# Probing anomalous right-handed top quark couplings in rare $B$ decays

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We explore the anomalous right-handed $\overline{t}sW$ and $\overline{t}bW$ couplings using $B\to X_s\gamma$ and $B\to X_s l^+l^-$ decays induced by the flavor-changing penguin diagrams. The anomalous $\overline{t}sW$ coupling can yield 10% enhancement of the $B\to X_s l^+l^-$ decay rate under the constraint from the present $B\to X_s\gamma$ data, while it does not affect the forward-backward asymmetry of the charged lepton. The allowed region for the anomalous $\overline{t}bW$ coupling by the $B\to X_s\gamma$ constraint is twofold: the small value region and the large value region. Although the effect of the small anomalous coupling on the $B\to X_s l^+l^-$ branching ratio is very small, it can yield a substantial change for the forward-backward asymmetry.

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After the discovery of the top quark at the Fermilab Tevatron [1,2], several properties of the top quark have been examined, such as the top quark mass [3], production cross section [4], and the production kinematics [5], etc. The production of $10^7$–$10^8$ top quark pairs per year is expected at the CERN Large Hadron Collider (LHC), which will allow us to study the detailed structure of top quark couplings [6]. The top quark dominantly decays through the $t\to bW$ channel and other channels are highly suppressed by small mixing angles. Thus the $\overline{t}bW$ coupling will be measured at the LHC with high precision. Effects of the anomalous $\overline{t}bW$ coupling have been studied in direct and indirect ways in many literatures [7–11]. The subdominant channel in the standard model (SM) is the Cabibbo-Kobayashi-Maskawa (CKM) nondiagonal decay $t\to sW$ of which the branching ratio is estimated as $\mathrm{Br}(t\to sW)\sim 1.6\times 10^{-3}$, when $|V_{ts}|=0.04$ is assumed. Although the branching ratio of this channel is rather small, the large number of top quarks expected to be produced at the LHC will give us a chance to measure the $t\to sW$ process and enable us to probe the $\overline{t}sW$ coupling responsible for this channel directly. Therefore the anomalous $\overline{t}sW$ coupling, which has not been seriously examined yet, is worth examining at present.

Before the LHC, we can study the top quark couplings indirectly in rare $B$ decays. Rare $B$ decays involving loop induced flavor-changing neutral transitions are sensitive to the properties of internal heavy particles, so they can provide a good probe of new physics beyond the SM. The radiative $b\to s\gamma$ and semileptonic $b\to s l^+l^-$ decays are the most promising channels to examine the new physics effects. The branching ratio of inclusive $B\to X_s\gamma$ decay has been measured by the CLEO [12] and ALEPH [13] groups and recently by the Belle Collaboration from a 5.8 $\mathrm{fb}^{-1}$ data sample [14]. We have the weighted average of the branching ratio of this channel as $\mathrm{Br}(B\to X_s\gamma)=(3.23\pm 0.41)\times 10^{-4}$ from those measurements. This channel has been intensively studied at next to leading order (NLO) in the SM [15,16] and has provided stringent constraints on various new physics models [7,17–20]. On the other hand, the first observation of $b\to s l^+l^-$ decay was reported by the Belle group through the exclusive $B\to K l^+l^-$ channel [21]: $\mathrm{Br}(B\to K l^-l^+)=(0.75^{+0.25}_{-0.21}\pm 0.09)\times 10^{-6}$, from 30 $\mathrm{fb}^{-1}$ data. The BaBar Collaboration also presents a bound on this mode and the $B\to K^*\mu^-\mu^+$ mode [22]. The inclusive $B\to X_s l^+l^-$ decay rate is to be measured soon as more data on the $B$ decay will be accumulated. The measurement of this mode provides a complementary study on the flavor-changing penguin decays.

In this work, we examine the effects of the anomalous right-handed $\overline{t}bW$ and $\overline{t}sW$ couplings on the inclusive $B\to X_s\gamma$ and $B\to X_s l^+l^-$ decays. We concentrate on the anomalous couplings of charged current interactions and ignore effects of new particles and the neutral current interactions. With the anomalous right-handed couplings, we write the effective Lagrangian as

$$\mathcal{L}=-\frac{g}{\sqrt{2}}\sum_{q=s,b} V_{tq}\overline{q}\gamma^{\mu}(P_L+\xi_q P_R)tW^-_{\mu}+\mathrm{H.c.}, \qquad (1)$$

where $\xi_q$ measures the new physics effects. Next, we present the effective Hamiltonian approach with the effective Lagrangian Eq. (1). The $B\to X_s\gamma$ and $B\to X_s l^+l^-$ decays are described in terms of the effective Hamiltonian and the effects of the anomalous couplings are analyzed later. Finally, our conclusion is given.

