Fragmentation-fraction ratio f_{Ξ_b}/f_{Λ_b} in b - and c -baryon decays

Hua-Yu Jiang¹, Fu-Sheng Yu^{1,2,a}

¹ School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China

² Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China

Received: 12 February 2018 / Accepted: 3 March 2018 / Published online: 16 March 2018

© The Author(s) 2018

Abstract We study the ratio of fragmentation fractions, f_{Ξ_b}/f_{Λ_b} , from the measurement of $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ with $\Xi_c^+/\Lambda_c^+ \rightarrow pK^- \pi^+$. With the branching fraction $\mathcal{B}(\Xi_c^+ \rightarrow pK^- \pi^+) = (2.2 \pm 0.8)\%$ obtained under the U-spin symmetry, the fragmentation ratio is determined as $f_{\Xi_b}/f_{\Lambda_b} = 0.054 \pm 0.020$. To reduce the above uncertainties, we suggest to measure the branching fractions of $\Xi_c^+ \rightarrow p\bar{K}^{*0}$ and $\Lambda_c^+ \rightarrow \Sigma^+ K^{*0}$ at BESIII, Belle II and LHCb.

1 Introduction

Bottom quarks can be produced at the high energy colliders, such as LHC and Tevatron, and then hadronized into B mesons and b -baryons. The probability of a bottom quark fragments into a certain weakly decaying b -hadron is called the fragmentation fractions, i.e. $f_{u,d,s} \equiv \mathcal{B}(b \rightarrow B^-, \bar{B}^0, \bar{B}_s^0)$, $f_{\Lambda_b} \equiv \mathcal{B}(b \rightarrow \Lambda_b^0)$, $f_{\Xi_b} \equiv \mathcal{B}(b \rightarrow \Xi_b^0, \Xi_b^-)$ and $f_{\Omega_b} \equiv \mathcal{B}(b \rightarrow \Omega_b^-)$. As non-perturbative effects, the fragmentation fractions can only be determined by experiments in some phenomenological approaches.

The B -meson fragmentation fractions have been measured by LEP, Tevatron and LHC with a relatively high precision [1, 2]. However, the current understanding of b -baryon productions is still a challenge. The total fragmentation fraction of b -baryon is the sum of all the weakly-decaying b -baryons,

$$f_{\text{baryon}} = f_{\Lambda_b} \left(1 + 2 \frac{f_{\Xi_b}}{f_{\Lambda_b}} + \frac{f_{\Omega_b}}{f_{\Lambda_b}} \right) = f_{\Lambda_b} (1 + \delta), \quad (1)$$

where the isospin symmetry is assumed as $f_{\Xi_b^-} = f_{\Xi_b^0} = f_{\Xi_b}$, and $\delta = 2 \frac{f_{\Xi_b}}{f_{\Lambda_b}} + \frac{f_{\Omega_b}}{f_{\Lambda_b}}$ is the correction from f_{Λ_b} to f_{baryon} . The averages of the total baryon production fractions are [2]

$$f_{\text{baryon}} = \begin{cases} 0.084 \pm 0.011, & \text{at LEP,} \\ 0.196 \pm 0.046, & \text{at Tevatron,} \end{cases} \quad (2)$$

which are inconsistent with each other, and of large uncertainties.

The total fraction of b -baryons has not been determined by LHCb because of its lack of measurements on $\Xi_b^{0,-}$ and Ω_b^- . It has been found that the ratio f_{Λ_b}/f_d depends on the p_T of the final states [3–6]. At LHCb, the kinematic averaging ratio is [5]

$$\left. \frac{f_{\Lambda_b}}{f_u + f_d} \right|_{\text{LHCb}} = 0.240 \pm 0.022. \quad (3)$$

It is required for the information of f_{Ξ_b} and f_{Ω_b} to determine the other fragmentation fractions at LHCb due to the constraint of

$$f_u + f_d + f_s + f_{\text{baryon}} = 1. \quad (4)$$

Since the production of Ω_b^- is suppressed compared to those of $\Xi_b^{0,-}$ by the production of an additional strange quark, the determination of f_{Ξ_b}/f_{Λ_b} is essential to understand the productions of b -baryons and B mesons.

So far, only Refs. [7, 8] have predicted the ratio f_{Ξ_b}/f_{Λ_b} , both based on the processes of $\Xi_b^- \rightarrow J/\psi \Xi^-$ and $\Lambda_b^0 \rightarrow J/\psi \Lambda$ with the data given by CDF and D0. At LHCb, the productions of Λ_b and Ξ_b have been measured by the heavy-flavor-conserving process of $\Xi_b^- \rightarrow \Lambda_b^0 \pi^-$ [9], and the charm-baryon involving decays of $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ via $\Xi_c^+/\Lambda_c^+ \rightarrow pK^- \pi^+$ [10]. All the results are listed in Table 1. The production with the charm-baryon involving method is of the most high precision. The ratio f_{Ξ_b}/f_{Λ_b} can be obtained as long as the related branching fractions are determined. Among them, the absolute branching fraction of $\Xi_c^+ \rightarrow pK^- \pi^+$ has never been measured [1], thus is of the largest ambiguity. In this work, we deter-

^a e-mail: yufsh@lzu.edu.cn

Table 1 List of measurements related to the fragmentation fraction ratio f_{Ξ_b}/f_{Λ_b}

