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Direct CP violation in two-body Λ_b decays

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We study the direct CP-violating asymmetries (CPAs) in the two-body Λ_b decays. We explain the observed decay branching ratios of $\Lambda_b \to (pK^-, p\pi^-)$, and find that their corresponding direct CPAs are $(5.8 \pm 0.2, -3.9 \pm 0.2)\%$. For $\Lambda_b \to (pK^{*-}, p\rho^-)$, the decay branching ratios and CPAs in the Standard Model are predicted to be $(2.5 \pm 0.5, 11.4 \pm 2.1) \times 10^{-6}$ and $(19.6 \pm 1.6, -3.7 \pm 0.3)\%$, respectively. We point out that the large CPA for $\Lambda_b \to pK^{*-}$ is promising to be measured by the CDF and LHCb experiments.

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1. Introduction

Recently, we have pointed out that the direct CP-violating asymmetries (CPAs) in the two-body baryonic Λ_b decays can be used to confirm the weak CP phase in the Standard Model (SM) [1]. Since the flavor conservation causes the Λ_b decays of $\Lambda_b \to pK^{(*)-}$ and $\Lambda_b \to p\pi^-(\rho^-)$ to have neither color-suppressed nor annihilation contribution, providing the controllable non-factorizable effects and traceable strong phases, their direct CPAs can be predictable with small hadronic and other uncertainties.

In this report, we will first explain the branching ratios of $\Lambda_b \to pK^-$ and $\Lambda_b \to p\pi^-$, recently observed to be [2, 3, 4]

$$\begin{aligned}
\mathscr{B}(\Lambda_b \to pK^-) &= (4.9 \pm 0.9) \times 10^{-6}\,,\\
\mathscr{B}(\Lambda_b \to p\pi^-) &= (4.1 \pm 0.8) \times 10^{-6}\,,\\
\mathscr{R}_{\pi K} \equiv \frac{\mathscr{B}(\Lambda_b \to p\pi^-)}{\mathscr{B}(\Lambda_b \to pK^-)} &= 0.84 \pm 0.22\,,
\end{aligned} \tag{1.1}$$

with $\mathscr{R}_{\pi K}$ the combined experimental value by CDF and LHCb. As the theoretical approach based on the generalized factorization can explain the data well, it is demonstrated to be reliable to study the direct CPAs in $\Lambda_b \to pK^-, p\pi^-$ and $\Lambda_b \to pK^{*-}, p\rho^-$.

2. Formalism

In the generalized factorization approach [5], the amplitudes of $\Lambda_b \to pM(V)$ with $M(V) = K^-(K^{*-})$ and $\pi^-(\rho^-)$ can be derived as

$$\begin{aligned}
\mathscr{A}(\Lambda_b \to pM) &= i\frac{G_F}{\sqrt{2}} m_b f_M \Big[\alpha_M \langle p|\bar{u}b|\Lambda_b\rangle + \beta_M \langle p|\bar{u}\gamma_5 b|\Lambda_b\rangle\Big]\,,\\
\mathscr{A}(\Lambda_b \to pV) &= \frac{G_F}{\sqrt{2}} m_V f_V \varepsilon^{\mu *} \alpha_V \langle p|\bar{u}\gamma_\mu(1-\gamma_5)b|\Lambda_b\rangle\,,
\end{aligned} \tag{2.1}$$

where G_F is the Fermi constant, $f_{M(V)}$ are the meson decay constants, and ε^*_μ is the polarization for the vector meson. The constants α_M (β_M) and α_V in Eq. (2.1) are related to the (pseudo)scalar and $V-A$ quark currents, given by $\alpha_M(\beta_M) = V_{ub}V^*_{uq}a_1 - V_{tb}V^*_{tq}(a_4 \pm r_M a_6)$ and $\alpha_V = V_{ub}V^*_{uq}a_1 - V_{tb}V^*_{tq}a_4$, where $r_M \equiv 2m_M^2/[m_b(m_q+m_u)]$, V_{ij} are the CKM matrix elements, $q = s$ or d, and the parameters $a_{1,4,6}$ can be found in Ref. [1]. The matrix elements of the $\Lambda_b \to p$ baryon transition in Eq. (2.1) have the general forms:

