Rare baryonic decays $\Lambda_b \rightarrow \Lambda l^+l^-$ in the $TTM$ model

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Abstract

In the framework of the top triangle mouse ($TTM$) model, we analyze the rare decays $\Lambda_b \rightarrow \Lambda l^+l^-$ ($l = e, \mu, \tau$) by using the form factors calculated in full $QCD$. We calculate the contributions of the new particles predicted by this model to observables, such as the branching ratios, forward-backward asymmetry ($A_{FB}$) and polarizations related these decay processes. We find that, in wide range of the parameter space, the values of the branching ratios are enhanced by one order of magnitude comparing to the $SM$ predictions. This model can also produce significant corrections to $A_{FB}$, normal polarization $P_N$ and transversal polarization $P_T$.

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1. Introduction

The rare decays $\Lambda_b \to \Lambda l^+ l^-(l = e, \mu, \tau)$ which are induced by the flavor-changing neutral current (FCNC) can be described by the processes $b \to sl^+ l^-$ at the quark level. In the standard model (SM), these FCNC transitions are forbidden at tree level, while can occur at loop level. New physics models beyond the SM can appear either through new contributions to the Wilson coefficients that enter into the effective Hamiltonian that describes these decays, or through new operators in the effective Hamiltonian which are absent in the SM. They can not only provide very important consistency check of the SM, but also are very sensitive to some new physics models beyond the SM. Furthermore, unlike the mesonic decays, the baryonic decays could maintain the helicity structure of the effective Hamiltonian for the $b \to s$ transition exactly explains why one gives more interest to them [1].

The SM predictions for branching ratios of the semileptonic decays $\Lambda_b \to \Lambda l^+ l^-$ have been studied in Ref. [2,3], which uses the related form factors calculated via light cone QCD sum rules in full theory. Their results show $Br(\Lambda_b \to \Lambda e^+ e^-) = (4.6 \pm 1.6) \times 10^{-6}$, $Br(\Lambda_b \to \Lambda \mu^+ \mu^-) = (4.0 \pm 1.2) \times 10^{-6}$, and $Br(\Lambda_b \to \Lambda \tau^+ \tau^-) = (0.8 \pm 0.3) \times 10^{-6}$. The first experimental result in investigation of the rare baryonic decays has recently been reported by the CDF collaboration at Fermilab, and they announced the result of the branching ratio $Br(\Lambda_b \to \Lambda l^+ l^-) = [1.73 \pm 0.42(\text{stat}) \pm 0.55(\text{syst})] \times 10^{-6}$ [4]. The LHCb collaboration at CERN has also started to search these decay channels. So studying of these rare baryonic decays is now entering a new interesting era.

As has already been noted, rare decays induced by $b \to s$ transition are quite promising for searching new physics beyond the SM. In recently years, many works about decays $\Lambda_b \to \Lambda l^+ l^-$ have been done in many new physics models, such as standard model with fourth generation ($SM4$) [5-7], supersymmetry ($SUSY$) model [8], the universal extra dimension($UED$) model [9-12], two Higgs doublet model ($2HDM$) [13], family non-universal $Z'$ model [14-16] and the covariant constituent quark model [17]. They have shown that some new physics models beyond the SM can indeed give significant
contributions to the rare decays $\Lambda_b \to \Lambda l^+ l^-$ and the present or future experimental results can be used to test or restrict these new physics models.

The large mass of the top quark might have a different origin from masses of other light quarks and leptons, a top quark condensate, $\langle t\bar{t} \rangle$, could be responsible for at least part of electroweak symmetry breaking ($EWSB$) [18]. The top triangle moose (TTM) model [19, 20] is one of interesting new physics models with separate sectors for dynamically generating the masses of the top quark and the weak gauge bosons $W^\pm$ and $Z$. $EWSB$ results largely from the Higgsless mechanism while the top quark mass is mainly generated by the topcolor mechanism. So, in this model, there are two sets of Goldstone bosons. One set is eaten by the gauge bosons $W^\pm$, $Z$, $W'^\pm$ and $Z'$ to generate their masses, while the other set remains in the spectrum, which is called the top-pions ($\pi_1^0$ and $\pi_1^\pm$) and the top-Higgs $h_0^t$. The properties of these new scalars have been recently studied in Refs. [20–22]. In this paper, we will consider the contributions of the TTM model to the rare decays $\Lambda_b \to \Lambda l^+ l^-$ ($l = e, \mu, \tau$) and compare our numerical results with those obtained in the $SM$.