Measurements	f_{Ξ_b}/f_{Λ_b}
$f_{\Lambda_b} \cdot \mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda) = (5.8 \pm 0.8) \times 10^{-5}$ [1] (CDF, D0)	0.11 ± 0.03 [7]
$f_{\Xi_b} \cdot \mathcal{B}(\Xi_b^- \rightarrow J/\psi \Xi^-) = (1.02^{+0.26}_{-0.21}) \times 10^{-5}$ [1] (CDF, D0)	0.108 ± 0.034 [8]
$\frac{f_{\Xi_b}}{f_{\Lambda_b}} \cdot \mathcal{B}(\Xi_b^- \rightarrow \Lambda_b^0 \pi^-) = (5.7 \pm 1.8^{+0.8}_{-0.9}) \times 10^{-4}$ [9] (LHCb)	0.29 ± 0.10 (MIT bag model) [11]
	0.08 ± 0.03 (diquark model) [11]
$\frac{f_{\Xi_b}}{f_{\Lambda_b}} \cdot \frac{\mathcal{B}(\Xi_b^0 \rightarrow \Xi_c^+ \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} \cdot \frac{\mathcal{B}(\Xi_c^+ \rightarrow p K^- \pi^+)}{\mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+)} = (1.88 \pm 0.04 \pm 0.03) \times 10^{-2}$ [10] (LHCb)	0.054 ± 0.020 (this work)

mine f_{Ξ_b}/f_{Λ_b} with $\mathcal{B}(\Xi_c^+ \rightarrow p K^- \pi^+)$ obtained under the U -spin symmetry.

This article is organized as follows. In Sect. 2, we introduce the status of f_{Ξ_b}/f_{Λ_b} . The branching fraction of $\Xi_c^+ \rightarrow p K^- \pi^+$ and f_{Ξ_b}/f_{Λ_b} are obtained in Sects. 3 and 4, respectively. Section 5 is the summary.

2 Status of f_{Ξ_b}/f_{Λ_b}

In some literatures, it is usually assumed that the difference between the productions of Ξ_b and Λ_b is from the strange quark and up or down quarks [10, 12],

$$\frac{f_{\Xi_b}}{f_{\Lambda_b}} \simeq \frac{f_s}{f_u}, \quad \text{or} \quad \frac{f_{\Xi_b}}{f_{\Lambda_b}} \simeq 0.2. \quad (5)$$

However, since the fragmentation fractions are non-perturbative effects, they can only be extracted from experimental data. In this section, we introduce the status of f_{Ξ_b}/f_{Λ_b} by means of the relevant measurements.

2.1 $\Xi_b^- \rightarrow J/\psi \Xi^-$ v.s. $\Lambda_b^0 \rightarrow J/\psi \Lambda$

So far, the only theoretical analysis on f_{Ξ_b}/f_{Λ_b} are performed in Refs. [7, 8] based on the experimental data of $\Xi_b^- \rightarrow J/\psi \Xi^-$ and $\Lambda_b^0 \rightarrow J/\psi \Lambda$. In Ref. [1], the relevant results averaging the measurements by CDF and D0 [13–16], are given as

$$\begin{aligned} f_{\Lambda_b} \cdot \mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda) &= (5.8 \pm 0.8) \times 10^{-5}, \\ f_{\Xi_b} \cdot \mathcal{B}(\Xi_b^- \rightarrow J/\psi \Xi^-) &= (1.02^{+0.26}_{-0.21}) \times 10^{-5}. \end{aligned} \quad (6)$$

The fragmentation fraction ratio of f_{Ξ_b}/f_{Λ_b} can be obtained unless the ratio of branching fractions of $\Xi_b^- \rightarrow J/\psi \Xi^-$ and $\Lambda_b^0 \rightarrow J/\psi \Lambda$ is known.

Both $\Xi_b^- \rightarrow J/\psi \Xi^-$ and $\Lambda_b^0 \rightarrow J/\psi \Lambda$ are the $b \rightarrow c\bar{c}s$ transitions with the spectators of $(ds - sd)/\sqrt{2}$ and $(ud - du)/\sqrt{2}$, respectively. Therefore, the two processes are related to each other under the flavor $SU(3)$ symmetry.

The width relation of

$$\Gamma(\Lambda_b^0 \rightarrow J/\psi \Lambda) = \frac{2}{3} \Gamma(\Xi_b^- \rightarrow J/\psi \Xi^-), \quad (7)$$

is given by Voloshin [7]. Using the experimental data in (6), the ratio of the fragmentation fractions can then be obtained as [7]

$$\frac{f_{\Xi_b}}{f_{\Lambda_b}} = 0.11 \pm 0.03. \quad (8)$$

Hsiao *et al* express the decay amplitudes of $\Xi_b^- \rightarrow J/\psi \Xi^-$ and $\Lambda_b^0 \rightarrow J/\psi \Lambda$ in the factorization approach [8]. They relate the form factors of b -baryon to light baryon octet transitions based on the $SU(3)$ symmetry, and obtain the ratio of branching fractions $\mathcal{B}(\Xi_b^- \rightarrow J/\psi \Xi^-)/\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda) = 1.63 \pm 0.04$. Utilizing the data in Eq. (6), the authors give a result similar to Eq. (8),

$$\frac{f_{\Xi_b}}{f_{\Lambda_b}} = 0.108 \pm 0.034. \quad (9)$$

2.2 Heavy-flavor-conserving decay $\Xi_b^- \rightarrow \Lambda_b^0 \pi^-$

The LHCb collaboration has observed the first heavy-flavor-conserving $\Delta S = 1$ hadronic weak decay $\Xi_b^- \rightarrow \Lambda_b^0 \pi^-$ [9], with

$$\frac{f_{\Xi_b}}{f_{\Lambda_b}} \cdot \mathcal{B}(\Xi_b^- \rightarrow \Lambda_b^0 \pi^-) = (5.7 \pm 1.8^{+0.8}_{-0.9}) \times 10^{-4}. \quad (10)$$

In Ref. [9], f_{Ξ_b}/f_{Λ_b} is assumed to be bounded between 0.1 and 0.3, and then obtain the branching fraction of $\Xi_b^- \rightarrow \Lambda_b^0 \pi^-$ lie in the range from $(0.57 \pm 0.21)\%$ to $(0.19 \pm 0.07)\%$. On the contrary, the fragmentation ratio f_{Ξ_b}/f_{Λ_b} can be obtained if $\mathcal{B}(\Xi_b^- \rightarrow \Lambda_b^0 \pi^-)$ is determined.

