Rare decays $B \to X_{s,d} \nu \bar{\nu}$ and $B_{s,d} \to l^+ l^-$ in the Topcolor-assisted Technicolor Model

Xiao Zhenjun$^{1,2}$, Jia Liqun$^3$, Lű Linxia$^1$ and Lu Gongru$^1$

1. Department of Physics, Henan Normal University, Xinxiang, 453002 P.R.China.
2. Department of Physics, Peking University, Beijing, 100871 P.R.China.
3. Department of Physics, Pingdingshan Teacher’s College, Pingdingshan, 467000 P.R.China.

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Abstract

We calculate the contributions to the rare decays $B \to X_{s,d} \nu \bar{\nu}$ and $B_{s,d} \to l^+ l^-$ from one-loop $Z^0$-penguin diagrams in the framework of Topcolor-assisted Technicolor Model. Within the parameter space, we find that: (a) the new contribution from technipions is less than 2% of the standard model prediction; (b) the top-pions can provide a factor of 10 to 30 enhancement to the ratios in question; (c) the topcolor-assisted technicolor model is consistent with the current experimental data.

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1 Introduction

The examination of indirect effects of new physics in Flavor Changing Neutral Current (FCNC) processes in B decays offers a complementary approach to the search for direct production of new particles at high energy colliders. Several FCNC transitions

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have been measured in B system. Many more are accessible at the present and planned colliders (CESR, LEP/SLC, Tevatron, B factories, HERA-B/LHC).

The new loop effects on the $B^0 \to \bar{B}^0$ mixing due to topcolor interactions has been estimated in refs. [2, 3]. And an upper bound can be placed on $\delta_{bd} \equiv |D_{Lbd} D_{Rbd}|$: $\delta_{bd}/m_H^2 < 10^{-12}\text{GeV}^{-2}$, which is an important constraint on the mixing factors.

In the Standard Model (SM), the rare decays $B \to X_{s,d} \nu \bar{\nu}$ and $B_{s,d} \to l^+ l^-$ are theoretically very clean [4]. The charm contribution is fully negligible, and the uncertainties related to the renormalization scale dependence can also be neglected. Consequently, these rare B-decay modes, as well as other clean rare K- and B-decays may play an important role in searching for the new physics beyond the SM.

In ref. [4], the authors studied the new physics effects in the rare decays $B \to X_{s,d} \gamma$ and found that the Multiscale Walking Technicolor Model (MWTCM) [5] was ruled out by the CLEO data [6] but the Topcolor-assisted Technicolor (TC2) Model [2] is still consistent with the data. In refs. [7], the authors studied the new physics effects in the rare decays $B \to (K, K^*) l^+ l^-$, and found that the new physics effects may be measurable at future experiments. In ref. [8] we found that the MWTCM was ruled out by the rare K-decay data [9]. In ref. [10] we calculated the contributions to rare decays $B \to X_{s,d} \nu \bar{\nu}$ and $B_{s,d} \to l^+ l^-$ from charged technipions $P^\pm$ and $P_8^\pm$ in the framework of One Generation Technicolor Model (OGTM) [11] and MWTCM [5], respectively. We found that the first model is still consistent with the rare B-decay data [12, 13], but the MWTCM is strongly disfavored by the data of $B(B \to X_s \nu \bar{\nu})$ [12].

In this paper, we will investigate the contributions to the rare B decays $B \to X_{s,d} \nu \bar{\nu}$ and $B_{s,d} \to l^+ l^-$ from one-loop $Z^0$-penguin diagrams induced by the charged top-pions and technipions appeared in the TC2 Model [2].

This paper is organized as follows. In Sec.2 we extract out the new effective $Z^0$-penguin couplings. In Sec.3 and Sec.4, we present the numerical results for the branching ratios $B(B \to X_{s,d} \nu \bar{\nu})$ and $B(B_{s,d} \to l^+ l^-)$ with the inclusion of new physics effects, respectively. The conclusions are also included in the section 4.

## 2 TC2 models and new effective couplings

Besides the Hill’s TC2 model [2], other similar models with different fermion contents and gauge group structures also proposed recently [14]. But the basic ideas in all these models are the same: Firstly, the electroweak symmetry is broken by technicolor with an extended technicolor (ETC), the large top quark mass is a combination of a dynamical condensate component $m_t^* = (1 - \epsilon) m_t$, generated by the new strong topcolor interaction, together with a small fundamental component, $m_{t1} = \epsilon m_t$ ($\epsilon \ll 1$), generated by the ETC. Secondly, the existence of the top-pions is an essential feature in the Topcolor scenarios [14], regardless of the differences between models constructed so far. Finally,
ordinary technipions should exist in all such models.