The layout of the present paper is as follows. In section 2, we simply review the essential features of the TTM model. The contributions of the TTM model to the observables, such as branching ratios, forward-backward asymmetry ($A_{FB}$) and polarizations, which are related the decays $\Lambda_b \to \Lambda l^+ l^-$, are given in section 3. In this section we also compare our numerical results with predictions of the $SM$. Our conclusion is given in section 4.

2. The essential features of the TTM model

The detailed description of the TTM model can be found in Refs.[17,18], and here we just want to briefly review its essential features, which are related to our calculation.

The electroweak gauge structure of the TTM model is $SU(2)_0 \times SU(2)_1 \times U(1)_2$. The nonlinear sigma field $\sum_{01}$ breaks the group $SU(2)_0 \times SU(2)_1$ down to $SU(2)$ and field $\sum_{12}$ breaks $SU(2)_1 \times U(1)_2$ down to $U(1)$. To separate top quark mass generation from $EWSB$, a top-Higgs field $\Phi$ is introduced to the TTM model, which couples preferentially
to the top quark. To ensure that most of the $EWSB$ comes from the Higgsless side, the $VEVs$ of the fields $\Sigma_{01}$ and $\Sigma_{12}$ are chosen to be $<\Sigma_{01}> = <\Sigma_{12}> = F = \sqrt{2} \nu \cos \omega$, in which $\nu = 246 GeV$ is the electroweak scale and $\omega$ is a new small parameter. The $VEV$ of the top-Higgs field is $f = <\Phi> = \nu \sin \omega$.

From above discussions, we can see that, for the $TTM$ model, there are six scalar degrees of freedom on the Higgsless sector and four on the top-Higgs sector. Six of these Goldstone bosons are eaten to give masses to the gauge bosons $W^\pm, Z, W'^\pm$ and $Z'$. Others remain as physical states in the spectrum, which are called the top-pions ($\pi_{t}^\pm$ and $\pi_{t}^0$) and the top-Higgs $h_{t}^0$. In this paper, we will focus our attention on the contributions of these new particles to the rare decays $\Lambda_b \to \Lambda l^+ l^-$ ($l = e, \mu, \tau$).

In general the couplings of the top-pions and top-Higgs to fermions are model dependent, which depend on the individual left-handed and right-handed rotations in the separate up- and down-quark sectors. According the assumptions given by Ref. [22], the couplings of the top-pions $\pi_{t}^0$ and $\pi_{t}^\pm$ to ordinary fermions, which are related our calculation, are given by

$$
\frac{i}{\nu} \left[ m_t \cot \omega t t_R + m_b \cot \omega b b_R + m_t \tan \omega t t_R \right] \pi_{t}^0 \\
+ \frac{i\sqrt{2}}{\nu} \left[ m_t V_{tb} \cot \omega t t_R b_L + m_b V_{tb} \tan \omega t t_R b_R + m_t V_{ts} \cot \omega t s b_L \right] \pi_{t}^\pm + h.c. 
$$

(1)

Here $V_{ij}$ is the $CKM$ matrix elements. The couplings of the top-Higgs $h_{t}^0$ to fermions are similar to those of the neutral top-pion $\pi_{t}^0$.