In order to study the rare decay processes of the $B$ meson, effective field theoretical approach is required to incorporate a consistent QCD correction, which is substantial in rare $B$ decays. We can write the $\Delta B=1$ effective Hamiltonian to describe the $b\to s\gamma$ and $b\to s l^+l^-$ processes as

$$\mathcal{H}_{eff}=-\frac{4G_F}{\sqrt{2}}V^*_{ts}V_{tb}\sum_{i=1}^{10}[C_i(\mu)O_i(\mu)+C'_i(\mu)O'_i(\mu)], \qquad (2)$$

where the dimension 6 operators $O_i$ constructed in SM are given in [23], and $O'_i$ are their chiral conjugate operators.

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Matching the effective theory (2) and the Lagrangian (1) at the $\mu=m_W$ scale, we have the Wilson coefficients $C_i(\mu=m_W)$ and $C_i'(\mu=m_W)$. When we let $\xi_q=0$, we have the Wilson coefficients in the SM, $C_2(m_W)=-1$, $C_7(m_W)=F(x_t)$, $C_8(m_W)=G(x_t)$,

$$C_9(m_W)=C_9^{\gamma}+C_9^{Z}+C_9^{\Box}$$
$$=-D_0(x_t)-4[1-(4\sin^2\theta_W)^{-1}]C_0(x_t)$$
$$-(\sin^2\theta_W)^{-1}B_0(x_t),$$

$$C_{10}(m_W)=C_{10}^{Z}+C_{10}^{\Box}$$
$$=-(\sin^2\theta_W)^{-1}C_0(x_t)+(\sin^2\theta_W)^{-1}B_0(x_t),$$

$C_i(m_W)=C_i'(m_W)=0$ otherwise, where $F(x),G(x),D_0(x)$, $C_0(x),B_0(x)$ are the well-known Inami-Lim loop functions and can be found in Refs. [23,24]. Let us switch to the right-handed $\overline{t}bW$ and $\overline{t}sW$ couplings. Keeping the effects of anomalous couplings in linear order, we obtain the modified Wilson coefficients $C_7\to C_7^{\rm SM}+\xi_b(m_t/m_b)\tilde{F}(x_t)$, $C_8\to C_8^{\rm SM}+\xi_b(m_t/m_b)\tilde{G}(x_t)$, $C_9\to C_9^{\rm SM}-\xi_b(m_b/m_t)\tilde{D}(x_t)$, and the new Wilson coefficients $C_7'=\xi_s(m_t/m_b)\tilde{F}(x_t)$, $C_8'=\xi_s(m_t/m_b)\tilde{G}(x_t)$, $C_9'=-\xi_s(m_b/m_t)\tilde{D}(x_t)$, with the new loop functions

$$\tilde{F}(x)=\frac{-20+31x-5x^2}{12(x-1)^2}+\frac{x(2-3x)}{2(x-1)^3}\ln x,$$

$$\tilde{G}(x)=-\frac{4+x+x^2}{4(x-1)^2}+\frac{3x}{2(x-1)^3}\ln x,$$

$$\tilde{D}(x)=\frac{x(59-38x+25x^2+2x^3)}{36(x-1)^4}$$
$$-\frac{2(x+1)}{3(x-1)^5}\ln x-\frac{x^2}{2(x-1)^4}\ln x.$$

Our new loop functions $\tilde{F}(x)$ and $\tilde{G}(x)$ agree with those in Ref. [19] and $\tilde{D}(x)$ is the first calculation. Note that the $\mathcal{O}(\xi)$ terms of the $Z$ penguin diagram are suppressed by the heavy mass of the $Z$ boson as $m_b^2/m_Z^2$ or $q^2/m_Z^2$, and we neglect them here. For the box diagram, the $\mathcal{O}(\xi)$ terms vanish by the chirality relation and the leading contribution is of $\xi^2$ order. As a consequence, the contribution of order $\mathcal{O}(\xi)$ comes only through the $\gamma$ penguin and gluon penguin diagrams. Thus there exists no new effect in $C_{10}$ and $C_{10}'=0$.