In TC2 model, the color-octet "coloron" $V_8$ (i.e., the top-gluons) and the color-singlet $Z'$ should be heavier than 1 TeV\cite{15, 16}. The three top-pions are nearly degenerate. If the top-pion is lighter than the top quark, then one has $\Gamma(t \to \tilde{\pi}^+ b) \approx (m_t^2 - m_{\tilde{\pi}}^2)^2 / (16\pi m_t F_{\tilde{\pi}}^2)$. At $2-\sigma$ level, the lower bound is $m_{\tilde{\pi}} \geq 100$ GeV from the Tevatron data\cite{22}. The relatively light top-pions and other bound states, may provide potentially large loop effects in low energy observables. This is the main motivation for us to investigate the contributions to the rare B-decays $B \to X_{s,d} \nu \bar{\nu}$ and $B_{s,d} \to l^+ l^-$ from the top-pions and technipions in the framework of TC2 model.

The couplings of the charged top-pions to t- and b-quarks take the form\cite{2}:

\[
\frac{m_t^*}{F_{\tilde{\pi}}} \left[ i\bar{t}_R b_L \tilde{\pi}^+ + i\bar{b}_L t_R \tilde{\pi}^- \right], \quad \frac{m_b^*}{F_{\tilde{\pi}}} \left[ i\bar{t}_L b_R \tilde{\pi}^+ + i\bar{b}_L t_R \tilde{\pi}^- \right] \tag{1}
\]

here, $m_t^*$ denotes the top quark mass generated by topcolor interactions, while $m_b^*$ is the bottom quark mass generated by $SU(3)_1$ instanton effects\cite{2}.

In TC2 models, If one uses the square root of the CKM mixing matrix for $(U_L, D_L)$ and assumes that the $U_R$ and $D_R$ are approximately diagonal, the constraints from the $B^0 - \overline{B^0}$, $b \to s \gamma$ and $D^0 - \overline{D^0}$ can be avoided\cite{3}. In this paper we use the square root of the CKM mixing matrix for $D_L$ and assume that the $U_R$ and $D_R$ are simply diagonal, which means that the possible contributions from so-called “b – pions” appeared in TC2 model must be very small and can be neglected safely. The mixings between the third and first two generation quarks are therefore can be written as:

\[
\frac{m_t^*}{F_{\tilde{\pi}}} \left[ i\tilde{\pi}^+ t_R (d_L D_{Ld} + s_L D_{Lt}) + h.c. \right]. \tag{2}
\]

In TC2 models, The new contributions to the rare B decays from technipions are suppressed roughly by a factor of $(m_{t1}/F_{\tilde{\pi}})^2 / (m_t^*/F_{\tilde{\pi}})^2 \sim 10^{-3}$, when compared with that from the top-pions.

The relevant gauge couplings of charged technipions and top-pions to $Z^0$ gauge boson are basically model-independent and can be found for instance in ref.\cite{18}. The effective Yukawa couplings of charged technipions to fermion pairs can be found in refs.\cite{3, 19, 18}.

The corresponding one-loop diagrams in the SM were evaluated long time ago and can be found in ref.\cite{20}. The new penguin diagrams can be obtained by replacing the internal $W^\pm$ lines with the unit-charged top-pion and technipion lines\cite{10}. The color-octet $p_8^\pm$ does not couple to the $l\nu$ lepton pairs, and therefore does not present in the box diagrams. For the color-singlet technipion and top-pion, they do couple to $l\nu$ pairs through box diagrams, but the relevant couplings are strongly suppressed by the lightness of $m_t$. Consequently, we can safely neglect the tiny contributions from technipion and top-pion through the box diagrams.
Because of the lightness of the $s$, $d$ and $b$ quarks when compared with the large top quark mass and the technipion masses we set $m_d = 0$, $m_s = 0$, $m_b^* = 0$ and $m_b = 0$ in the calculation. We will use dimensional regularization to regulate all the ultraviolet divergences in the virtual loop corrections and adopt the Modified Minimal Subtraction ($\overline{MS}$) renormalization scheme. It is easy to show that all ultraviolet divergences are canceled for $P^\pm$, $D^\pm_8$ and $\tilde{\pi}^\pm$ respectively, and therefore the total sum is finite.