In Ref. [11], the branching fraction of $\Xi_b^- \rightarrow \Lambda_b^0 \pi^-$ is calculated in the MIT bag model and the diquark model,

$$\mathcal{B}(\Xi_b^- \rightarrow \Lambda_b^0 \pi^-) = \begin{cases} 2.0 \times 10^{-3}, & \text{MIT bag model,} \\ 6.9 \times 10^{-3}, & \text{diquark model.} \end{cases} \quad (11)$$

Subsequently, we can obtain the ratio of fragmentation fractions according to Eq. (10) as,

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = 0.29 \pm 0.10, \quad \text{MIT bag model,} \quad (12)$$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = 0.08 \pm 0.03, \quad \text{diquark model.} \quad (13)$$

$$2.3 \quad \Xi_b^0 \rightarrow \Xi_c^+ \pi^- \text{ v.s. } \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \text{ via } \Xi_c^+/\Lambda_c^+ \rightarrow pK^- \pi^+$$

In the above two methods, the experimental measurements are of large uncertainties, as seen in Eqs. (6) and (10). In the decay of $\Xi_b^- \rightarrow J/\psi \Xi^-$, the efficiency of reconstruction of Ξ^- with $\Xi^- \rightarrow \Lambda \pi^-$ and $\Lambda \rightarrow p \pi^-$, is very small in the hadron colliders [13, 14]. On the other hand, the branching fraction of $\Xi_b^- \rightarrow \Lambda_b^0 \pi^-$ is expected to be very small.

Compared to the above processes, the relative production ratio between $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ has been measured by LHCb with much higher precision [10],

$$\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \cdot \frac{\mathcal{B}(\Xi_b^0 \rightarrow \Xi_c^+ \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} \cdot \frac{\mathcal{B}(\Xi_c^+ \rightarrow pK^- \pi^+)}{\mathcal{B}(\Lambda_c^+ \rightarrow pK^- \pi^+)} = (1.88 \pm 0.04 \pm 0.03) \times 10^{-2}. \quad (14)$$

As long as the branching fractions of the relevant b - and c -baryon decays are known, Eq. (14) could provide a good determination of f_{Ξ_b}/f_{Λ_b} . In Ref. [10], with naively expected values of $\mathcal{B}(\Xi_b^0 \rightarrow \Xi_c^+ \pi^-)/\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-) \approx 1$ and $\mathcal{B}(\Xi_c^+ \rightarrow pK^- \pi^+)/\mathcal{B}(\Lambda_c^+ \rightarrow pK^- \pi^+) \approx 0.1$, it can be obtained that $f_{\Xi_b}/f_{\Lambda_b} \approx 0.2$.

The branching fraction of $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$ has not been directly measured in experiment. $\mathcal{B}(\Xi_b^0 \rightarrow \Xi_c^+ \pi^-)$ and $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)$ are equal to each other in the heavy quark limit and the flavor $SU(3)$ symmetry. In literatures, only Refs. [17] and [18] calculate both the branching fractions of $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$. With the transition form factors in the non-relativistic quark model, the ratio of branching fractions involving the factorizable contribution can be obtained in [17]:

$$\begin{aligned} \frac{\mathcal{B}(\Xi_b^0 \rightarrow \Xi_c^+ \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} &= \frac{\Gamma(\Xi_b^0 \rightarrow \Xi_c^+ \pi^-)}{\Gamma(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} \\ &= \frac{0.33a_1^2 \times 10^{10}s^{-1}}{0.31a_1^2 \times 10^{10}s^{-1}} = 1.07, \end{aligned} \quad (15)$$

where the difference in the lifetimes is neglected since $\tau(\Xi_b^0)/\tau(\Lambda_b^0) = 1.006 \pm 0.021$, and $a_1 = C_1 + C_2/3$ is the effective Wilson coefficient. The deviation from unity results from the mass difference between $m_{\Xi_b} + m_{\Xi_c}$ and $m_{\Lambda_b} + m_{\Lambda_c}$, i.e. the $SU(3)$ breaking effect. In the soft-collinear effective theory, the non-factorizable contributions from the color-commensurate and the W -exchange diagrams are suppressed by $\mathcal{O}(\Lambda_{\text{QCD}}/m_b)$ [19]. In Ref. [18] in a relativistic three-quark model, it is found that the non-factorizable contributions amount up to 30% of the factorizable ones, with the ratio of $\mathcal{B}(\Xi_b^0 \rightarrow \Xi_c^+ \pi^-)/\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-) = 1.25$. Therefore, even without a reliable study in a QCD-based approach, it can still be expected that the deviation of the ratio from unity is under control.

The absolute branching fraction of $\Lambda_c^+ \rightarrow pK^- \pi^+$ has been well measured by Belle and BESIII [20, 21], with $\mathcal{B}(\Lambda_c^+ \rightarrow pK^- \pi^+) = (6.35 \pm 0.33)\%$ [1]. However, branching fraction of $\Xi_c^+ \rightarrow pK^- \pi^+$ is of large ambiguity. The ratio of $\mathcal{B}(\Xi_c^+ \rightarrow pK^- \pi^+)/\mathcal{B}(\Lambda_c^+ \rightarrow pK^- \pi^+) \approx 0.1$ used in [10], is only naively assumed by the Cabibbo factor. In the next section, we will obtain the branching fraction of $\Xi_c^+ \rightarrow pK^- \pi^+$ via U -spin analysis, and then determine f_{Ξ_b}/f_{Λ_b} .