$$\begin{aligned}
\langle p|\bar{u}\gamma_\mu b|\Lambda_b\rangle &= \bar{u}_p \left[f_1\gamma_\mu + \frac{f_2}{m_{\Lambda_b}} i\sigma_{\mu\nu}q^\nu + \frac{f_3}{m_{\Lambda_b}} q_\mu\right] u_{\Lambda_b}\,,\\
\langle p|\bar{u}\gamma_\mu\gamma_5 b|\Lambda_b\rangle &= \bar{u}_p \left[g_1\gamma_\mu + \frac{g_2}{m_{\Lambda_b}} i\sigma_{\mu\nu}q^\nu + \frac{g_3}{m_{\Lambda_b}} q_\mu\right] \gamma_5 u_{\Lambda_b}\,,\\
\langle p|\bar{u}b|\Lambda_b\rangle &= f_S \bar{u}_p u_{\Lambda_b}\,, \langle p|\bar{u}\gamma_5 b|\Lambda_b\rangle = f_P \bar{u}_p \gamma_5 u_{\Lambda_b}\,,
\end{aligned} \tag{2.2}$$

where f_j (g_j) ($j = 1,2,3,S$ and P) are the form factors. For the $\Lambda_b \to p$ transition, f_j and g_j from different currents can be related by the SU(3) flavor and SU(2) spin symmetries [6, 7], giving rise to $f_1 = g_1$ and $f_{2,3} = g_{2,3} = 0$. These relations are also in accordance with the derivations from the heavy-quark and large-energy symmetries in Ref. [8]. Note that the helicity-flip terms of $f_{2,3}$ and $g_{2,3}$ vanish due to the symmetries. Moreover, as shown in Refs. [8, 9, 10], $f_{2,3}$ ($g_{2,3}$) can only be contributed from the loops, resulting in that they are smaller than $f_1(g_1)$ by one order of magnitude, and can be safely ignored. By equation of motion, we get $f_S = [(m_{\Lambda_b} - m_p)/(m_b - m_u)]f_1$ and $f_P = [(m_{\Lambda_b} + m_p)/(m_b + m_u)]g_1$. In the double-pole momentum dependences, f_1 and g_1 are in the forms of $f_1(q^2) = C_F/(1-q^2/m^2_{\Lambda_b})^2$ and $g_1(q^2) = C_F/(1-q^2/m^2_{\Lambda_b})^2$, with $C_F \equiv f_1(0) = g_1(0)$. To calculate the branching ratio of $\Lambda_b \to pM$ or pV, we take the averaged decay width $\Gamma \equiv (\Gamma_{M(V)} + \Gamma_{\bar{M}(\bar{V})})/2$ with $\Gamma_{M(V)}$ ($\Gamma_{\bar{M}(\bar{V})}$) for $\Lambda_b \to pM(V)$ ($\bar{\Lambda}_b \to \bar{p}\bar{M}(\bar{V})$). The direct CP asymmetry is defined by $\mathscr{A}_{CP} = (\Gamma_{M(V)} - \Gamma_{\bar{M}(\bar{V})})/(\Gamma_{M(V)} + \Gamma_{\bar{M}(\bar{V})})$.

3. Numerical Results and Discussions

For the numerical analysis, the theoretical inputs of the meson decay constants and the Wolfenstein parameters for the CKM matrix are taken as $(f_\pi, f_K, f_\rho, f_{K^*}) = (130.4\pm0.2,\ 156.2\pm0.7,\ 210.6\pm0.4,\ 204.7\pm6.1)$ MeV and $(\lambda, A, \rho, \eta) = (0.225,\ 0.814,\ 0.120\pm0.022,\ 0.362\pm0.013)$ from the PDG [2], respectively. We note that f_{ρ,K^*} are extracted from the τ decays of $\tau^- \to (\rho^-, K^{*-})\nu_\tau$, and $V_{ub} = A\lambda^3(\rho - i\eta)$ and $V_{td} = A\lambda^3(1 - i\eta - \rho)$ are used to provide the weak phase for CP violation. According to the adoption of Ref. [1], the parameters $a_{1,4,6}$ can be used to estimate the non-factorizable effects, which are related to the effective Wilson coefficients defined in Ref. [5], providing the strong phases. For the $\Lambda_b \to p$ transition form factors, we use $C_F = 0.136\pm0.009$ [1], which is close to $C_F = 0.14\pm0.03$ from the light-cone sum rules in Ref. [8], and agrees with those in other QCD models [9, 10].

