

Analysis of $\Lambda_b \rightarrow pK^-$ and $p\pi^-$ decays in a flavor changing Z' model*

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Abstract: In this paper, we calculate the branching ratios of $\Lambda_b \rightarrow pK^-$ and $p\pi^-$ decays in the flavor changing Z' model. We find that the branching ratios for these two decay modes are sensitive to the contributions of the Z' boson. For $\Lambda_b \rightarrow pK^-$ decay, if the left-handed couplings are equal to the right-handed couplings, the branching ratio of this decay could match up to the currently experimental data for $\xi_s=0.01$ and $-52^\circ < \phi_s^L < 132^\circ$, or $\xi_s=0.004$ and $0^\circ < \phi_s^L < 84^\circ$; if only the left-handed couplings are considered, it could match up to the experimental data for $\xi_s=0.01$ and $-10^\circ < \phi_s^L < 138^\circ$. And for $\Lambda_b \rightarrow p\pi^-$ decay, if the left-handed and right-handed couplings are equal, the branching ratio of $\Lambda_b \rightarrow p\pi^-$ decay may be consistent with the currently experimental data with $\xi_d=0.05$ and $-135^\circ < \phi_d^L < 43^\circ$, if only the left-handed couplings are considered, it may be consistent with $\xi_d=0.05$ and $-114^\circ < \phi_d^L < 8^\circ$.

Key words: Z' model, Λ_b decay, branching ratio

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1 Introduction

Nonleptonic weak decays of heavy baryons arouse great interest since they provide a good area to understand the standard model (SM) and search new physics (NP) beyond the SM. For the branching ratios of $\Lambda_b \rightarrow pK^-$ and $p\pi^-$ decays, the CDF Collaboration has presently reported [1]

$$\begin{aligned} Br(\Lambda_b \rightarrow pK^-) &= (5.6 \pm 0.8 \pm 1.5) \times 10^{-6}, \\ Br(\Lambda_b \rightarrow p\pi^-) &= (3.5 \pm 0.6 \pm 0.9) \times 10^{-6}. \end{aligned} \quad (1)$$

In the SM, $\Lambda_b \rightarrow pK^-$ and $\Lambda_b \rightarrow p\pi^-$ decays have been discussed [2, 3]. The authors used the generalized and naive factorization approaches to handle the hadronic matrix elements, respectively. However, the branching ratios for these two decay modes are significantly lower than the present experiment values. Specially in Ref. [3], the measured branching ratio for $\Lambda_b \rightarrow pK^-$ could be easily accommodated in the fourth quark generation model. In this paper, using the QCD factorization approach, we shall discuss the branching ratios for $\Lambda_b \rightarrow pK^-$ and $p\pi^-$

decays in a flavor changing Z' model [4, 5].

The paper is organized as follows. In the next section we shall discuss the nonleptonic decays of Λ_b baryon. In Section 3, we shall analyze these decay modes in a flavor changing Z' model. Section 4 contains our conclusions.

2 $\Lambda_b \rightarrow pK^-$ and $p\pi^-$ decays

For the nonleptonic Λ_b decay modes $\Lambda_b \rightarrow pK^-$ and $p\pi^-$, which are induced by the quark level transition $b \rightarrow p\bar{u}u$ ($p=d,s$), the effective Hamiltonian can be written as [6]

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \left[V_{ub}V_{up}^* \sum_{i=1,2} C_i(\mu) O_i - V_{tb}V_{tp}^* \sum_{i=3}^{10} C_i(\mu) O_i \right], \quad (2)$$

where C_i are the effective Wilson coefficients and O_i the relevant four-quark operations.