By analytical evaluations of the Feynman diagrams, we find the effective $b\tilde{\pi}Z$ vertex induced by the charged top-pion exchange,

$$\Gamma_{Z\mu}^t = \frac{1}{16\pi^2} g^3 \cos \theta_W \sum_j \lambda_j s_L \gamma_\mu b_L C_0^{New}(\xi_j), \quad (3)$$

$$C_0^{New}(\xi_j) = \frac{D_{Lj}^+ m_{\tilde{\pi}}^2 \xi_j}{2\sqrt{2} V_{js} F_\pi^2 G_F M_W^2} \left[ \frac{(-1 + 2\sin^2 \theta_W - 3\xi_j + 2\sin^2 \theta_W \xi_j)}{8(1 - \xi_j)} - \frac{\cos^2 \theta_W \xi_j \ln[\xi_j]}{2(1 - \xi_j)^2} \right] \quad (4)$$

where $\lambda_j = V_{js}^* V_{jb}$, $\xi_l = m_t^2/m_{\tilde{\pi}}^2$, $\xi_j = m_j^2/m_{\tilde{\pi}}^2$ for $j = c, u$, $\sin \theta$ is the Weinberg angle, $M_W$ is the W boson mass and $G_F$ is the Fermi coupling constant. For the case of the effective $bdZ$ vertex, the $s$ in eqs $3, 4$ should be replaced by $d$. In TC2 models, one usually uses $F_\pi = 50 \sim 70$ GeV [2; 3].

For the case of technipions, the functions $C_0^{New}(y_j)$ and $C_0^{New}(z_j)$ are

$$C_0^{New}(y_j) = \frac{m_{p_{1j}}^2 y_j}{3\sqrt{2} F_\pi^2 G_F M_W^2} \left[ \frac{(-1 + 2\sin^2 \theta_W - 3y_j + 2\sin^2 \theta_W y_j)}{8(1 - y_j)} - \frac{\cos^2 \theta_W y_j \ln[y_j]}{2(1 - y_j)^2} \right] \quad (5)$$

$$C_0^{New}(z_j) = \frac{8m_{p_{8j}}^2 z_j}{3\sqrt{2} F_\pi^2 G_F M_W^2} \left[ \frac{(-1 + 2\sin^2 \theta_W - 3z_j + 2\sin^2 \theta_W z_j)}{8(1 - z_j)} - \frac{\cos^2 \theta_W z_j \ln[z_j]}{2(1 - z_j)^2} \right] \quad (6)$$

where $y_t = m_{t1}^2/m_{\tilde{\pi}}^2$, $z_t = m_{t1}/m_{p_{8}}$ and $F_\pi = 123$ GeV is the technipion weak decay constant. In the above calculations, we used the unitary relation $\sum_{j=u,c,t} \lambda_j \cdot constant = 0$ wherever possible, and neglected the masses for all external lines. We also used the functions $(B_0, B_\mu, C_0, C_\mu, C_{\mu})$ whenever needed to make the integrations, and the explicit forms of these complicated functions can be found, for instance, in ref. [21].

Within the standard model, the rare B-decays under consideration depend on the functions $X(x_t)$ and/or $Y(x_t)$ ($x_t = m_t^2/m_W^2$), they are currently known at the NLO level [4]. When the new contributions from charged technipions and top-pions are included, the functions $X$, and $Y$ can be written as

$$X = X(x_t) + C_0^{New}(\xi_t) + C_0^{New}(y_t) + C_0^{New}(z_t), \quad (7)$$

$$Y = Y(x_t) + C_0^{New}(\xi_t) + C_0^{New}(y_t) + C_0^{New}(z_t). \quad (8)$$

In the numerical calculations, we fix the relevant parameters as follows and use them as the standard input(SIP) [1; 23]: $M_W = 80.41$ GeV, $G_F = 1.16639 \times 10^{-5}$ GeV$^{-2}$, $\alpha = 1/129$, $\sin^2 \theta_W = 0.23$, $m_t \equiv m_t(m_t) = 170$ GeV, $\tau(B_s) = \tau(B_d) = 1.6$ ps, $\Lambda^{(5)}_{MS} = 0.225$ GeV,
\[ F_{B_s} = 0.210 \text{GeV}, \quad m_{B_s} = 5.38 \text{GeV}, \quad m_{B_d} = 5.28 \text{GeV}, \quad A = 0.84, \quad \lambda = 0.22, \quad \rho = 0, \quad \eta = 0.36. \]

For \( \alpha_s(\mu) \) we use the two-loop expression as given in ref. [1].

