.3), (2.5), and (2.6), to obtain

$$\mathcal{O}_{\Delta B=2} = \left[ \frac{G_F^2 m_t^2}{16\pi^2} - \frac{1}{f_2^4} \left( \frac{m_t}{v} \right)^2 \sin^2 \phi \right] \left( \frac{f_2}{4\pi} \right)^4 \left( \frac{f_2}{v} \right)^6 (V_{td})^2 (\bar{b}_L \gamma^\mu d_L)^2 \sin^2 \phi$$

(2.8)

A similar analysis gives us the operator responsible for the $B_S^0 \to B_S^0$ mass difference

$$\mathcal{O}_{\Delta B=2} = \left[ \frac{G_F^2 m_t^2}{16\pi^2} - \frac{1}{f_2^4} \left( \frac{m_t}{v} \right)^2 \sin^2 \phi \right] \left( \frac{f_2}{4\pi} \right)^4 \left( \frac{f_2}{v} \right)^6 (V_{td})^2 (\bar{b}_L \gamma^\mu s_L)^2 \sin^2 \phi$$

(2.9)

The CTSM parameters in (2.8) and (2.9) were estimated in ref. [4] by naive dimensional analysis. Assuming the values, $f_1 \approx 130$ TeV, $f_2 \approx 1.4$ TeV, $\phi' \approx 1$, and $m_t \approx 100$ GeV, from ref. [4], and $\phi \approx 0.04$ from the magnitude of $V_{tb}$, we may estimate the three contributions to the $\Delta B = 2$ operators. We find

$$\mathcal{O}_{\Delta B=2} = \left[ 9 \times 10^{-9} - 2 \times 10^{-8} + 2 \times 10^{-7} \right] (\text{GeV}^{-2}) (V_{td})^2 (\bar{b}_L \gamma^\mu q_L)^2$$

(2.10)

for $q = d$ or $s$. Clearly the non-standard contributions are likely to be as important as the contribution from the standard model box diagram. While it is tempting to make a stronger statement based on the large size of the third term in (2.10), our estimate of this contribution is by far the most uncertain, given the the sensitive dependence of (2.5) on the unknown scale $f_2$. In any event, if we knew the top quark mass and had an accurate, independent measure of $V_{td}$ and $V_{ts}$, then these results suggest that the mass splittings in the $B^0$ and $\bar{B}^0$ systems could differ significantly from the standard model predictions, while remaining in the expected ratio, $(V_{td}/V_{ts})^2$. Unfortunately, testing this prediction would require independent measurement of these CKM elements from the semileptonic decays of $T$ mesons, which is unlikely anytime in the near future.

A more realistic method of uncovering for the effects of (2.8) and (2.9) is by testing the standard model unitarity relation

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

(2.11)

which defines a triangle in the complex plane. As has been discussed extensively in the literature [9], the unitarity triangle provides a sensitive test of the standard model, and in particular, of the CKM picture of CP violation. If future experiments at B factories reveal that the unitarity triangle fails to close, it would imply the existence of new physics. What has provoked much excitement is the realization that CP asymmetries in certain exclusive B-meson decays can be related to the angles of the unitarity triangle in a simple way, often without hadronic uncertainties. The $B$ decays of interest are ones in which the final state can be reached by both $B^0$ and $\bar{B}^0$ decay. Since a $B^0$ meson created at time zero becomes a mixture of $B^0$ and $\bar{B}^0$ at time $t$, the decay amplitudes of each component to the final state $f$ interfere, giving a time dependent asymmetry:

$$a = \frac{\Gamma(B^0(t) \to f) - \Gamma(\bar{B}^0(t) \to f)}{\Gamma(B^0(t) \to f) + \Gamma(\bar{B}^0(t) \to f)} = \sin \Delta m t \ \text{Im} \left( \frac{p}{q} \rho \right)$$

(2.12)

where in the standard notation

$$\left( \frac{p}{q} \right)^2 = \frac{M_{12} - i \Gamma_{12}}{M_{12} - i \Gamma_{12}} \quad \text{and} \quad \rho = \frac{A(B^0 \to f)}{A(\bar{B}^0 \to f)}$$

