

Two-body charmed-anticharmed baryonic B decays

Chun-Kiang Chua[✉]

Department of Physics and Center for High Energy Physics, *Chung Yuan Christian University*,
Chung-Li, Taiwan 320, Republic of China



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We study the rates of two-body charmed-anticharmed baryonic $\bar{B} \rightarrow \mathcal{B}_c \bar{\mathcal{B}}_c$ decays using the topological amplitude approach. All amplitudes of $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$, $\mathcal{B}_c(\mathbf{6}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$, $\mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$, and $\mathcal{B}_c(\mathbf{6}_f) \bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays are decomposed topologically. SU(3) breaking effects on these amplitudes, depending on the position of the s -quark line, are modeled. Using existing data as input, we obtained the following results: (i) In the low-lying $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays, we find that the exchange diagram is sizable. Furthermore, there is a large cancellation between internal W -tree and exchange- W -tree amplitudes. The SU(3) breaking is sizable, 35% SU(3) breaking effects are needed, and they work differently in different amplitudes. Namely, the internal W -tree amplitude is enlarged, while the exchange- W -tree amplitude is reduced. The rates of $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays with excited $\mathcal{B}_c(\bar{\mathbf{3}}_f)$, such as $\Lambda_c(2595)^+$, $\Xi_c(2790)^{+,0}$, are also studied. (ii) The $\bar{B} \rightarrow \mathcal{B}_c(\mathbf{6}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays, with low-lying $\bar{\mathcal{B}}_c(\mathbf{3}_f)$ and low-lying and excited $\mathcal{B}_c(\mathbf{6}_f)$ baryons, such as $\Sigma_c(2520)^{+,0}$, $\Xi_c(2645)^{+,0}$, $\Omega_c(2770)^0$, are studied with some predictions on rates obtained. Furthermore, as the excited states are spin-3/2 states, some of their rates are highly suppressed by the kinematic factor. (iii) The $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays with low-lying charmed-anticharmed baryons are studied with some predictions on rates obtained. (iv) Uncertainties in most predicted rates are large, reflecting our current poor understanding of the related SU(3) breaking effects. Measuring these rates can provide very useful information about these effects.

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I. INTRODUCTION

Recently, there has been some progress in two-body charmed-anticharmed baryonic B decays. The current situation is summarized in Table I [1–6]. In particular, the $B^- \rightarrow \Xi_c^+ \bar{\Sigma}_c(2455)^{-}$, $\bar{B}^0 \rightarrow \Xi_c^0 \bar{\Sigma}_c(2455)^0$, $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$, and $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$ decays were reported in 2025 by Belle II [4] and LHCb [5], respectively.

We summarize in Table II the quantum numbers of the charmed baryons related to those in Table I, see Ref. [1] (and also [7]). One can see that the modes shown in Table I belong to $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$, $\mathcal{B}_c(\mathbf{6}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$, and $\mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays, where $\bar{\mathbf{3}}_f$ and $\mathbf{6}_f$ are SU(3) antitriplet and sextet multiplets, respectively, with low-lying and excited charmed-anticharmed baryon final states. Indeed, we have data on the rates of four low-lying $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays, one $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay with an excited $\mathcal{B}_c(\bar{\mathbf{3}}_f)$, one low-lying and one excited

$\bar{B} \rightarrow \mathcal{B}_c(\mathbf{6}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay, and two low-lying $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays; in total, nine modes. Given the recent experimental progress, it is timely and interesting to investigate these decays systematically.

There are some theoretical studies on low-lying $\bar{B} \rightarrow \mathcal{B}_c \bar{\mathcal{B}}_c$ decays [8–15]. Early calculations often yield overly large rates. As the direct theoretical calculations of the decays of these modes remain challenging, we shall use the well-established topological amplitude formalism [16–23] in this study. This approach has been applied to baryonic B decays; see, for example, Refs. [24–27].

The importance of the contribution from the W -exchange diagram and the need for SU(3) breaking in low-lying $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays have been reported by LHCb [5]. In fact, the need for W -exchange diagrams has been pointed out in Ref. [13], see also Ref. [28], and the need for SU(3) breaking is also pointed out in Ref. [14]. We shall include both internal W -tree and W -exchange diagrams with modeling of SU(3)-breaking effects in these topological amplitudes. Existing data shown in Table I will be used as inputs to predict the rates of other modes. Although data on $\bar{B} \rightarrow \mathcal{B}_c(\mathbf{6}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$ and $\mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays are relatively less, as we shall see, these modes are internal W -tree

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TABLE I. Experimental results of $\bar{B}_{u,d,s} \rightarrow \mathbf{B}_c \bar{\mathbf{B}}_c$ branching ratios in units of 10^{-4} . The upper limits are at 90% confidence level.