The renormalization group (RG) evolution of the Wilson coefficients $\mathbf{C}=(C_i,C_i')^{\dagger}$ given by $\mu(d/d\mu)\mathbf{C}(M_W)=-(g_s^2/16\pi^2)\gamma^T\mathbf{C}(M_W)$, is governed by a $20\times 20$ anomalous dimension matrix $\gamma$. Since the strong interaction preserves chirality, the operators $Q_i'$ are evolved separately without mixing between those and the SM operators. Thus the $20\times 20$ anomalous dimension matrix $\gamma$ is decomposed into two identical $10\times 10$ matrices $\gamma_0$ given in the SM as $\gamma=\left(\begin{smallmatrix}\gamma_0 & 0\\ 0 & \gamma_0\end{smallmatrix}\right)$. The $10\times 10$ anomalous dimension matrix $\gamma_0$ has been calculated to leading logarithmic level in Refs. [25,26]. Using the initial condition at $\mu=m_W$, $(C_i(M_W),C_i'(M_W))=(0,-1,0,0,0,0,C_7,C_8,C_9,C_{10},0,0,0,0,0,0,C_7',C_8',C_9',0)$, we can solve the RG equation to obtain the Wilson coefficients evolved from $\mu=m_W$ to $\mu=m_b$ scales.

The branching ratio of the $B\to X_s\gamma$ process with the right-handed interactions are obtained at NLO as:

$$\mathrm{Br}(B\to X_s\gamma)=[\mathrm{Br}(B\to X_c e\overline{\nu})/10.5\%]$$
$$\times\{B_{22}(\delta)+B_{77}(\delta)(|r_7|^2+|r_7'|^2)$$
$$+B_{88}(\delta)(|r_8|^2+|r_8'|^2)+B_{27}(\delta)\mathrm{Re}(r_7)+B_{28}(\delta)\mathrm{Re}(r_8)$$
$$+B_{78}(\delta)[\mathrm{Re}(r_7r_8^{\star})+\mathrm{Re}(r_7'r'^{\star}_8)]\},$$

where the ratios $r_i$ and $r_i'$ are defined by

$$r_i=\frac{C_i(m_W)}{C_i^{SM}(m_W)}=1+\frac{C_i^{\rm new}(m_W)}{C_i^{SM}(m_W)},\quad r_i'=\frac{C_i'(m_W)}{C_i^{SM}(m_W)}.$$

The components $B_{ij}(\delta)$ depend on the kinematic cut $\delta$, of which numerical values are given in Ref. [15].

With the measured branching ratio, we can set the conservative bounds on the parameter $\xi_b$ and $\xi_s$ as $-0.0021<\xi_b<0.0031$ (A), $|\xi_s|<-0.0485<\xi_b<-0.0433$ (B), $|\xi_s|<0.012$, at the $2\sigma$ level. We assume that $\xi_b$ and $\xi_s$ are real for simplicity. The anomalous coupling $\xi_b$ contributes in linear and quadratic order while $\xi_s$ dominantly contributes in quadratic order since the contribution of the linear order is strongly suppressed by the ratio $m_s^2/m_b^2$. Thus the parameter $\xi_s$ is less constrained by the $B\to X_s\gamma$ measurement than $\xi_b$ in general. Due to the cancellation by the interference term $B_{27}\mathrm{Re}(r_7)$, however, the large $|\xi_b|$ solution in region B is also allowed, which gives the positive Wilson coefficient $C_7(m_W)>0$.

The dilepton invariant mass distribution of $B\to X_s l^+l^-$ decays consists of the following contributions: $d\mathrm{Br}(B\to X_s l^-l^+)/d\hat{s}=(dB_0/d\hat{s})+(dB_{1/m_b^2}/d\hat{s})+(dB_{1/q^2}/d\hat{s})$, where the first term denotes the decay at the parton level, the second term the power correction in the heavy quark effective theory (HQET), and the last term is due to the nonperturbative virtual quark loop effects with the soft gluon. We have the explicit expression including the HQET corrections of order $\mathcal{O}(1/m_b^2)$ given in Refs. [27–29],