3 Branching fraction of $\Xi_c^+ \rightarrow pK^- \pi^+$

The understanding of charmed baryon decays are still of high deficiency both in theory and in experiment. So far, there has not been any measurement on the absolute branching fraction of $\Xi_c^{0,+}$ decays [1]. The ratio of $\mathcal{B}(\Xi_c^+ \rightarrow pK^- \pi^+)/\mathcal{B}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)$ has been measured to be 0.21 ± 0.04 [1, 22, 23]. But it is still unknown for the absolute branching fraction of $\Xi_c^+ \rightarrow pK^- \pi^+$.

It is first found in Ref. [24] that $\mathcal{B}(\Xi_c^+ \rightarrow pK^- \pi^+) = (2.2 \pm 0.8)\%$ can be obtained from the measured ratio of $\mathcal{B}(\Xi_c^+ \rightarrow p\bar{K}^{*0})/\mathcal{B}(\Xi_c^+ \rightarrow pK^- \pi^+) = 0.54 \pm 0.10$ [22], and the U -spin relation between $\Xi_c^+ \rightarrow p\bar{K}^{*0}$ and $\Lambda_c^+ \rightarrow \Sigma^+ K^{*0}$. We show the U -spin analysis in detail in the present work.

The decays of $\Xi_c^+ \rightarrow p\bar{K}^{*0}$ and $\Lambda_c^+ \rightarrow \Sigma^+ K^{*0}$ are both singly Cabibbo-suppressed modes, with the transition of $c \rightarrow (s\bar{s} - d\bar{d})u$ where the minus sign between $s\bar{s}$ and $d\bar{d}$ comes from the Cabibbo–Kobayashi–Maskawa matrix elements, $V_{cd}^* V_{ud} = -V_{cs}^* V_{us}$. Note that the U -spin doublets are $(|d\rangle, |s\rangle)$ and $(|\bar{s}\rangle, -|\bar{d}\rangle)$. The effective Hamiltonian of $c \rightarrow (s\bar{s} - d\bar{d})u$ changes the U -spin by $\Delta U = 1$, $\Delta U_3 = 0$, i.e. $|\mathcal{H}_{\text{eff}}\rangle = \sqrt{2}|1, 0\rangle$. Ξ_c^+ and Λ_c^+ form a U -spin doublet of (Λ_c^+, Ξ_c^+) . We have

$$\mathcal{H}_{\text{eff}}|\Xi_c^+\rangle = \sqrt{2}\left|1, 0; \frac{1}{2}, -\frac{1}{2}\right\rangle = \frac{2}{\sqrt{3}}\left|\frac{3}{2}, -\frac{1}{2}\right\rangle + \sqrt{\frac{2}{3}}\left|\frac{1}{2}, -\frac{1}{2}\right\rangle, \quad (16)$$

$$\mathcal{H}_{\text{eff}}|\Lambda_c^+\rangle = \sqrt{2}\left|1, 0; \frac{1}{2}, \frac{1}{2}\right\rangle = \frac{2}{\sqrt{3}}\left|\frac{3}{2}, \frac{1}{2}\right\rangle - \sqrt{\frac{2}{3}}\left|\frac{1}{2}, \frac{1}{2}\right\rangle. \quad (17)$$

The U -spin representations of the $|p\bar{K}^{*0}\rangle$ and $|\Sigma^+K^{*0}\rangle$ states are

$$|p\bar{K}^{*0}\rangle = \left|\frac{1}{2}, \frac{1}{2}; 1, -1\right\rangle = \frac{1}{\sqrt{3}}\left|\frac{3}{2}, -\frac{1}{2}\right\rangle - \sqrt{\frac{2}{3}}\left|\frac{1}{2}, -\frac{1}{2}\right\rangle, \quad (18)$$

$$|\Sigma^+K^{*0}\rangle = \left|\frac{1}{2}, -\frac{1}{2}; 1, 1\right\rangle = \frac{1}{\sqrt{3}}\left|\frac{3}{2}, \frac{1}{2}\right\rangle + \sqrt{\frac{2}{3}}\left|\frac{1}{2}, \frac{1}{2}\right\rangle. \quad (19)$$

The decay amplitudes are then

$$\mathcal{A}(\Xi_c^+ \rightarrow p\bar{K}^{*0}) = \langle p\bar{K}^{*0} | \mathcal{H}_{\text{eff}} | \Xi_c^+ \rangle = \frac{2}{3}A_{3/2} - \frac{2}{3}A_{1/2}, \quad (20)$$

$$\mathcal{A}(\Lambda_c^+ \rightarrow \Sigma^+K^{*0}) = \langle \Sigma^+K^{*0} | \mathcal{H}_{\text{eff}} | \Lambda_c^+ \rangle = \frac{2}{3}A_{3/2} - \frac{2}{3}A_{1/2}, \quad (21)$$

where $A_{3/2}$ and $A_{1/2}$ are the amplitudes of U -spin of $3/2$ and $1/2$, respectively. It is clear that the amplitudes satisfy

$$\mathcal{A}(\Xi_c^+ \rightarrow p\bar{K}^{*0}) = \mathcal{A}(\Lambda_c^+ \rightarrow \Sigma^+K^{*0}). \quad (22)$$

This relation can also be seen from the topological diagrams in Fig. 1.