Firstly, we discuss $\Lambda_b \rightarrow pK^-$ decay in the SM. The amplitude for this process in the factorization approximation is given as [2]

$$\begin{aligned} \mathcal{A}(\Lambda_b(p) \rightarrow p(p')K^-(q)) &= \frac{G_F}{\sqrt{2}} [(V_{ub}V_{us}^* a_1 - V_{tb}V_{ts}^* (a_4 + a_{10} + (a_6 + a_8)R_1)) \langle p(p') | \bar{s}\gamma^\mu b | \Lambda_b(p) \rangle + (V_{ub}V_{us}^* a_1 \\ &\quad - V_{tb}V_{ts}^* (a_4 + a_{10} - (a_6 + a_8)R_2)) \langle p(p') | \bar{s}\gamma^\mu \gamma_5 b | \Lambda_b(p) \rangle] \langle K^-(q) | \bar{u}\gamma_\mu (1 - \gamma_5) u | 0 \rangle, \end{aligned} \quad (3)$$

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where

$$R_1 = \frac{2m_K^2}{(m_b - m_u)(m_s + m_u)}, \quad (4)$$

$$R_2 = \frac{2m_K^2}{(m_b + m_u)(m_s + m_u)}.$$

The matrix elements of the various hadronic currents between the initial Λ_b and final p baryon are parameterized in terms of various form factors as [7]

$$\langle p(p') | \bar{s} \gamma^\mu b | \Lambda_b(p) \rangle = \bar{u}_p(p') [g_1(q^2) \gamma_\mu + i g_2(q^2) \sigma^{\mu\nu} q^\nu + g_3(q^2) q_\mu] u_{\Lambda_b}(p), \quad (5)$$

$$\langle p(p') | \bar{s} \gamma^\mu \gamma_5 b | \Lambda_b(p) \rangle = \bar{u}_p(p') [G_1(q^2) \gamma_\mu + i G_2(q^2) \sigma^{\mu\nu} q^\nu + G_3(q^2) q_\mu] \gamma_5 u_{\Lambda_b}(p), \quad (6)$$

where q is the momentum transfer, i.e., $q = p - p'$. g_i and G_i are the vector and axial vector form factors, respectively. For the final state of K^- meson, it can be written as

$$\langle K^-(q) | \bar{u} \gamma^\mu \gamma_5 u | 0 \rangle = i f_K q^\mu / \sqrt{2}, \quad (7)$$

where f_K is the decay constant of K meson. The amplitude of $\Lambda_b \rightarrow p K^-$ decay is given as [2]

$$\begin{aligned} \mathcal{A}(\Lambda_b(p) \rightarrow p(p') K^-(q)) &= i \frac{G_F}{\sqrt{2}} f_K \bar{u}_p(p') \times [(V_{ub} V_{us}^* a_1 - V_{tb} V_{ts}^* (a_4 + a_{10} + (a_6 + a_8) R_1)) \\ &\times (g_1(q^2)(m_{\Lambda_b} - m_p) + g_3(q^2) m_K^2) + (V_{ub} V_{us}^* a_1 - V_{tb} V_{ts}^* (a_4 + a_{10} - (a_6 + a_8) R_2)) \\ &\times (G_1(q^2)(m_{\Lambda_b} + m_p) - G_3(q^2) m_K^2) \gamma_5] u_{\Lambda_b}(p) = i \bar{u}_p(p') (A + B \gamma_5) u_{\Lambda_b}(p), \end{aligned} \quad (8)$$

with

$$A = \frac{G_F}{2} f_K (V_{ub} V_{us}^* a_1 - V_{tb} V_{ts}^* (a_4 + a_{10} + (a_6 + a_8) R_1)) (g_1(q^2)(m_{\Lambda_b} - m_p) + g_3(q^2) m_K^2), \quad (9)$$

$$B = \frac{G_F}{2} f_K (V_{ub} V_{us}^* a_1 - V_{tb} V_{ts}^* (a_4 + a_{10} - (a_6 + a_8) R_2)) (G_1(q^2)(m_{\Lambda_b} + m_p) - G_3(q^2) m_K^2),$$

thus the branching ratio for this process can be written as [8]

$$Br(\Lambda_b \rightarrow p K^-) = \tau_{\Lambda_b} \frac{p_{cm}}{8\pi} \left[\frac{(m_{\Lambda_b} + m_p)^2 - m_K^2}{m_{\Lambda_b}^2} |A|^2 + \frac{(m_{\Lambda_b} - m_p)^2 - m_K^2}{m_{\Lambda_b}^2} |B|^2 \right]. \quad (10)$$