(2.13)

where $M_{12}$ and $\Gamma_{12}$ are the off-diagonal mass and widths. Note that the decay amplitudes in the definition of $\rho$ are those of pure $B^0$ and $\bar{B}^0$ states. For the $B^0$ system, $M_{12} \gg \Gamma_{12}$, so $p/q$ simply tells us the phase of the off-diagonal mass. Furthermore, if the decay proceeds through a single weak interaction diagram, and if $f$ is a CP eigenstate, one can show that $\rho$ is also purely a phase, allowing us to write

$$\text{Im} \left( \frac{p}{q} \rho \right) = \sin 2\Phi$$

(2.14)

In the standard model, the angle $\Phi$ can be expressed in terms of the phases of the CKM matrix elements relevant to the mixing and to the specific decay channel. For the decays $B^0_S \to \rho K_S$, $B^0 \to \psi K^0_S$, and $B^0 \to \pi^+ \pi^-$, it has been shown that $\Phi$ is identically $\alpha$, $\beta$, and $\gamma$, respectively, the three angles of the unitarity triangle, as labelled in Fig.2. [10].

The new four quark interactions in our composite technicolor model are approximately superweak; they are suppressed by at least a factor of $G_F/f_2^2$ in
comparison to the standard model operators. Therefore, we do not expect large corrections to any weak decay amplitudes, except in the case of rare decays that are induced at one-loop in the standard model. For the tree-level decays that are of interest to us here, it follows that $\rho$ will not be altered from its standard model value. On the other hand, $p/q$ tells us the overall phase of the operators that contribute to the off-diagonal mass $M_{12}$. If the new $\Delta B = 2$ operators in our model had a phase differing from the standard model box diagram, then $p/q$ would be altered, and $\Phi$ would no longer give us the correct angles of the unitarity triangle. However, the operators in the CTSM model that contribute to $M_{12}$ have the same phase as the top quark box diagram, and it just happens that this diagram dominates over the other standard model contributions, as we saw in (2.3). As a result, $p/q$ will be the same as in the standard model, and the relation between CP asymmetries and the angles in the unitarity triangle will not be affected.

Also notice that two of the sides of the unitarity triangle are unchanged by the superweak interactions in our model. Both $|V_{ub}|$ and $|V_{cb}|$ will be determined accurately from semileptonic $B$ decays, fixing the length of two of the sides. Since two sides and three angles of the unitarity triangle would be immune to CTSM effects, we would conclude that the third side has the correct orientation to close the triangle. However, the length of the third side, $|V_{td}|$, is likely to be extracted from $B^0-\bar{B}^0$ mixing, which is drastically altered by CTSM effects, as we saw in (2.8). A unitarity triangle that is plausible in every way, except for the length of the side $V_{td}$, as in Fig.2, would give us indication of the additional $\Delta B = 2$ interactions in the CTSM model.

3 D-Meson Physics

While the CTSM operators can have a potentially large effect on $B^0-\bar{B}^0$ mixing, they do not leave us with a unique signature for the model. In the $D^0$ system, however, the situation may be more promising if the composite technicolor operators are large. From (1.1), the relevant four-quark interaction is

$$\frac{1}{f_1^2} (V_{ub}^* V_{cb})^2 \frac{(1 - \cos(\phi - \phi'))^2}{\sin^2 \phi} (\bar{c}_L \gamma^\mu u_L)^2$$

(3.1)

Note that there is no contribution to the $\Delta C = 2$ operator from symmetry breaking terms of the form (2.4), from the scale $f_2$. To get an idea of the size of (3.1), we will estimate its contribution to the $D^0-\bar{D}^0$ mass splitting. Using the characteristic values of the CTSM parameters from Section 2, and the vacuum insertion approximation to estimate the matrix element, we find

$$\Delta M_{CTSM} \approx 4 \times 10^{-12} \text{ MeV}$$

(3.2)

As we will see below, this result is interesting in that it is potentially larger than the standard model estimate. Note that it is well below the current experimental limit [13]

$$\Delta M_{exp} < 1.3 \times 10^{-10} \text{ MeV}$$

(3.3)