Mode	LHCb	Belle/Belle-II	PDG [1]
$B^- \rightarrow \Xi_c^0 \bar{\Lambda}_c^-$		$9.51 \pm 2.10 \pm 0.88$ [2]	9.5 ± 2.3
$B^- \rightarrow \Xi_c^0 \bar{\Lambda}_c^-$		3.4 ± 2.0 [3]	< 6.5
$B^- \rightarrow \Xi_c^0(2645) \bar{\Lambda}_c^-$		4.4 ± 2.4 [3]	< 7.9
$B^- \rightarrow \Xi_c^0(2790) \bar{\Lambda}_c^-$		1.1 ± 0.4 [3]	1.1 ± 0.4
$B^- \rightarrow \Xi_c^+ \bar{\Sigma}_c(2455)^--$		$5.74 \pm 1.11 \pm 0.42^{+2.47}_{-1.53}$ [4]	
$\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Lambda}_c^-$		$11.6 \pm 4.2 \pm 1.5$ [6]	11 ± 8
$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$	$0.101^{+0.027}_{-0.028} \pm 0.008 \pm 0.015$ [5]		< 0.16
$\bar{B}^0 \rightarrow \Xi_c^0 \bar{\Sigma}_c(2455)^0$		$4.83 \pm 1.12 \pm 0.37^{+0.72}_{-0.60}$ [4]	
$\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$	$0.50 \pm 0.13 \pm 0.05 \pm 0.08$ [5]		< 0.8

TABLE II. The quantum numbers of charmed baryons involved in this study, see Ref. [1] (and also [7]).

$\mathcal{B}_c$	SU(3) multiplet	J^P
$\Lambda_c^+, \Xi_c^{+,0}$	$\bar{\mathbf{3}}_f$	$\frac{1}{2}^+$
$\Lambda_c(2595)^+, \Xi_c(2790)^{+,0}$	$\bar{\mathbf{3}}_f$	$\frac{1}{2}^-$
$\Sigma_c(2455)^{++,+}, \Xi_c'^{+,0}, \Omega_c^0$	$\mathbf{6}_f$	$\frac{1}{2}^+$
$\Sigma_c(2520)^{++,+}, \Xi_c(2645)^{+,0}, \Omega_c(2770)^0$	$\mathbf{6}_f$	$\frac{3}{2}^+$

modes. It is expected that their amplitudes, for final states within the same multiplets, are highly related. Hence, even with these data, it is likely that some predictions on rates can still be made.

The layout of this paper is as follows. Formalism is given in Sec. II, where topological amplitudes in SU(3) limit and modeling of SU(3)-breaking effects are introduced. The resulting decompositions of all $\bar{B} \rightarrow \mathcal{B}_c \bar{\mathcal{B}}_c$ decay amplitudes and formulas of rates are given in Sec. III. In Sec. IV, numerical results on rates of $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$,

$\mathcal{B}_c(\mathbf{6}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$, and $\mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays with low-lying and some excited final states are shown. We give our conclusions in Sec. V, which is followed by an Appendix.

II. FORMALISM

We follow [24,29] to obtain the decomposition of decay amplitudes in terms of topological amplitudes. We consider the SU(3) symmetric case first and include the modeling of SU(3)-breaking effects later.