According to the relation in Eq. (22), the branching ratio of $\Xi_c^+ \rightarrow p\bar{K}^{*0}$ can be obtained by

$$\mathcal{B}(\Xi_c^+ \rightarrow p\bar{K}^{*0}) = \frac{m_{\Lambda_c^+}^2}{m_{\Xi_c^+}^2} \cdot \frac{\tau_{\Xi_c^+}}{\tau_{\Lambda_c^+}} \cdot \frac{|p_c(m_{\Xi_c}, m_p, m_{K^*})|}{|p_c(m_{\Lambda_c}, m_{\Sigma}, m_{K^*})|} \cdot \mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+K^{*0}), \quad (23)$$

where $|p_c(M, m_1, m_2)| = \sqrt{[M^2 - (m_1 + m_2)^2][M^2 - (m_1 - m_2)^2]}/2M$. The data of masses and lifetimes are taken from PDG [1]: $m_{\Xi_c} = 2468 \text{ MeV}$, $m_{\Lambda_c} = 2286 \text{ MeV}$, $m_p = 938 \text{ MeV}$, $m_{\Sigma} = 1189 \text{ MeV}$, $m_{K^*} = 892 \text{ MeV}$, $\tau_{\Xi_c^+} = (4.42 \pm 0.26) \times 10^{-13} \text{ s}$, $\tau_{\Lambda_c^+} = (2.00 \pm 0.06) \times 10^{-13} \text{ s}$. Besides, $\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+\pi^+\pi^-) = (4.57 \pm 0.29)\%$ [1, 21], and the branching ratios are [22, 25]

$$\frac{\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+K^{*0})}{\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+\pi^+\pi^-)} = 0.078 \pm 0.022, \quad (24)$$

$$\frac{\mathcal{B}(\Xi_c^+ \rightarrow p\bar{K}^{*0})}{\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+)} = 0.54 \pm 0.10. \quad (25)$$

Then we can obtain

$$\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+) = (2.2 \pm 0.8)\%. \quad (26)$$

The uncertainty is dominated by the ratios of branching fractions of Λ_c^+ and Ξ_c^+ decays in Eqs. (24) and (25).

The central value of $\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+)$ at the order of percent, is larger than the typical order of 10^{-3} of the ordinary singly Cabibbo-suppressed processes, such as $\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+K^{*0}) = (3.6 \pm 1.0) \times 10^{-3}$. This can be clarified by Eq. (23). Firstly, the lifetime of Ξ_c^+ is two times larger than that of Λ_c^+ . Secondly, the phase space of $\Xi_c^+ \rightarrow p\bar{K}^{*0}$ is larger than that of $\Lambda_c^+ \rightarrow \Sigma^+K^{*0}$ by another factor of two, i.e. $|p_c(m_{\Xi_c}, m_p, m_{K^*})| = 828 \text{ MeV}$ and $|p_c(m_{\Lambda_c}, m_{\Sigma}, m_{K^*})| = 470 \text{ MeV}$. Due to the larger lifetime and phase space, the branching fraction of $\Xi_c^+ \rightarrow p\bar{K}^{*0}$ is then at the order of percent, $(1.2 \pm 0.4)\%$.

The understanding of the dynamics of charmed baryon decays is still a challenge at the current stage. Recent theoretical studies are mostly based on the flavor $SU(3)$ analysis [26–30] and the current algebra [31]. They have not yet been applied to the singly Cabibbo-suppressed charmed baryon decays into a light baryon and a vector meson. Therefore, it is not available to estimate the U -spin breaking effects in the above analysis of Eq. (26). In the D -meson decays, the U -spin breaking effects, or say the $SU(3)$ breaking effects, are mainly from the transition form factors and decay constants in the factorizable amplitudes, the difference between $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ produced from vacuum in the W -exchange and W -annihilation amplitudes, and the Glauber strong phase with pion in the non-factorizable contributions [32, 33]. In Fig. 1, both amplitudes in the $\Xi_c^+ \rightarrow p\bar{K}^{*0}$ and $\Lambda_c^+ \rightarrow \Sigma^+K^{*0}$ decay are non-factorizable. The vacuum production of $d\bar{d}$ and $s\bar{s}$ in the W -exchange diagrams would be a main source of U -spin breaking. In the modes involving a vector meson and a pseudoscalar meson in the final states of D -meson decays, the difference between $d\bar{d}$ and $s\bar{s}$ production in the W -exchange diagrams can be seen from $\chi_d^E e^{i\phi_d^E} = (0.49 \pm 0.03)e^{i(92 \pm 4)^\circ}$ and $\chi_s^E e^{i\phi_s^E} = (0.54 \pm 0.03)e^{i(128 \pm 5)^\circ}$ [34] where χ and ϕ are the magnitude and strong phase of the non-perturbative parameters in the W -exchange diagrams, and the subscripts d and s denotes the quark flavor of $q\bar{q}$ produced from the vacuum. It can be found that the U -spin breaking effects are not large in $D \rightarrow VP$ modes. The W -exchange diagrams in charmed baryon decays are similar to the ones in charmed meson decays, with an additional spectator quark. It can be expected that the U -spin breaking effects between $\Xi_c^+ \rightarrow p\bar{K}^{*0}$ and $\Lambda_c^+ \rightarrow \Sigma^+K^{*0}$ would not be large, and thus the prediction of $\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+) = (2.2 \pm 0.8)\%$ would be under control.