In the SM, using the SIP, we have \( X(x_t) = 1.54, \quad Y(x_t) = 1.06. \) For \( m_{p1} = (50 \sim 250) \text{GeV}, \quad m_{p8} = (100 \sim 600) \text{GeV} \) and \( \epsilon = (0.05 \sim 0.1) \), we have \( |C_0^{New}(y_t)| \leq 5.5 \times 10^{-4}, \quad |C_0^{New}(z_t)| \leq 1.8 \times 10^{-2}. \) For \( m_{\tilde{t}} = (100 \sim 350) \text{GeV} \) and \( \epsilon = 0.05 \) (0.1), we have \( |C_0^{New}(\xi_t)| = 4.52 \sim 0.81 (3.91 \sim 0.61) \), which is much larger than \( |C_0^{New}(y_t)| \) and \( |C_0^{New}(z_t)| \). Consequently, top-pions \( \tilde{t}^\pm \) will dominate the new contribution.

### 3 The decay \( B \to X_{s,d} \nu \bar{\nu} \)

Within the Standard Model, the effective Hamiltonian for \( B \to X_s \nu \bar{\nu} \) are now available at the NLO level [1],

\[ H_{eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_W} V_{tb}^* V_{ts} X(x_t) (\bar{b}s)(\bar{\ell}l) + \text{h.c.} \quad (9) \]

with \( s \) replaced by \( d \) in the case of \( B \to X_d \nu \bar{\nu} \).

Using the effective Hamiltonian (9), normalizing to \( B(B \to X_c e \bar{\nu}) \) and summing over the three neutrino flavors one finds

\[ B(B \to X_s \nu \bar{\nu}) = B(B \to X_c e \bar{\nu}) \frac{3\alpha^2}{4\pi^2 \sin^4 \theta_W} \frac{|V_{ts}|^2 |X(x_t)|^2}{V_{cb}^2} \frac{\eta}{f(z)} \frac{\bar{\eta}}{\kappa(z)} \quad (10) \]

where \( f(z) = 0.542, \quad \kappa(z) = 0.880, \quad \eta = 0.831 \) for \( z = m_c/m_b = 0.29 \). In the case of \( B \to X_d \nu \bar{\nu} \) one has to replace \( V_{ts} \) by \( V_{td} \) which results in a decrease of the branching ratio by roughly an order of magnitude.

Within the SM, using the SIP, and setting \( B \to X_c e \bar{\nu} = 10.5% \) and \( |V_{ts}/V_{cb}|^2 = 0.95 \), one finds

\[ B(B \to X_s \nu \bar{\nu})^{SM} = 3.54 \times 10^{-5}, \quad B(B \to X_d \nu \bar{\nu})^{SM} = 2.04 \times 10^{-6} \quad (11) \]

which is consistent with the result given in ref. [1].

Using the SIP, and assuming \( F_{\tilde{t}} = 50 \text{GeV}, \quad \epsilon = 0.05 \) and \( 100 \text{GeV} \leq m_{\tilde{t}} \leq 350 \text{GeV} \), one finds

\[ 8.19 \times 10^{-5} \leq B(B \to X_s \nu \bar{\nu}) \leq 5.48 \times 10^{-4}, \quad (12) \]

\[ 3.2 \times 10^{-6} \leq B(B \to X_d \nu \bar{\nu}) \leq 1.24 \times 10^{-5}. \quad (13) \]

In Fig.1, the solid (short-dash) curve shows the theoretical prediction when new contributions from technipions and top-pions are all included for \( \epsilon = 0.1 \) (0.05). The upper dots line corresponds to the ALEPH data [12]: \( B(B \to X_s \nu \bar{\nu}) < 7.7 \times 10^{-4} \), which is a factor of 20 above the SM expectation (dot-dash line), and is still consistent with the
theoretical expectations when the new contributions from the charged technipions and top-pions are included. For larger $F_\tilde{\pi}$, the size of the new contribution from top-pions will be decreased accordingly. For the decay $B \to X_d\nu\bar{\nu}$ no experimental bound is available currently.