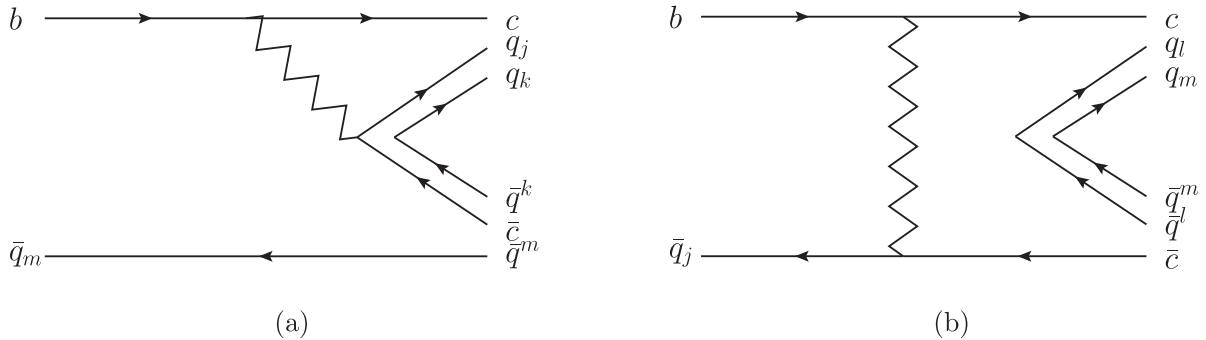


FIG. 1. Topological diagrams of (a) C (internal W -tree) and (b) E (W -exchange) amplitudes in $\bar{B}$ to charmed baryon pair decays. These are flavor flow diagrams.

A. SU(3) symmetric case

For low-lying sextet ($\mathbf{6}_f$) charmed baryons, we have

$$\begin{aligned}\mathcal{B}_c^{\{11\}} &= \sqrt{2}\Sigma_c^{++}, & \mathcal{B}_c^{\{12\}} &= \mathcal{B}_c^{\{21\}} = \Sigma_c^+, \\ \mathcal{B}_c^{\{22\}} &= \sqrt{2}\Sigma_c^0, & \mathcal{B}_c^{\{13\}} &= \mathcal{B}_c^{\{31\}} = \Xi_c^+, \\ \mathcal{B}_c^{\{23\}} &= \mathcal{B}_c^{\{32\}} = \Xi_c^0, & \mathcal{B}_c^{\{33\}} &= \sqrt{2}\Omega_c^0,\end{aligned}\quad (1)$$

while for low-lying antitriplet $\bar{\mathbf{3}}_f$ charmed baryons, we have

$$\begin{aligned}\mathcal{B}_c^{[12]} &= -\mathcal{B}_c^{[21]} = \Lambda_c^+, & \mathcal{B}_c^{[23]} &= -\mathcal{B}_c^{[32]} = \Xi_c^0, \\ \mathcal{B}_c^{[31]} &= -\mathcal{B}_c^{[13]} = \Xi_c^+.\end{aligned}\quad (2)$$

For simplicity, we only show the assignments for low-lying charmed baryons in the above equations. One can readily obtain similar assignments for excited charmed baryons based on their SU(3) quantum numbers.

The $\bar{B} \rightarrow \mathcal{B}_c \bar{\mathcal{B}}_c$ decays are governed by a $(\bar{s}c)_{V-A}(\bar{c}b)_{V-A}$ operator. The flavor structure of the above operator can be expressed as $(\bar{q}_j H^j c)(\bar{c} b)$ with $q^j = (u, d, s)$ and

$$H = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}. \quad (3)$$

Consequently, the Hamiltonians governing various $\bar{B} \rightarrow \mathcal{B}_c \bar{\mathcal{B}}_c$ decays are given by

$$\begin{aligned}H_{\text{eff}}(\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)) &= C_1 \bar{B}_m H^j \bar{\mathcal{B}}_{c[jk]} \mathcal{B}_c^{[km]} + \frac{1}{2} E_1 \bar{B}_j H^j \bar{\mathcal{B}}_{c[lm]} \mathcal{B}_c^{[ml]}, \\ H_{\text{eff}}(\bar{B} \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)) &= C_2 \bar{B}_m H^j \bar{\mathcal{B}}_{c\{jk\}} \mathcal{B}_c^{[km]}, \\ H_{\text{eff}}(\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)) &= C_3 \bar{B}_m H^j \bar{\mathcal{B}}_{c[jk]} \mathcal{B}_c^{\{km\}}, \\ H_{\text{eff}}(\bar{B} \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)) &= C_4 \bar{B}_m H^j \bar{\mathcal{B}}_{c\{jk\}} \mathcal{B}_c^{\{km\}} + \frac{1}{2} E_4 \bar{B}_j H^j \bar{\mathcal{B}}_{c\{lm\}} \mathcal{B}_c^{\{ml\}}.\end{aligned}\quad (4)$$

These C and E amplitudes denote internal W -tree and W -exchange amplitudes, respectively, see Fig. 1. Note that following Refs. [13,14], we do not include penguin amplitudes, as their contributions to averaged rates are expected to be subleading and can be neglected. We have two topological amplitudes in $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays and another two topological amplitudes in $\bar{B} \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays, but only need one topological amplitude each in $\bar{B} \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ or $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decay.