The precise standard model contribution to $\Delta M$, on the other hand, is far more difficult to determine. A number of authors have estimated that the dispersive contribution to $M_{12}$ in the $D^0$ system from two pion exchange is more than an order of magnitude larger than the short distance contribution from the standard model box diagram [11]. These authors have argued that

$$\Delta M_{SM} \approx 10^{-12} \text{ MeV}$$

(3.4)
from an estimate of the long distance effects. If we take this at face value, we conclude that the $D^0,\overline{D}^0$ mass splitting is enhanced in the CTSM model, though perhaps by not enough for us to distinguish the new short distance effect from the uncertainty in (3.4). If this is the case, then there is not much more we can say. However, there is a great deal of theoretical uncertainty in both (3.2) and (3.4). Our estimate could easily be made an order of magnitude larger by adjusting the magnitudes of the CKM factors within their allowed ranges, or by adopting a smaller value for the unknown scale $f_1$. Furthermore, a recent reformulation [12] of the standard model estimate in the language of the heavy quark effective theory has suggested that the results of ref. [11] may prove to be an overestimate. With these uncertainties in mind, it is not unreasonable to consider the possibility that $\Delta M_{CTSM} \approx 10 \Delta M_{SM}$. Assuming that this is the case, we will ignore the standard model contribution to $D^0,\overline{D}^0$ mixing all together, and derive our predictions from (3.1).

If the CTSM operator is large, then it is the primary source of indirect CP-violation in the $D^0$ system. In this limit, we can carry over the formalism introduced in Section 2 to study the CP violating asymmetries in $B$ decays. Recall that the combination of parameters effected by the additional superweak interactions in the model was $p/q$

\[
\left( \frac{p}{q} \right)^2 = \frac{M_{12} - i\Gamma_{12}}{M_{12}^* - i\Gamma_{12}} \approx \frac{M_{12}}{M_{12}}_{CTSM}
\]  

(3.5)

where $M_{12}$ is now the off-diagonal mass for the $D^0$ system. Notice that the approximate equality in (3.5) follows from our assumption that the new short distance contribution $M_{12}^{CTSM}$ dominates the total standard model contributions to both $M_{12}$ and $\Gamma_{12}$. From (3.1), we conclude that

\[
\frac{p}{q} \approx \frac{V_{ub}^* V_{cb}}{V_{ub} V_{cb}}
\]  

(3.6)

The parameter $\rho$, which is uneffected by the CTSM interactions, again is most easily evaluated in decays to a CP eigenstate that proceed predominantly through a single weak interaction amplitude. For the decay $D^0 \rightarrow K_S^0\pi^0$, for example, we obtain

\[
\rho \approx \frac{V_{us}^* V_{cd}}{V_{us} V_{cd}}
\]  

(3.7)

The CP violating decay asymmetry is then determined by the angle $\Phi$ defined in (2.14),

\[
\Phi \approx \text{Arg} \left( V_{ub}^* V_{cb} V_{us} V_{cd}^* \right) \approx \alpha
\]  

(3.8)

where $\alpha$ is the angle in the unitarity triangle shown in Fig. 2. From this example, it is clear that we would obtain the same result for any appropriately chosen $D^0$ decay mode; in the parameterization in which the phase of $V_{ub}$ is large, the only other CKM factors that enter the definition of $\Phi$ (from the upper left two by two block of the CKM matrix) will have phases that are much smaller, and we again would find that the asymmetry depends on the angle $\alpha$. With $\alpha$ determined independently from the CP asymmetry in $B^0 \rightarrow \rho K_S^0$, as discussed in Section 2, our result (3.8) provides us with a potentially testable prediction of the effects of the CTSM operator on $D^0$ decay asymmetries. However, as we shall see in the next section, these decay asymmetries will be quite small, and difficult to measure.

## 4 K-Meson Physics

As in the $B^0$ system, three operators contribute to the low-energy $\Delta S = 2$ effective Hamiltonian. From the symmetry breaking term (2.4) we obtain the operator

\[
\mathcal{O}_1^{S=2} = \frac{G_F^2}{(4\pi)^2} \left( \xi^K m^2_t + \xi^K m^2_s \right) \left( f_2/v \right) \left( d_L \gamma^\mu s_L \right)^2
\]  

(4.1)

where

\[
\xi^K = V_{qg} V^*_{qg}
\]  

(4.2)

The $\Delta S = 2$ piece of the new operator (1.2) is given by

\[
\mathcal{O}_2^{S=2} = \frac{1}{f_1^2} \left( V_{ts}^* V_{td} \right)^2 \frac{1}{\sin^2 \phi} \left( d_L \gamma^\mu s_L \right)^2
\]  

(4.3)

Finally, we include the contribution from the standard model box diagram

\[
\mathcal{O}_{S.M.}^{S=2} = \frac{G_F^2}{16\pi^2} \left( \xi^K m^2_t + \xi^K m^2_s \right) \left( m^2_t \ln \left( \frac{m^2_t}{m^2_s} \right) + (\xi^K)^2 m^2_s \right) \left( d_L \gamma^\mu s_L \right)^2
\]  