Reference[17] has extensively studied the couplings of the new heavy gauge bosons $W'^\pm$ and $Z'$ to other particles and has shown that the couplings of these new gauge bosons to two heavy quarks (light partners) are proportional to $1/x$ with $x$ being a small parameter. However, their couplings to ordinary quarks (light quarks) are very small. At the ideal fermion delocalization case, the coupling $g_{W'ud}$ equals to zero, while the couplings $g_{Z'uu}$ and $g_{Z'dd}$ are proportional to $x$, in which $u$ and $d$ are light up- and down-quarks, respectively. Thus the contributions of the $TTM$ model to the rare decays $\Lambda_b \to \Lambda l^+ l^-$ are mainly come from the new scalars ($\pi_{t}^\pm, \pi_{t}^0$ and $h_{t}^0$). In the succedent section, we will calculate the contributions of these new scalars to the observables, such as branching
ratios, forward-backward asymmetry \( (A_{FB}) \) and polarizations, which are related to the decays \( \Lambda_b \to \Lambda l^+ l^- \) (\( l = e, \mu, \tau \)).

3. Numerical results

At the quark level, the baryonic decays \( \Lambda_b \to \Lambda l^+ l^- \) can be described by the FCNC transitions \( b \to s l^+ l^- \), whose effective Hamiltonian in the SM is written as:

\[
\mathcal{H}^{eff} = \frac{G_F \alpha_{em} V_{tb} V_{ts}^*}{2\sqrt{2}\pi} \left[ C_9^{eff} \bar{s} \gamma_\mu (1 - \gamma_5) b \bar{l} \gamma^\mu l + C_{10} \bar{s} \gamma_\mu (1 - \gamma_5) b \bar{l} \gamma^\mu \gamma_5 l \\
-2m_b C_7^{eff} \frac{1}{q^2} \bar{s} i\sigma_{\mu\nu} q^\nu (1 + \gamma_5) b \bar{l} \gamma^\mu l \right],
\]

(2)

where \( q \) is the sum of 4 momenta of \( l^+ \) and \( l^- \), \( G_F \) is the Fermi constant, \( \alpha_{em} \) is the fine structure constant. The Wilson coefficients \( C_7^{eff}, C_9^{eff} \) and \( C_{10} \) represent different interactions respectively, whose specific expressions can be obtained in Refs. [23–25]. The transition matrix elements for \( \Lambda_b \to \Lambda l^+ l^- \) can be obtained by sandwiching the effective Hamiltonian between the initial and final baryonic states, which can be parameterized in terms of twelve form factors \( f_i, g_i, f_i^T \) and \( g_i^T (i = 1, 2, 3) \) in full QCD theory and can be expressed in the following manners:

\[
\langle \Lambda(p)| \bar{s} \gamma_\mu (1 - \gamma_5) b|\Lambda_b(p + q) \rangle = \bar{u}_\Lambda(p) \left[ \gamma_\mu f_1(q^2) + i\sigma_{\mu\nu} q^\nu f_2(q^2) + q^\mu f_3(q^2) \\
-\gamma_\mu \gamma_5 g_1(q^2) - i\sigma_{\mu\nu} \gamma_5 q^\nu g_2(q^2) - q^\mu \gamma_5 g_3(q^2) \right] u_{\Lambda_b}(p + q),
\]

\[
\langle \Lambda(p)| \bar{s} i\sigma_{\mu\nu} q^\nu (1 + \gamma_5) b|\Lambda_b(p + q) \rangle = \bar{u}_\Lambda(p) \left[ \gamma_\mu f_1^T(q^2) + i\sigma_{\mu\nu} q^\nu f_2^T(q^2) + q^\mu f_3^T(q^2) \\
+\gamma_\mu \gamma_5 g_1^T(q^2) + i\sigma_{\mu\nu} \gamma_5 q^\nu g_2^T(q^2) + q^\mu \gamma_5 g_3^T(q^2) \right] u_{\Lambda_b}(p + q).
\]

(3)

The specific expressions of these form factors have been calculated in Ref. [2] in the framework of full QCD theory. Using above transition matrixes, we can get the angular dependent differential decay rate of the \( \Lambda_b \to \Lambda l^+ l^- \) decay in the whole physical region \( 4m_l^2/m_{\Lambda_b}^2 \leq \hat{s} \leq (1 - \sqrt{7})^2 \) which has the following form:

\[
\frac{d\Gamma}{d\hat{s}dz} = \frac{G_F^2 \alpha_{em}^2 m_{\Lambda_b}}{16384\pi^5 |V_{tb} V_{ts}^*|^2 \sqrt{\hat{s}}} \left[ \Theta(\hat{s}) + \Theta_1(\hat{s}) + \Theta_2(\hat{s}) \hat{s} \right],
\]