As a result, we obtain

$$\mathscr{R}_{\pi K} = 0.84\pm0.09\,, \tag{3.1}$$

where the error is from the CKM matrix elements only, which reflects that $\mathscr{R}_{\pi K}$ as the ratio of the branching ratios can eliminate the uncertainties from the form factors and non-factorizable effects. For the first time, since the theoretical calculations in Eq. (3.1) can simultaneously explain the data in Eq. (1.1), it is reliable that we extend our approach to the vector counterparts, and the direct CP violating asymmetries, which are predicted in Table 1. Our predictions of $\mathscr{A}_{CP}(\Lambda_b \to p\pi,\ pK^-)$ are around $(-3.9,\ 5.8)\%$ with the errors less than 0.2%, while the results from the data [11] are given to be consistent with zero. It is worth to note that $\mathscr{A}_{CP}(\Lambda_b \to pK^{*-}) = (19.6\pm1.6)\%$ is another example of the large and clean CP violating effects without hadronic uncertainties as the process in the baryonic B decays of $B^\pm \to K^{*\pm}\bar{p}p$ [12].

4. Conclusions

In sum, we have simultaneously explained the recent observed decay branching ratios in $\Lambda_b \to pK^-$ and $\Lambda_b \to p\pi^-$ and obtained $\mathscr{R}_{\pi K} = 0.84\pm0.09$, demonstrating a reliable theoretical approach to study the two-body Λ_b decays. We have also predicted that $\mathscr{A}_{CP}(\Lambda_b \to pK^-) = (5.8\pm0.2)\%$ and $\mathscr{A}_{CP}(\Lambda_b \to p\pi^-) = (-3.9\pm0.2)\%$ with well-controlled uncertainties, whereas the current data for these CPAs are consistent with zero. Particularly, $\mathscr{A}_{CP}(\Lambda_b \to pK^{*-},\ p\rho^-) = (19.6\pm1.6,\ -3.7\pm0.3)\%$ demonstrated to have limited uncertainties would be the most promised direct CPAs to be measured by the experiments at the CDF and LHCb to test the SM.

Table 1: Decay branching ratios and direct CP asymmetries of $\Lambda_b \to pM(V)$, where the errors for $\mathscr{B}(\Lambda_b \to pM(V))$ arise from $f_{M(V)}$ and $f_1(g_1)$, the CKM matrix elements and non-factorizable effects, while those for $\mathscr{A}_{CP}(\Lambda_b \to pM(V))$ are from the CKM matrix elements and non-factorizable effects, respectively.

$\Lambda_b \to pM(V)$	our result	data
$10^6\mathscr{B}(\Lambda_b \to pK^-)$	$4.8 \pm 0.7 \pm 0.1 \pm 0.3$	4.9 ± 0.9 [2]
$10^6\mathscr{B}(\Lambda_b \to p\pi^-)$	$4.2 \pm 0.6 \pm 0.4 \pm 0.2$	4.1 ± 0.8 [2]
$10^6\mathscr{B}(\Lambda_b \to pK^{*-})$	$2.5 \pm 0.3 \pm 0.2 \pm 0.3$	—
$10^6\mathscr{B}(\Lambda_b \to p\rho^-)$	$11.4 \pm 1.6 \pm 1.2 \pm 0.6$	—
$10^2\mathscr{A}_{CP}(\Lambda_b \to pK^-)$	$5.8 \pm 0.2 \pm 0.1$	$-10 \pm 8 \pm 4$ [11]
$10^2\mathscr{A}_{CP}(\Lambda_b \to p\pi^-)$	$-3.9 \pm 0.2 \pm 0.0$	$6 \pm 7 \pm 3$ [11]
$10^2\mathscr{A}_{CP}(\Lambda_b \to pK^{*-})$	$19.6 \pm 1.3 \pm 1.0$	—
$10^2\mathscr{A}_{CP}(\Lambda_b \to p\rho^-)$	$-3.7 \pm 0.3 \pm 0.0$	—

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