(4.4)

To determine the $K^0,\overline{K}^0$ mass splitting, we adopt the values of the parameters presented in Section 2, and estimate the hadronic matrix element using the vacuum insertion approximation. We find

\[
\Delta M_{CTSM} = (\pm 0.6 + 3.2 + 0.6) \times 10^{-15}\text{GeV}
\]  

(4.5)

where the three terms shown come from (4.1), (4.3), and (4.4), respectively. Notice that this is consistent with the experimental result

\[
\Delta M_{exp} = 3.522 \times 10^{-15}\text{GeV}
\]  

(4.6)
considering the large hadronic uncertainties involved.

The imaginary piece of the $\Delta S = 2$ Hamiltonian contributes to indirect CP violation in the $K^0$ system, and hence to the $\epsilon$ parameter. In the standard phase convention, $\epsilon$ is given by

$$\epsilon \approx \frac{e^{i\pi/2} \text{Im} M_{12}}{\sqrt{\Delta M}}$$

(4.7)

It is straightforward to compute the imaginary parts of the the operators (4.1), (4.3), and (4.4), which contribute to $\text{Im} M_{12}$. We find

$$[\pm 3 \times 10^{-7} + 3 \times 10^{-6} + 9 \times 10^{-9}] \text{ (GeV}^{-2}) \text{Im}(\xi_d^K)^2 (\sigma \gamma \mu d_L)^2$$

(4.8)

Clearly, the new operator (4.3) dominates (4.8) and is two orders of magnitude larger than the standard model contribution. This will force us to place a tight constraint on the size of the CP violating phase in the CKM matrix, given the experimental information on the real part of $\epsilon$. From (4.8), we find

$$\text{Im} M_{12} \approx (1 \times 10^{-15}) \sin(2 \text{Arg} V_{td})$$

(4.9)

where we have assumed that the phase of $M_{12}$ comes purely from the CKM factors in the $\Delta S = 2$ operator. Then, we obtain

$$\text{Re} \epsilon \approx (0.15) \sin(2 \text{Arg} V_{td})$$

(4.10)

The real part of $\epsilon$ has been extracted from the observed CP violating charge asymmetry in semileptonic $K_L$ decay [13],

$$\text{Re} \epsilon \approx 1.635 \times 10^{-3}$$

(4.11)

which leads us to conclude that $(2 \text{Arg} V_{td})$ is of the order $10^{-2}$. With CKM phase angles of this size, the time-dependent decay asymmetries discussed in Sections 2 and 3 should have amplitudes of approximately 1%. While this result is not encouraging from an experimental point of view, at least we can say that larger asymmetries would immediately rule out the model. The smallness of the CKM phase angle also alters the theoretical prediction for $|\epsilon'/\epsilon|$. Standard model estimates of this ratio that assume a top quark mass of 100 GeV, and a CKM phase of order 1 give results that are no larger than $\mathcal{O}(10^{-3})$ [14]; since our phase is constrained to be two orders of magnitude smaller, we conclude

$$\epsilon'/\epsilon \leq \mathcal{O}(10^{-5})$$

(4.12)

While this result is in conflict with the experimental value for $\epsilon'/\epsilon$ quoted in the Particle Data Book, we must emphasize that the experimental results are uncertain. The global fit to $\epsilon'/\epsilon$ quoted by the Particle Data Group is only 2$\sigma$ away from zero [13], with some individual groups claiming measurements consistent with zero [15]. Clearly, future experimental measurements of $\epsilon'/\epsilon$ will provide a stringent test of the viability of this model.

5 Conclusions

We have considered flavor changing neutral current effects and CP violation arising from non-standard four-quark interactions in a composite technicolor model. We have shown that the mass splittings of the CP eigenstates in the $B^0$, $D^0$, and $K^0$ systems may each receive large contributions from the CTSM operators. While we have discussed in some detail the pattern of small CP violating decay asymmetries in the $B^0$ and $D^0$ systems due to the composite technicolor interactions, we have found that the most dramatic implication of the model is that $\epsilon'/\epsilon$ in the $K^0$ system should be two orders of magnitude smaller than most standard model estimates. We suggest that this result may prove fatal to this model if experiments conclusively establish a large non-zero value for $\epsilon'/\epsilon$.

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