(4)
where \( z = \cos \theta \), \( \theta \) being the angle between the momenta of \( \Lambda_b \) and \( l^- \) in the center of mass of leptons, \( \hat{s} = q^2/m_{\Lambda_b}^2 \), \( r = m_\Lambda/m_{\Lambda_b} \), \( \lambda = \lambda(1, r, \hat{s}) = 1 + r^2 + \hat{s}^2 - 2r - 2\hat{s} - 2r\hat{s} \) and \( \nu = \sqrt{1 - \frac{4m_l^2}{\hat{s}}} \) is the lepton velocity. The functions \( \Theta(\hat{s}), \Theta_1(\hat{s}), \Theta_2(\hat{s}) \) are given by Ref. [2].

Integrating out the angular dependent differential decay rate, the branching ratios can be obtained as following manner:

\[
Br(\Lambda_b \to \Lambda l^+ l^-) = \frac{\tau G_F^2 \alpha^2 \epsilon m_{\Lambda_b} |V_{tb} V_{ts}^*|^2}{8192\pi^5} \int \frac{d\hat{s}}{m_{\Lambda_b}^2} \sqrt{\lambda} \left[ \Theta(\hat{s}) + \frac{1}{3} \Theta_2(\hat{s}) \right] d\hat{s},
\]

where \( \tau \) is the lifetime of \( \Lambda_b \).

The forward-backward asymmetry \( A_{FB} \) is defined in terms of the differential decay rate as [26]:

\[
A_{FB}(\hat{s}) = \frac{\int_0^1 \frac{d\Gamma}{d\hat{s}}(z, \hat{s}) dz - \int_{-1}^0 \frac{d\Gamma}{d\hat{s}}(z, \hat{s}) dz}{\int_0^1 \frac{d\Gamma}{d\hat{s}}(z, \hat{s}) dz + \int_{-1}^0 \frac{d\Gamma}{d\hat{s}}(z, \hat{s}) dz}.
\]

The normal polarization \( P_N \) and transversal polarization \( P_T \) are defined as:

\[
P_i(q^2) = \frac{\frac{d}{dq^2}(\vec{\xi} = \vec{e}_i)}{\frac{d}{dq^2}(\vec{\xi} = -\vec{e}_i)} - \frac{\frac{d}{dq^2}(\vec{\xi} = -\vec{e}_i)}{\frac{d}{dq^2}(\vec{\xi} = \vec{e}_i)},
\]

where the unit vector \( \vec{\xi} \) represent the spin direction along \( \Lambda \) baryon, \( i = N \) or \( T \). The explicit expressions of them can be obtained in Ref. [26].

For the decay processes \( \Lambda_b \to \Lambda l^+ l^- \), the \( TTM \) model can give new contributions to the Wilson coefficients \( C_7^{eff}, C_9^{eff} \) and \( C_{10} \) by effecting the Inami-Lim functions \( C_0(x_t), D_0(x_t), E_0(x_t) \) and \( E_0'(x_t) \) whose explicit expressions can be obtained in Ref. [27]. In the \( TTM \) model, the detailed expressions of the corresponding functions \( C_0^{TTM}(x_t), D_0^{TTM}(x_t), E_0^{TTM}(x_t), E_0'^{TTM}(x_t) \) including the contributions of the new scalars \((\pi_0^\pm, \pi_0^0\))
Figure 1: The branching ratios $Br(Λ_b \rightarrow Λe^+e^-)$, $Br(Λ_b \rightarrow Λµ^+µ^-)$ and $Br(Λ_b \rightarrow Λτ^+τ^-)$ as functions of $M_π$ with $\sin ω = 0.3, 0.5, 0.7$ in the $TTM$ model.