The number of topological amplitudes can be easily understood as follows. Recall that one has the following SU(3) decompositions:

$$\begin{aligned}\bar{\mathbf{3}} \otimes \mathbf{3} &= \mathbf{8} \oplus \mathbf{1}, \\ \mathbf{6} \otimes \mathbf{3} &= \mathbf{8} \oplus \mathbf{10}, \\ \bar{\mathbf{3}} \otimes \bar{\mathbf{6}} &= \mathbf{8} \oplus \bar{\mathbf{10}}, \\ \mathbf{6} \otimes \bar{\mathbf{6}} &= \mathbf{27} \oplus \mathbf{8} \oplus \mathbf{1}.\end{aligned}\quad (5)$$

The decaying $\bar{B}$ meson and the tree operator form a product of $\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1}$, while the final states $\mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ and $\mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ each also have an $\mathbf{8}$ and a $\mathbf{1}$, which can match the $\mathbf{8}$ and the $\mathbf{1}$ in the combination of the decaying $\bar{B}$ meson and the tree operator, giving two independent amplitudes in each case. This is, however, not

the case in the other two decays. Although $\mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ and $\mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ final states each have an $\mathbf{8}$ that can match to the $\mathbf{8}$ in the decaying $\bar{B}$ meson and the tree operator, they do not have any $\mathbf{1}$, resulting only one independent amplitude in each case.

The above effective Hamiltonians are for the $\Delta S = -1$ transition, and they can be easily transformed into those for the $\Delta S = 0$ transition, by simply replacing H in Eq. (3) with

$$H' = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \quad (6)$$

and with C_i and E_i replaced by C'_i and E'_i , respectively. It is understood that these amplitudes are related by the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, namely,

$$C'_i = \frac{V_{cb} V_{cd}^*}{V_{cb} V_{cs}^*} C_i, \quad E'_i = \frac{V_{cb} V_{cd}^*}{V_{cb} V_{cs}^*} E_i. \quad (7)$$

B. Including SU(3) breaking

To model the SU(3) breaking in $\bar{B} \rightarrow \mathcal{B}_c \bar{\mathcal{B}}_c$ decays, we define

$$M = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (8)$$

which can generate SU(3)-breaking terms in amplitudes, as the breaking originates from the relatively large s -quark mass. Including the SU(3)-breaking parts, the Hamiltonians for the $\Delta S = -1$ transition now become