The process of $\Xi_c^+ \rightarrow pK^-\pi^+$ with all the charged final particles is widely used to study the properties of, or to search

Fig. 1 The topological diagrams of $\Xi_c^+ \rightarrow p \bar{K}^{*0}$ and $\Lambda_c^+ \rightarrow \Sigma^+ K^{*0}$. The top and bottom diagrams are color-commensurate and W-exchange ones, respectively

for some heavier baryons. The mass and lifetime of Ξ_b^0 are measured with the most high precision via $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$, $\Xi_c^+ \rightarrow p K^- \pi^+$ [10]. New states of $\Xi_b^{\prime-}(\frac{1}{2}^+)$ and $\Xi_b^{*-}(\frac{3}{2}^+)$ are observed in the $\Xi_b^0 \pi^-$ spectrum with $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$, $\Xi_c^+ \rightarrow p K^- \pi^+$ [35]. Five new Ω_c^0 resonances are observed in the final states of $\Xi_c^+ K^-$ with $\Xi_c^+ \rightarrow p K^- \pi^+$ [36]. It is suggested to search for the doubly charmed baryons in the decay of $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ with $\Xi_c^+ \rightarrow p K^- \pi^+$ [24, 37]. In this work, the ratio of fragmentation fractions f_{Ξ_b}/f_{Λ_b} can be obtained as long as the branching fraction of $\Xi_c^+ \rightarrow p K^- \pi^+$ is determined by Eq. (14).

4 f_{Ξ_b}/f_{Λ_b} and its implications

Utilizing the prediction of $\mathcal{B}(\Xi_c^+ \rightarrow p K^- \pi^+)$ in Eq. (26), the measured value of $\mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+) = (6.35 \pm 0.33)\%$ [1] and the reasonable theoretical ratio $\mathcal{B}(\Xi_b^0 \rightarrow \Xi_c^+ \pi^-)/\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-) \approx 1$, the ratio of the fragmentation fraction for b quark into Ξ_b^0 and Λ_b^0 can be obtained from Eq. (14) as

$$\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} = 0.054 \pm 0.020. \quad (27)$$

The uncertainty is mainly from the branching fraction of $\Xi_c^+ \rightarrow p K^- \pi^+$ in Eq. (26). This result of f_{Ξ_b}/f_{Λ_b} is much smaller than the naive estimation of f_s/f_u or 0.2 in Eq. (5), and the MIT bag model for the branching fraction of $\Xi_b^- \rightarrow \Lambda_b^0 \pi^-$ in Eq. (12). The central value of

our result in Eq. (27) is one half of those obtained via $\Xi_b^- (\Lambda_b^0) \rightarrow J/\Psi \Xi^- (\Lambda)$ in Eqs. (8) and (9). Only the prediction in the diquark model for $\Xi_b^- \rightarrow \Lambda_b^0 \pi^-$ in Eq. (13) is consistent with our result within the uncertainties, while the central value is larger as well.

The total b -baryon fraction can be obtained by the ratio f_{Ξ_b}/f_{Λ_b} in Eq. (27). The production of Ω_b^- is doubly suppressed by two strange quarks, estimated as 15% of the Ξ_b [38]. It is smaller than the error of f_{Ξ_b}/f_{Λ_b} in Eq. (27), and thus can be neglected in the total fraction of b -baryons. We then have

$$\begin{aligned} f_{\text{baryon}} &= f_{\Lambda_b} + 2f_{\Xi_b} + f_{\Omega_b} \approx f_{\Lambda_b} + 2f_{\Xi_b} \\ &= (1.11 \pm 0.04)f_{\Lambda_b}. \end{aligned} \quad (28)$$

It is equivalent that the correction δ in Eq. (1) is $\delta = 0.11 \pm 0.04$, which is smaller than the estimation of $\delta = 0.25 \pm 0.10$ in Ref. [38].

With the result of f_{Ξ_b}/f_{Λ_b} in Eq. (27), the branching fraction of $\Xi_b^- \rightarrow \Lambda_b^0 \pi^-$ can be determined from Eq. (10),

$$\mathcal{B}(\Xi_b^- \rightarrow \Lambda_b^0 \pi^-) = (1.06 \pm 0.54)\%. \quad (29)$$

This is consistent with the diquark model, but larger than the MIT bag model, seen in Eq. (11).

The precision of our result of f_{Ξ_b}/f_{Λ_b} in Eq. (27) can be significantly improved by the measurements of $\Xi_c^+ \rightarrow p \bar{K}^{*0}$ and $\Lambda_c^+ \rightarrow \Sigma^+ K^{*0}$ at LHCb, BESIII and Belle II. The large uncertainty of $\mathcal{B}(\Xi_c^+ \rightarrow p K^- \pi^+)$ in Eq. (26), inducing the major uncertainty of f_{Ξ_b}/f_{Λ_b} , is dominated by two

ratios of branching fractions: $\mathcal{B}(\Xi_c^+ \rightarrow p\bar{K}^{*0})/\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+) = 0.54 \pm 0.10$ by FOCUS in 2001 [22] and $\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+K^{*0})/\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+\pi^+\pi^-) = 0.078 \pm 0.022$ measured by FOCUS in 2002 [25]. For the former, a more precise measurement can be performed by LHCb with partial wave analysis. At LHCb with the data of 3.3 fb^{-1} , there are already 1×10^6 events of $\Xi_c^+ \rightarrow pK^-\pi^+$ [36], which is four orders of magnitude larger than 200 events in Ref. [22]. The latter can be improved by the BESIII or Belle(II) experiments, which have recently performed a dozen measurements of Λ_c^+ decays [20, 21, 39–46], especially the observation of some singly or doubly Cabibbo-suppressed processes [44–46]. With the updated measurements of $\Xi_c^+ \rightarrow p\bar{K}^{*0}$ and $\Lambda_c^+ \rightarrow \Sigma^+K^{*0}$ in the near future, f_{Ξ_b}/f_{Λ_b} could be of higher precision.