and $h_0^0$) are shown as:

\[
C_{0,TTM}^{TTM}(y_t) = \frac{M_π^2}{\sqrt{2G_F}} \frac{\cot^2 ω}{M_W^2} \left( -\frac{y_t^2}{8(y_t - 1)} - \frac{y_t^2}{8(y_t - 1)^2} \ln[y_t] \right),
\]

\[
D_{0,TTM}^{TTM}(y_t) = \frac{\cot^2 ω}{\sqrt{2G_F} M_W^2} \left( \frac{47 - 79y_t + 38y_t^2}{108(1 - y_t)^3} + \frac{3 - 6y_t^2 + 4y_t^3}{18(1 - y_t)^4} \ln[y_t] \right),
\]

\[
E_{0,TTM}^{TTM}(y_t) = \frac{\cot^2 ω}{\sqrt{2G_F} M_W^2} \left( \frac{7 - 29y_t + 16y_t^2}{36(1 - y_t)^3} - \frac{3y_t^2 - 2y_t^3}{6(1 - x)^4} \ln[y_t] \right),
\]

\[
E_{0,TTM}^{'TTM}(y_t) = \frac{\cot^2 ω}{2\sqrt{2G_F} M_W^2} \left( -\frac{5 - 19y_t + 20y_t^2}{6(y_t - 1)^3} + \frac{y_t^2 - 2y_t^3}{(1 - y_t)^4} \ln[y_t] \right),
\]

where $y_t = m_t^2/M_π^2$ and we have taken $M_π = M_{π^0} = M_{h_0^0} = M_{π^±}$.

In our numerical calculation, we take the $SM$ input parameters as [28]: $M_W = $
The observables about the decay processes $\Lambda_b \rightarrow \Lambda l^+ l^-$ depend on the model dependent parameters: the mass of scalars $M_s$ and the free parameter $\sin \omega$, which indicates the fraction of $EWSB$ provided by the top condensate. The top-pion masses depend on the amount of top-quark mass arising from the ETC sector and on the effects of electroweak gauge interactions, and thus their values model-dependent. In the context of the TTM model, Ref.[18] has obtained the constraints on the top-pion mass via studying its effects on the relevant experimental observables. In our numerical calculation, we will assume that the values of the free parameters $\sin \omega$ and $M_s$ are in the ranges of $0.2 \sim 0.8$ and $200 \sim 600 GeV$, respectively.

Considering the contributions of the TTM model to the rare decays $\Lambda_b \rightarrow \Lambda l^+ l^-$, the branching ratios $Br(\Lambda_b \rightarrow \Lambda l^+ l^-)$ are plotted in Fig.1 as functions of mass parameter $M_s$ with the free parameter $\sin \omega = 0.3, 0.5$, and $0.7$, in which Fig.1 (a), (b), and (c) represent the results of $Br(\Lambda_b \rightarrow \Lambda e^+ e^-)$, $Br(\Lambda_b \rightarrow \Lambda \mu^+ \mu^-)$ and $Br(\Lambda_b \rightarrow \Lambda \tau^+ \tau^-)$, respectively. We can see that enhancing the values of the mass parameter $M_s$ or the free parameter $\sin \omega$ can make the values of the branching ratios decrease. Comparing to the $SM$ predictions, one easily see that the values of branching ratios $Br(\Lambda_b \rightarrow \Lambda l^+ l^-)$ can be enhanced by about one order of magnitude in wide range of the parameter space of the TTM model. It is obvious that the experimental measurement value of the branching ratio $Br(\Lambda_b \rightarrow \Lambda \mu^+ \mu^-) = [1.73 \pm 0.42(stat) \pm 0.55(syst)] \times 10^{-6}$ [3] is smaller than that given by the TTM model. The more experimental data can give constraints on the free parameters of the TTM model in the future.