$$d\mathrm{Br}(B\to X_s l^-l^+)/d\hat{s}=2B_0\{[\tfrac{1}{3}(1-\hat{s})^2(1+2\hat{s})(2+\hat{\lambda}_1)$$
$$+(1-15\hat{s}^2+10\hat{s}^3)\hat{\lambda}_2](|C_9|^2+|C_9'|^2+|C_{10}|^2)$$
$$+[\tfrac{4}{3}(1-\hat{s})^2(2+\hat{s})(2+\hat{\lambda}_1)$$
$$+4(-6-3\hat{s}+5\hat{s}^3)\hat{\lambda}_2](|C_7|^2+|C_7'|^2)/\hat{s}$$
$$+[4(1-\hat{s})^2(2+\hat{\lambda}_1)$$
$$+4(-5-6\hat{s}+7\hat{s}^2)\hat{\lambda}_2)]\mathrm{Re}(C_7C_9^{*}+C_7'C'^{*}_9)\},$$

where $\hat{s}=(p_+ + p_-)^2/m_b^2$ is the normalized dilepton invariant mass, $\hat{\lambda}_{1,2}=\lambda_{1,2}/m_b^2$ the normalized HQET parameters, and the normalization constant is given by

$$B_0 \equiv \mathrm{Br}(B\to X_c e \bar{\nu}) \frac{3\alpha^2}{16\pi^2} \frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2} \frac{1}{f(\hat{m}_c)\kappa(\hat{m}_c)},$$

with the phase space function $f(\hat{m}_c)$ and the perturbative QCD correction $\kappa(\hat{m}_c)$ of $B\to X_c l\nu$ decay. The long distance correction due to the virtual $c\bar{c}$ loop is considered in Ref. [30]. Numerically this correction is at the 1–2 % level in the region of $\hat{s}$ considered here away from the resonances, and we ignore it. We plot the differential branching ratio with respect to $\hat{s}$ in Fig. 1. The values of $\xi_{b,s}$ given earlier are used. We consider the region for $\hat{s}$ as $1\ \mathrm{GeV}^2 < \hat{s} m_b^2 < 7.5\ \mathrm{GeV}^2$ in order to avoid the large resonant contribution of $J/\psi$ and $\psi'$. We show that the total decay rate over this region is enhanced by the anomalous couplings. $\xi_s=0.012$ leads to 10% enhancement of the branching ratio. The enhancement by $\xi_b$ in region A is less than 1% and the branching ratio with $\xi_b$ in region B is more than twice the SM prediction since there is no interference term between $C_2$ and $C_7$ in the $B\to X_s l^- l^+$ decay rate, which cancels the enhanced $|C_7|^2$ contribution. Hence such a enhancement should be observed in the near future, if $\xi_b$ coupling in region B exists.

The forward-backward (FB) asymmetry $A_{FB}$ is defined as

$$\frac{dA_{FB}}{d\hat{s}} = \int_0^1 \frac{d^2\mathrm{Br}}{d\hat{s}\, d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d^2\mathrm{Br}}{d\hat{s}\, d\cos\theta} d\cos\theta,$$

where the angle $\theta$ is measured between the $b$ quark and the positively charged lepton $l^+$ in the dilepton center-of-mass (c.m.) frame. The $A_{FB}$ distribution with respect to $\hat{s}$ is depicted in the Fig. 2. We find that $\xi_b$ in region A can bring a substantial shift of the differential FB asymmetry although the branching ratio is not much affected. It is because the branching ratio is dominated by the SM contribution $|C_9|^2 + |C_{10}|^2$ but $A_{FB}$ is proportional to the substantial Wilson coefficient $C_{10}$ and shifted by the term $\sim \xi_b C_{10}$. As a consequence, $A_{FB}$ summed over the region considered here is enhanced by four times with $\xi_b=-0.0021$ and even its sign is changed if $\xi_b=0.0031$. With $\xi_b$ in the region B, the shift of $dA_{FB}/d\hat{s}$ is huge as is the case of the decay rate, because of the large shift of $C_7$. In addition, the anomalous $\overline{t}sW$ coupling does not affect $A_{FB}$, since $C'_{10}=0$.