5 Summary

In this work, we study the ratio of fragmentation fractions f_{Ξ_b}/f_{Λ_b} with the data of $\Xi_b^0 \rightarrow \Xi_c^+\pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$, $\Xi_c^+/\Lambda_c^+ \rightarrow pK^-\pi^+$ at LHCb, which is the most precise measurement related to the fragmentations of Ξ_b and Λ_b , seen in Table 1. The least known branching fraction of $\Xi_c^+ \rightarrow pK^-\pi^+$ is obtained under the U -spin symmetry, $\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+) = (2.2 \pm 0.8)\%$. The ratio f_{Ξ_b}/f_{Λ_b} is then determined to be $f_{\Xi_b}/f_{\Lambda_b} = 0.054 \pm 0.020$. This is the first analysis of f_{Ξ_b}/f_{Λ_b} using the LHCb data. It helps to understand the production of b -baryons. To improve the precision, we suggest to measure the ratios of branching fractions $\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+K^{*0})/\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^+\pi^+\pi^-)$ and $\mathcal{B}(\Xi_c^+ \rightarrow p\bar{K}^{*0})/\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+)$ at BESIII, Belle(II) and LHCb using the current data set or in the near future.

Acknowledgements This research was supported by the National Natural Science Foundation of China under the Grant No. 11505083 and U1732101.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. Funded by SCOAP³.

References

1. C. Patrignani et al. [Particle Data Group], Chin. Phys. C **40**(10), 100001 (2016). <https://doi.org/10.1088/1674-1137/40/10/100001>
2. Y. Amhis et al. [HFLAV Collaboration], Eur. Phys. J. C **77**(12), 895 (2017). <https://doi.org/10.1140/epjc/s10052-017-5058-4>. arXiv:1612.07233 [hep-ex]
3. T. Aaltonen et al. [CDF Collaboration], Phys. Rev. D **77**, 072003 (2008). <https://doi.org/10.1103/PhysRevD.77.072003>. arXiv:0801.4375 [hep-ex]
4. T. Aaltonen et al. [CDF Collaboration], Phys. Rev. D **79**, 032001 (2009). <https://doi.org/10.1103/PhysRevD.79.032001>. arXiv:0810.3213 [hep-ex]
5. R. Aaij et al. [LHCb Collaboration], Phys. Rev. D **85**, 032008 (2012). <https://doi.org/10.1103/PhysRevD.85.032008>. arXiv:1111.2357 [hep-ex]
6. R. Aaij et al. [LHCb Collaboration], JHEP **1408**, 143 (2014). [https://doi.org/10.1007/JHEP08\(2014\)143](https://doi.org/10.1007/JHEP08(2014)143). arXiv:1405.6842 [hep-ex]
7. M. B. Voloshin. arXiv:1510.05568 [hep-ph]
8. Y. K. Hsiao, P. Y. Lin, L. W. Luo, C. Q. Geng, Phys. Lett. B **751**, 127 (2015). <https://doi.org/10.1016/j.physletb.2015.10.013>. arXiv:1510.01808 [hep-ph]
9. R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. **115**(24), 241801 (2015). <https://doi.org/10.1103/PhysRevLett.115.241801>. arXiv:1510.03829 [hep-ex]
10. R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. **113**, 032001 (2014). <https://doi.org/10.1103/PhysRevLett.113.032001>. arXiv:1405.7223 [hep-ex]
11. H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin, T. M. Yan and H. L. Yu, JHEP **1603**, 028 (2016). [https://doi.org/10.1007/JHEP03\(2016\)028](https://doi.org/10.1007/JHEP03(2016)028). arXiv:1512.01276 [hep-ph]
12. I. Heredia-De La Cruz [D0 Collaboration]. arXiv:1109.6083 [hep-ex]
13. T. Aaltonen et al. [CDF Collaboration], Phys. Rev. D **80**, 072003 (2009). <https://doi.org/10.1103/PhysRevD.80.072003>. arXiv:0905.3123 [hep-ex]
14. V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. **99**, 052001 (2007). <https://doi.org/10.1103/PhysRevLett.99.052001>. arXiv:0706.1690 [hep-ex]
15. V. M. Abazov et al. [D0 Collaboration], Phys. Rev. D **84**, 031102 (2011). <https://doi.org/10.1103/PhysRevD.84.031102>. arXiv:1105.0690 [hep-ex]
16. F. Abe et al., [CDF Collaboration], Phys. Rev. D **55**, 1142 (1997). <https://doi.org/10.1103/PhysRevD.55.1142>
17. H. Y. Cheng, Phys. Rev. D **56**, 2799 (1997). <https://doi.org/10.1103/PhysRevD.56.2799>. arXiv:hep-ph/9612223
18. M.A. Ivanov, J.G. Korner, V.E. Lyubovitskij, A.G. Rusetsky, Mod. Phys. Lett. A **13**, 181 (1998). <https://doi.org/10.1142/S0217732398000231>. arXiv:hep-ph/9709325
19. A.K. Leibovich, Z. Ligeti, I.W. Stewart, M.B. Wise, Phys. Lett. B **586**, 337 (2004). <https://doi.org/10.1016/j.physletb.2004.02.033>. arXiv:hep-ph/0312319
20. A. Zupanc et al. [Belle Collaboration], Phys. Rev. Lett. **113**(4), 042002 (2014). <https://doi.org/10.1103/PhysRevLett.113.042002>. arXiv:1312.7826 [hep-ex]
21. M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. **116**(5), 052001 (2016). <https://doi.org/10.1103/PhysRevLett.116.052001>. arXiv:1511.08380 [hep-ex]
22. J. M. Link et al. [FOCUS Collaboration], Phys. Lett. B **512**, 277 (2001). [https://doi.org/10.1016/S0370-2693\(01\)00590-1](https://doi.org/10.1016/S0370-2693(01)00590-1). arXiv:hep-ex/0102040
23. E. Vazquez-Jauregui et al. [SELEX Collaboration], Phys. Lett. B **666**, 299 (2008). <https://doi.org/10.1016/j.physletb.2008.07.072>. arXiv:0804.2298 [hep-ex]
24. F. S. Yu, H. Y. Jiang, R. H. Li, C. D. Lu, W. Wang and Z. X. Zhao. arXiv:1703.09086 [hep-ph]
25. J. M. Link et al. [FOCUS Collaboration], Phys. Lett. B **540**, 25 (2002). [https://doi.org/10.1016/S0370-2693\(02\)02103-2](https://doi.org/10.1016/S0370-2693(02)02103-2). arXiv:hep-ex/0206013
26. C. D. Lu, W. Wang, F. S. Yu, Phys. Rev. D **93**(5), 056008 (2016). <https://doi.org/10.1103/PhysRevD.93.056008>. arXiv:1601.04241 [hep-ph]
27. D. Wang, P. F. Guo, W. H. Long and F. S. Yu. arXiv:1709.09873 [hep-ph]