Our numerical results for the forward-backward asymmetry $A_{FB}(\Lambda_b \rightarrow \Lambda l^+ l^-)$ are given in Fig.2, in which the horizontal solid line represent their $SM$ predictions. From these figures, we can see that the absolute values of $A_{FB}$ increase as the increasing of the free parameters $M_s$ and $\sin \omega$. In wide range of the parameter space, the TTM model can produce positive contributions to the forward-backward asymmetry $A_{FB}$ and the absolute values of $A_{FB}$ are smaller than the corresponding $SM$ predictions.
Figure 2: The forward-backward asymmetry $A_{FB}(\Lambda_b \to \Lambda e^+e^-)(a)$, $A_{FB}(\Lambda_b \to \Lambda\mu^+\mu^-)(b)$ and $A_{FB}(\Lambda_b \to \Lambda\tau^+\tau^-)(c)$ are plotted as functions of $M_\pi$ for different values of the free parameter $\sin \omega$ in the TTM model.
Figure 3: The normal polarization $P_N(\Lambda_b \to \Lambda^+ l^-)$ as function of $M_\pi$ for different values of the free parameter $\sin \omega$ in the $TTM$ model.
Figure 4: The transversal polarization $P_T(\Lambda_b \rightarrow \Lambda l^+ l^-)$ as function of $M_\pi$ for different values of the free parameter $\sin \omega$ in the $TTM$ model.
The numerical results for the normal polarization $P_N(\Lambda_b \to \Lambda^+l^-)$ and transversal polarization $P_T(\Lambda_b \to \Lambda^+l^-)$ in the TTM model are given in Fig.3 and Fig.4, respectively, in which the horizontal solid line represent their SM predictions. It is obvious that the absolute values of $P_N(\Lambda_b \to \Lambda^+l^-)$ increase as the increasing of free parameters $M_\pi$ and $\sin \omega$, while the values of $P_T(\Lambda_b \to \Lambda^+l^-)$ increase as these free parameters increasing. In most of the parameter space of the TTM, the absolute values of $P_N$ are smaller than those for the SM predictions, but the values of $P_T$ are much smaller than the corresponding SM predictions. However, for large values for the free parameters $M_\pi$ and $\sin \omega$, all values of $P_N$ and $P_T$ approach the values of the SM predictions. This means that the contributions of the TTM model to polarization observables become smaller for large values of the relevant free parameters.

4. Conclusions

It is well known that FCNC transitions $b \to s$ are considered as excellent probes of new physics models beyond the SM. Combing Higgsless and topcolor mechanisms, a new physics model was proposed, called the TTM model, which can be seen as the deconstructed version of the topcolor-assisted technicolor (TC2) model. This model predicts the new gauge bosons and scalars, which can produce significant contributions to some observables. We consider the decay processes $\Lambda_b \to \Lambda^+l^-$ in the context of this model.

We have calculated the contributions of the TTM model to the branching ratios, forward-backward asymmetry and polarizations related the decay channels $\Lambda_b \to \Lambda^+l^-$ using the form factors obtained from full QCD. The numerical results indicate that, due to the small couplings of the new heavy gauge bosons $W'^\pm$ and $Z'$ with the SM fermions, their contributions can be safely neglected and the contributions of the TTM model to observables mainly come from the new scalars ($\pi^\pm_t$, $\pi^0_t$ and $h^0_t$). In wide range of the parameter space, its contributions to branching ratios $Br(\Lambda_b \to \Lambda^+l^-)$ can enhance the corresponding SM predictions by about one order of magnitude. In most of the parameter space of the TTM, their values are larger than those in the SM4 theory [4,5,6] or in the SUSY model [7]. The TTM model can also produce significant corrections to the
observables $A_{FB}, P_N$ and $P_T$, while their values are larger or smaller than those given by the SM4 theory or the SUSY model depending on the relevant free parameters. Certainly, the errors of the form factors [2] can make our numerical results has uncertainties. However, the theoretical uncertainties are much smaller the discrepancies between the $TTM$ and $SM$ predictions. Thus, we expect that our results will be helpful to constrain or test the $TTM$ model at the $LHCb$ via the decay processes $\Lambda_b \to \Lambda l^+ l^-$. 

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