4 The decay $B_{s,d} \to l^+l^-$

The effective Hamiltonian for $B_{s,d} \to l^+l^-$ is known at the NLO level $^4$,

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_W} \bar{V}_{ib} V_{ts} Y(x_t) (\bar{b}s)(\bar{l}l) + h.c.$$

(14)

with $s$ replaced by $d$ in the case of $B_d \to l^+l^-$. Using the effective Hamiltonian (14) and summing over three neutrino flavors one finds

$$B(B_{s,d} \to l^+l^-) = \tau(B_{s,d}) \frac{G_F^2}{\pi} \frac{\alpha}{4\pi \sin^2 \theta_W} F_{B_{s,d}}^2 m^2_{B_{s,d}} \left( 1 - \frac{4m^2_l}{m^2_{B_{s,d}}} \right) |V_{ib} V_{ts}|^2 Y(x_t)^2$$

(15)

with $s$ replaced by $d$ in the case of $B_d \to l^+l^-$, and $B_s (B_d)$ denotes the flavor eigenstate $\bar{b}s (\bar{b}d)$ and $F_{B_s} (F_{B_d})$ is the corresponding decay constant.

Again the new contributions from technipions are very small. The dominant enhancement due to the unit-charged top-pion can be as large as a factor of 30 at the level of the SM predictions. The numerical results for various decay modes are given in Table 1. In the numerical calculations, we use the SIP, assuming $100\text{GeV} \leq m_{\tilde{\pi}} \leq 350\text{GeV}$, $m_{p1} = 50\text{GeV}$, $m_{p8} = 100\text{GeV}$, and setting $|V_{ib} V_{ts}|^2 = 0.0021$, $|V_{ib} V_{td}|^2 = 1.3 \times 10^{-4}$, and $D_{Lts}/V_{ts} = D_{Ltd}/V_{td} = 1/2$. The currently available experimental bounds are$^13$: $B(B_s \to e^+e^-) < 5.4 \times 10^{-5}$ at $90\% C.L.$, $B(B_s \to \mu^+\mu^-) < 2.0 \times 10^{-6}$ at $90\% C.L.$, and $B(B_d \to \mu^+\mu^-) < 6.8 \times 10^{-7}$ at the $90\% C.L$. It is easy to see that the current experimental bounds are still about 2 orders of magnitude away from the theoretical prediction even if the large enhancements due to charged top-pions are taken into account. CDF and BarBar may reach the sensitivity of $1 \times 10^{-8}$ and $4 \times 10^{-8}$ for $B(B_s \to \mu^+\mu^-)$ and $B(B_d \to \mu^+\mu^-)$ in the near future. Such sensitivity is on the margin to probe the effects due to unit-charged top-pions.

In summary, the contributions due to technipions are less than 2% of the SM predictions and can be neglected safely. Within the considered parameter space, the top-pions can provide a factor of 10 to 30 enhancement to the branching ratios in question. The theoretical prediction of $B(B \to X_s\mu\bar{\nu})$ is now close to the experimental bound as illustrated in Fig.1. The TC2 model is still consistent with currently available data. Further improvement in the sensitivity of the relevant data will be very helpful to find the signal of charged top-pions or put some limits on their mass spectrum.
Table 1: The branching ratios of $B_{s,d} \to l^+l^-$, and $\epsilon = 0.05$.

| Branching ratio | SM          | plus technipion | SM + New | Data          |
|-----------------|-------------|-----------------|----------|---------------|
| $B(B_s \to e^+e^-)$ | $0.72 \times 10^{-13}$ | $0.71 \times 10^{-13}$ | $(0.22 \sim 2.01) \times 10^{-12}$ | $< 5.4 \times 10^{-5}$ |
| $B(B_s \to \mu^+\mu^-)$ | $3.09 \times 10^{-9}$ | $3.05 \times 10^{-9}$ | $(0.96 \sim 8.58) \times 10^{-8}$ | $< 2.0 \times 10^{-6}$ |
| $B(B_s \to \tau^+\tau^-)$ | $0.66 \times 10^{-9}$ | $0.65 \times 10^{-9}$ | $(0.20 \sim 1.82) \times 10^{-5}$ |          |
| $B(B_d \to e^+e^-)$ | $0.44 \times 10^{-14}$ | $0.43 \times 10^{-14}$ | $(0.16 \sim 1.22) \times 10^{-13}$ |          |
| $B(B_d \to \mu^+\mu^-)$ | $1.88 \times 10^{-10}$ | $1.85 \times 10^{-10}$ | $(0.58 \sim 5.21) \times 10^{-9}$ | $< 6.8 \times 10^{-7}$ |
| $B(B_d \to \tau^+\tau^-)$ | $0.40 \times 10^{-7}$ | $0.39 \times 10^{-7}$ | $(0.12 \sim 1.11) \times 10^{-6}$ |          |

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**Figure Captions**

**Fig.1:** Plots of the branching ratios $B(B \to X_s\nu \bar{\nu})$ vs the mass $m_{\tilde{g}}$. For more details see the text.