Similarly, the amplitude of $\Lambda_b \rightarrow p \pi^-$ decay may be given as [6]

$$\begin{aligned} \mathcal{A}(\Lambda_b \rightarrow p \pi^-) &= i \frac{G_F}{\sqrt{2}} f_\pi \bar{u}_p(p') [(V_{ub} V_{ud}^* a_1 - V_{tb} V_{td}^* (a_4 + a_{10} + (a_6 + a_8) R_1)) (g_1(q^2)(m_{\Lambda_b} - m_p) + g_3(q^2) m_\pi^2) \\ &+ (V_{ub} V_{ud}^* a_1 - V_{tb} V_{td}^* (a_4 + a_{10} - (a_6 + a_8) R_2)) (G_1(q^2)(m_{\Lambda_b} + m_p) - G_3(q^2) m_\pi^2) \gamma_5] u_{\Lambda_b}(p), \end{aligned} \quad (11)$$

where

$$R_1 = \frac{2m_\pi^2}{(m_b - m_u)(m_d + m_u)}, \quad (12)$$

$$R_2 = \frac{2m_\pi^2}{(m_b + m_u)(m_d + m_u)},$$

and we can also obtain the branching ratio for $\Lambda_b \rightarrow p \pi^-$ decay using Eq. (10).

For numerical analysis, the form factors in the space-like region can be parameterized by the following three-parameters fit [9]

$$F_i(q^2) = \frac{F_i(0)}{(1 - q^2/m_{\Lambda_b}^2)(1 - a(q^2/m_{\Lambda_b}^2) + b(q^4/m_{\Lambda_b}^4))}, \quad (13)$$

where the values of the parameters $F_i(0)$, a and b have

been presented in Table 1. We have already used these parameters to handle the $\Lambda_b \rightarrow \Lambda \rho^0$, $p K^{*-}$ and $p \rho^-$ decays in Ref. [10]. The masses of these particles, the decay constants of π , K mesons, the lifetime of Λ_b baryon, and the CKM elements can be found in Refs. [11] and [12].

Table 1. The form factors of $\Lambda_b \rightarrow p$ transition.

F	$F(0)$	a	b
g_1	0.1131	1.70	1.60
g_3	-0.0356	2.5	2.57
G_1	0.1112	1.65	1.60
G_3	-0.0097	2.8	2.7

Combining the above formulas, we can obtain the

branching ratios of $\Lambda_b \rightarrow pK^-$ and $p\pi^-$ decays in the SM

$$\begin{aligned} Br(\Lambda_b \rightarrow pK^-) &= (2.73_{-0.10}^{+0.17}) \times 10^{-6}, \\ Br(\Lambda_b \rightarrow p\pi^-) &= (1.36_{-0.09}^{+0.14}) \times 10^{-6}. \end{aligned} \quad (14)$$

Comparing with Eq. (1), we can find that the branching ratios of $\Lambda_b \rightarrow pK^-$ and $p\pi^-$ decays are lower than the present experimental values at about 4σ level.

3 Numerical analysis in the flavor changing Z' model

A flavor changing Z' model can lead to FCNC processes at the tree level due to the non-diagonal chiral coupling matrix, and the formalism of the model has been discussed explicitly in Refs. [4, 5]. Here we shall briefly review the ingredients needed in this paper.

If we neglect the right-handed flavor changing couplings, the effective Hamiltonian of the $b \rightarrow p\bar{u}$ transition mediated by the Z' can be written as [13]

$$H_{\text{eff}}^{Z'} = \frac{4G_F}{\sqrt{2}} \left(\frac{g' M_Z}{g M_{Z'}} \right)^2 B_{pb}^L (B_{uu}^L O_9 + B_{uu}^R O_7) + \text{h.c.}, \quad (15)$$

where $p=d,s$ and $M_{Z'}$ denotes the mass of new Z' gauge boson. Thus the additional contributions to the SM Wilson coefficients at the M_W scale are

$$\Delta C_{9,7} = \frac{4}{V_{tb} V_{tp}^*} \left(\frac{g' M_Z}{g M_{Z'}} \right)^2 B_{pb}^L B_{uu}^{L,R}, \quad (16)$$

where our assumption that there is no significant renormalization group (RG) running effect between $M_{Z'}$ and M_W scales, and the RG evolution of the modified Wilson coefficients is exactly the same as the ones in the SM [14].