28. C. Q. Geng, Y. K. Hsiao, C. W. Liu and T. H. Tsai. [arXiv:1801.03276](#) [hep-ph]
29. C. Q. Geng, Y. K. Hsiao, C. W. Liu and T. H. Tsai, JHEP **1711**, 147 (2017). [https://doi.org/10.1007/JHEP11\(2017\)147](https://doi.org/10.1007/JHEP11(2017)147). [arXiv:1709.00808](#) [hep-ph]
30. C. Q. Geng, Y. K. Hsiao, Y. H. Lin, L. L. Liu, Phys. Lett. B **776**, 265 (2018). <https://doi.org/10.1016/j.physletb.2017.11.062>. [arXiv:1708.02460](#) [hep-ph]
31. H. Y. Cheng, X. W. Kang and F. Xu. [arXiv:1801.08625](#) [hep-ph]
32. H. n. Li, C. D. Lu, F. S. Yu, Phys. Rev. D **86**, 036012 (2012). <https://doi.org/10.1103/PhysRevD.86.036012>. [arXiv:1203.3120](#) [hep-ph]
33. H. n. Li, C. D. Lu, Q. Qin, F. S. Yu, Phys. Rev. D **89**(5), 054006 (2014). <https://doi.org/10.1103/PhysRevD.89.054006>. [arXiv:1305.7021](#) [hep-ph]
34. H. Y. Jiang, F. S. Yu, Q. Qin, H. n. Li and C. D. Lu. [arXiv:1705.07335](#) [hep-ph]
35. R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. **114**, 062004 (2015). <https://doi.org/10.1103/PhysRevLett.114.062004>. [arXiv:1411.4849](#) [hep-ex]
36. R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. **118**(18), 182001 (2017). <https://doi.org/10.1103/PhysRevLett.118.182001>. [arXiv:1703.04639](#) [hep-ex]
37. W. Wang, F. S. Yu and Z. X. Zhao, Eur. Phys. J. C **77**(11), 781 (2017). <https://doi.org/10.1140/epjc/s10052-017-5360-1>. [arXiv:1707.02834](#) [hep-ph]
38. R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. **118**, no. 5, 052002 (2017) Erratum: [Phys. Rev. Lett. **119**(16), 169901 (2017)]. <https://doi.org/10.1103/PhysRevLett.119.169901>. <https://doi.org/10.1103/PhysRevLett.118.052002>. [arXiv:1612.05140](#) [hep-ex]
39. B. Pal et al. [Belle Collaboration], Phys. Rev. D **96**(5), 051102 (2017). <https://doi.org/10.1103/PhysRevD.96.051102>. [arXiv:1707.00089](#) [hep-ex]
40. M. Ablikim et al. [BESIII Collaboration], Phys. Lett. B **767**, 42 (2017). <https://doi.org/10.1016/j.physletb.2017.01.047>. [arXiv:1611.04382](#) [hep-ex]
41. M. Ablikim et al. [BESIII Collaboration], Phys. Lett. B **772**, 388 (2017). <https://doi.org/10.1016/j.physletb.2017.06.065>. [arXiv:1705.11109](#) [hep-ex]
42. M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. **118**(11), 112001 (2017). <https://doi.org/10.1103/PhysRevLett.118.112001>. [arXiv:1611.02797](#) [hep-ex]
43. M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. **115**(22), 221805 (2015). <https://doi.org/10.1103/PhysRevLett.115.221805>. [arXiv:1510.02610](#) [hep-ex]
44. S. B. Yang et al. [Belle Collaboration], Phys. Rev. Lett. **117**(1), 011801 (2016). <https://doi.org/10.1103/PhysRevLett.117.011801>. [arXiv:1512.07366](#) [hep-ex]
45. M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. **117**(23), 232002 (2016) Addendum: [Phys. Rev. Lett. **120**(2), 029903 (2018)]. <https://doi.org/10.1103/PhysRevLett.117.232002>. <https://doi.org/10.1103/PhysRevLett.120.029903>. [arXiv:1608.00407](#) [hep-ex]
46. M. Ablikim et al. [BESIII Collaboration], Phys. Rev. D **95**(11), 111102 (2017). <https://doi.org/10.1103/PhysRevD.95.111102>. [arXiv:1702.05279](#) [hep-ex]
47. R. Aaij et al. [LHCb Collaboration], JHEP **1605**, 081 (2016). [https://doi.org/10.1007/JHEP05\(2016\)081](https://doi.org/10.1007/JHEP05(2016)081). [arXiv:1603.00413](#) [hep-ex]