We studied rare $B$ decays with the anomalous right-handed $\overline{t}bW$ and $\overline{t}sW$ couplings in a model-independent way. This kind of anomalous coupling can be obtained in the general left-right (LR) model based on the $SU(2)_L \times SU(2)_R \times U(1)$ gauge group [31] or the dynamical electroweak symmetry breaking model [32]. In the LR model, the right-handed quark mixing is also an observable. If we do not demand that the symmetry between left- and right-handed sectors is manifest, the right-handed quark mixing is not necessarily identical to the left-handed quark mixing described by the CKM matrix. Thus we have right-handed charged current interactions, which is suppressed by the heavy mass of the extra $W$ boson but still enhanced relatively by the right-handed quark mixing matrix. On the other hand, when the electroweak symmetry breakdown is dynamical, one may expect that some nonuniversal interactions exist which lead to anomalous couplings on charged current interactions.

The constraint on $\xi_s$ by the $B\to X_s\gamma$ data is weaker than that of $\xi_b$ in the region A because of the chirality relation. As a result, a considerable enhancement of the branching ratios for $B\to X_s l^+ l^-$ decay is possible with the anomalous $\overline{t}sW$ coupling while the influence of the anomalous $\overline{t}bW$ coupling in region A is rather small. In addition, the anomalous $\overline{t}bW$ coupling can change the forward-backward asymmetry considerably under the $B\to X_s\gamma$ constraints, and even the sign of $A_{FB}$ may be reversed while the anomalous $\overline{t}sW$ coupling

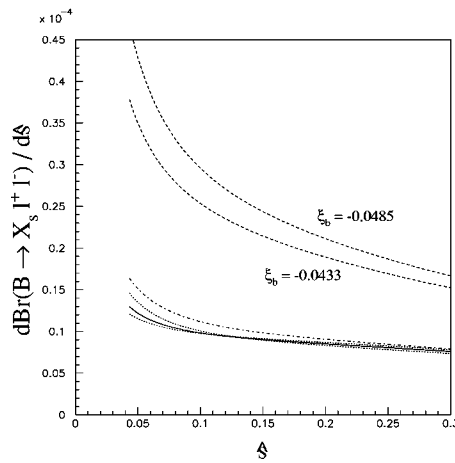


FIG. 1. The differential branching ratio of $B\to X_s l^+ l^-$ decays. The solid line denotes the SM prediction, the dotted the prediction with $\xi_b$ in the region A, the dashed the prediction with $\xi_b$ in the region B, and the dash-dotted the prediction with $\xi_s=0.012$.

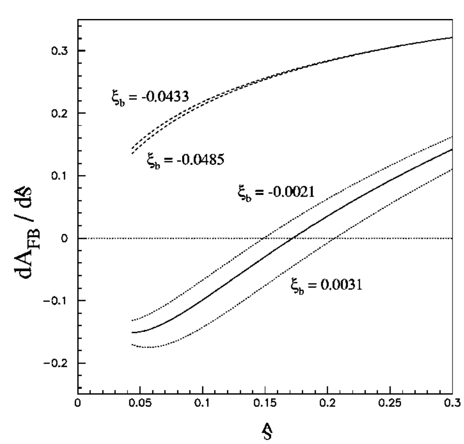


FIG. 2. The forward-backward asymmetry of $B\to X_s l^+ l^-$ decays. The solid line denotes the SM prediction, the dotted the prediction with $\xi_b$ in the region A, and the dashed the prediction with $\xi_b$ in the region B.

does not affect $A_{FB}$. Therefore it is possible to discriminate the effects of the anomalous $\overline{t}bW$ and $\overline{t}sW$ couplings if we combine the analysis of the branching ratio and $A_{FB}$ for $B \to X_s l^+ l^-$ process. On the other hand, a relatively large value of $|\xi_b|$ in region B is also allowed due to the cancellation between the $C_2 C_7$ and $|C_7|^2$ terms for $B \to X_s \gamma$ decay, which leads to a much larger branching ratio and altered $A_{FB}$ for $B \to X_s l^+ l^-$ decay. The measured branching ratio of the exclusive $B \to K l^+ l^-$ decay given earlier is rather higher than the SM prediction, although it is still consistent with the SM [33] due to the large errors and theoretical uncertainties. Thus it may be a clue of the new physics signal and the anomalous coupling $\xi_b$ in region B might be a candidate for the new physics. If we measure $A_{FB}$ in the future, it will be a clear probe of the nature of the top quark anomalous couplings.

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