The diagonal elements of the effective matrices $B_{uu}^{L,R}$ are real due to the Hermiticity of the effective Hamiltonian. However, the off-diagonal ones of B_{pb}^L may contain a new weak phase ϕ_p^L . Moreover, Eq. (16) can also be simplified as

$$\Delta C_{9,7} = 4 \frac{|V_{tb} V_{tp}^*|}{V_{tb} V_{tp}^*} \xi_p^{LL,LR} e^{i\phi_p^L}, \quad (17)$$

where the real NP parameters $\xi_p^{LL,LR}$ and ϕ_p^L are defined respectively as

$$\xi_p^{LL,LR} = \left(\frac{g' M_Z}{g M_{Z'}} \right)^2 \left| \frac{B_{pb}^L B_{uu}^{L,R}}{V_{tb} V_{tp}^*} \right|, \quad (18)$$

$$\phi_p^L = \text{Arg}[B_{pb}^L].$$

Obviously, the total decay amplitudes of $\Lambda_b \rightarrow pK^-$ and $p\pi^-$ decays depend on three additional real parameters ξ_p^{LL} , ξ_p^{LR} and ϕ_p^L when the contributions coming from the Z' boson are considered.

For the sake of simplicity, we shall take the following two cases to estimate the effects of new Z' gauge boson for $\Lambda_b \rightarrow pK^-$ decay. Case I: considering the left-handed and right-handed couplings are equal, i.e., $\xi_s^{LL} = \xi_s^{LR} = \xi_s$; and Case II: only considering the left-handed couplings and neglecting the right-handed couplings, i.e., $\xi_s^{LL} = \xi_s$, $\xi_s^{LR} = 0$. For each case, We shall take $\xi_s = 0.01$ and 0.004 as representative values for numerical analysis as in Ref. [15].

We plot the branch ratio $Br(\Lambda_b \rightarrow pK^-)$ versus the NP weak phase ϕ_s^L given in Fig. 1. From this figure, we can find that (i) for Case I, we obtain $-52^\circ < \phi_s^L < 132^\circ$ and $0^\circ < \phi_s^L < 84^\circ$ for $\xi_s = 0.01$ and 0.004 , respectively; (ii) for Case II, we can get $-10^\circ < \phi_s^L < 138^\circ$ for $\xi_s = 0.01$, however, when we take $\xi_s^{LL} = \xi_s = 0.004$, the branching ratio for $\Lambda_b \rightarrow pK^-$ decay could not be consistent with the currently experimental data no matter what values ϕ_s^L are take. Therefore, the branching ratio of $\Lambda_b \rightarrow pK^-$ decay may match up to the currently experimental data for Case I with $\xi_s = 0.01$ and 0.004 and for Case II with $\xi_s = 0.01$.

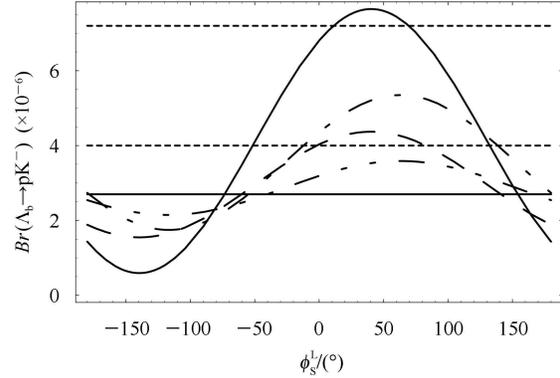


Fig. 1. The branch ratio $Br(\Lambda_b \rightarrow pK^-)$ versus the weak phase ϕ_s^L . The horizontal lines are the branching ratios in the SM, the dotted curves are the currently experimental data of $Br(\Lambda_b \rightarrow pK^-)$ within 2σ . The solid and dashed curves for Case I with $\xi_s^{LL} = \xi_s^{LR} = 0.01, 0.004$, and the single-dot-dashed and double-dot-dashed curves for Case II with $\xi_s^{LL} = 0.01, 0.004$, respectively.

For $\Lambda_b \rightarrow p\pi^-$ decay, we also take the two cases, Case I: $\xi_d^{LL} = \xi_d^{LR} = \xi_d$ and Case II: $\xi_d^{LL} = \xi_d$, $\xi_d^{LR} = 0$. We shall take $\xi_d = 0.05$ and 0.02 as representative values for numerical analysis according to the relation $\xi_d^{LL,LR} \simeq 5\xi_s^{LL,LR}$ obtained in Ref. [16]. We plot the $Br(\Lambda_b \rightarrow p\pi^-)$ versus the NP weak phase ϕ_d^L in Fig. 2. From this figure, it is found that, (i) when $\xi_d = 0.05$, we can obtain $-135^\circ < \phi_d^L < 43^\circ$ for Case I and $-114^\circ < \phi_d^L < 8^\circ$ for Case II, respectively; so the branching ratio of $\Lambda_b \rightarrow p\pi^-$ decay may be consistent with the currently experimental data when ϕ_d^L take values from these regions, (ii) when

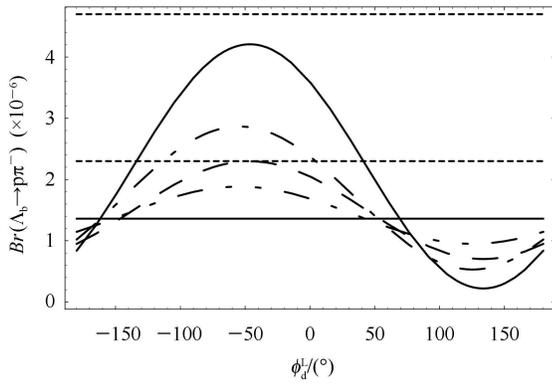


Fig. 2. The curve of $Br(\Lambda_b \rightarrow p\pi^-)$ vs. the weak phase ϕ_d^L . The horizontal lines and the dotted curves are the same as in Fig. 1 but for $Br(\Lambda_b \rightarrow p\pi^-)$. The solid and dashed curves for Case I with $\xi_d^{LL} = \xi_d^{LR} = 0.05, 0.02$, and the single-dot-dashed and double-dot-dashed curves for Case II with $\xi_d^{LL} = 0.05, 0.02$, respectively.

$\xi_d = 0.02$, whether the right-handed couplings are considered or not, the branching ratio for $\Lambda_b \rightarrow p\pi^-$ decay could not be enhanced to be consistent with the currently experimental data no matter what values ϕ_d^L are taken.

4 Conclusions

In this paper we have investigated the effects of $\Lambda_b \rightarrow pK^-$ and $p\pi^-$ decays in the flavor changing Z' model. For $\Lambda_b \rightarrow pK^-$ decay, we find that if the left-handed couplings are equal to the right-handed couplings, the branching ratio of $\Lambda_b \rightarrow pK^-$ decay could match up to the currently experimental data for $\xi_s = 0.01$ and $-52^\circ < \phi_s^L < 132^\circ$, or $\xi_s = 0.004$ and $0^\circ < \phi_s^L < 84^\circ$; if only the left-handed couplings are considered, it could match up to the experimental data for $\xi_s = 0.01$ and $-10^\circ < \phi_s^L < 138^\circ$, but when $\xi_s = 0.004$, it will not be consistent with the currently experimental data no matter what values ϕ_s^L may take. And for $\Lambda_b \rightarrow p\pi^-$ decay, our conclusions are that, if the left-handed and right-handed couplings are equal, the branching ratio of $\Lambda_b \rightarrow p\pi^-$ decay may be consistent with the currently experimental data with $\xi_d = 0.05$ and $-135^\circ < \phi_d^L < 43^\circ$, if only the left-handed couplings are considered, it may be consistent with the currently experimental data with $\xi_d = 0.05$ and $-114^\circ < \phi_d^L < 8^\circ$, but when $\xi_d = 0.02$, whether the right-handed couplings are considered or not, the branching ratio for $\Lambda_b \rightarrow p\pi^-$ decay could not be enhanced to be consistent with the currently experimental data no matter what values ϕ_d^L may take.

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