$$\begin{aligned} H_{\text{eff}}(\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)) &= C_1 \bar{B}_m H^j \bar{\mathcal{B}}_{c[jk]} \mathcal{B}_c^{[km]} + \delta_v C_1 \bar{B}_m H^j M_j^{j'} \bar{\mathcal{B}}_{c[j'k]} \mathcal{B}_c^{[km]} \\ &\quad + \delta_s C_1 \bar{B}_{m'} M_m^{m'} H^j \bar{\mathcal{B}}_{c[jk]} \mathcal{B}_c^{[km]} + \delta_c C_1 \bar{B}_m H^j \bar{\mathcal{B}}_{c[jk']} M_k^{k'} \mathcal{B}_c^{[km]} \\ &\quad + \frac{1}{2} E_1 \bar{B}_j H^j \bar{\mathcal{B}}_{c[lm]} \mathcal{B}_c^{[ml]} + \frac{1}{2} \delta_v E_1 \bar{B}_{j'} M_j^{j'} H^j \bar{\mathcal{B}}_{c[lm]} \mathcal{B}_c^{[ml]} \\ &\quad + \frac{1}{2} \delta_c E_1 \bar{B}_j H^j (\bar{\mathcal{B}}_{c[l'm]} M_l^{l'} \mathcal{B}_c^{[ml]} + \bar{\mathcal{B}}_{c[lm']} M_m^{m'} \mathcal{B}_c^{[ml]}), \\ H_{\text{eff}}(\bar{B} \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)) &= C_2 \bar{B}_m H^j \bar{\mathcal{B}}_{c\{jk\}} \mathcal{B}_c^{[km]} + \delta_v C_2 \bar{B}_m H^j M_j^{j'} \bar{\mathcal{B}}_{c\{j'k\}} \mathcal{B}_c^{[km]} \\ &\quad + \delta_s C_2 \bar{B}_{m'} M_m^{m'} H^j \bar{\mathcal{B}}_{c\{jk\}} \mathcal{B}_c^{[km]} + \delta_c C_2 \bar{B}_m H^j \bar{\mathcal{B}}_{c\{jk'\}} M_k^{k'} \mathcal{B}_c^{[km]}, \\ H_{\text{eff}}(\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)) &= C_3 \bar{B}_m H^j \bar{\mathcal{B}}_{c[jk]} \mathcal{B}_c^{\{km\}} + \delta_v C_3 \bar{B}_m H^j M_j^{j'} \bar{\mathcal{B}}_{c[j'k]} \mathcal{B}_c^{\{km\}} \\ &\quad + \delta_s C_3 \bar{B}_{m'} M_m^{m'} H^j \bar{\mathcal{B}}_{c[jk]} \mathcal{B}_c^{\{km\}} + \delta_c C_3 \bar{B}_m H^j \bar{\mathcal{B}}_{c[jk']} M_k^{k'} \mathcal{B}_c^{\{km\}}, \\ H_{\text{eff}}(\bar{B} \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)) &= C_4 \bar{B}_m H^j \bar{\mathcal{B}}_{c\{jk\}} \mathcal{B}_c^{\{km\}} + \delta_v C_4 \bar{B}_m H^j M_j^{j'} \bar{\mathcal{B}}_{c\{j'k\}} \mathcal{B}_c^{\{km\}} \\ &\quad + \delta_s C_4 \bar{B}_{m'} M_m^{m'} H^j \bar{\mathcal{B}}_{c\{jk\}} \mathcal{B}_c^{\{km\}} + \delta_c C_4 \bar{B}_m H^j \bar{\mathcal{B}}_{c\{jk'\}} M_k^{k'} \mathcal{B}_c^{\{km\}} \\ &\quad + \frac{1}{2} E_4 \bar{B}_j H^j \bar{\mathcal{B}}_{c\{lm\}} \mathcal{B}_c^{\{ml\}} + \frac{1}{2} \delta_v E_4 \bar{B}_{j'} M_j^{j'} H^j \bar{\mathcal{B}}_{c\{lm\}} \mathcal{B}_c^{\{ml\}} \\ &\quad + \frac{1}{2} \delta_c E_4 \bar{B}_j H^j (\bar{\mathcal{B}}_{c\{l'm\}} M_l^{l'} \mathcal{B}_c^{\{ml\}} + \bar{\mathcal{B}}_{c\{lm'\}} M_m^{m'} \mathcal{B}_c^{\{ml\}}), \end{aligned} \quad (9)$$

and the Hamiltonians for the $\Delta S = 0$ transition can be obtained readily.

To simplify the notation, we define

$$\begin{aligned} C_{i,v}^{(\prime)} &\equiv C_i^{(\prime)} + \delta_v C_i^{(\prime)} \equiv (1 + \delta_v^{c_i}) C_i^{(\prime)}, \\ C_{i,s}^{(\prime)} &\equiv C_i^{(\prime)} + \delta_s C_i^{(\prime)} \equiv (1 + \delta_s^{c_i}) C_i^{(\prime)}, \\ C_{i,c}^{(\prime)} &\equiv C_i^{(\prime)} + \delta_c C_i^{(\prime)} \equiv (1 + \delta_c^{c_i}) C_i^{(\prime)}, \\ C_{i,vs}^{(\prime)} &\equiv C_i^{(\prime)} + \delta_v C_i^{(\prime)} + \delta_s C_i^{(\prime)} \equiv (1 + \delta_v^{c_i} + \delta_s^{c_i}) C_i^{(\prime)}, \\ C_{i,cs}^{(\prime)} &\equiv C_i^{(\prime)} + \delta_c C_i^{(\prime)} + \delta_s C_i^{(\prime)} \equiv (1 + \delta_c^{c_i} + \delta_s^{c_i}) C_i^{(\prime)}, \\ C_{i,vcs}^{(\prime)} &\equiv C_i^{(\prime)} + \delta_v C_i^{(\prime)} + \delta_c C_i^{(\prime)} + \delta_s C_i^{(\prime)} \equiv (1 + \delta_v^{c_i} + \delta_c^{c_i} + \delta_s^{c_i}) C_i^{(\prime)}, \end{aligned} \quad (10)$$

for $i = 1-4$, and, likewise,

$$\begin{aligned} E_{j,v}^{(\prime)} &\equiv E_j^{(\prime)} + \delta_v E_j^{(\prime)} \equiv (1 + \delta_v^{e_j}) E_j^{(\prime)}, \\ E_{j,c}^{(\prime)} &\equiv E_j^{(\prime)} + \delta_c E_j^{(\prime)} \equiv (1 + \delta_c^{e_j}) E_j^{(\prime)}, \\ E_{j,cc}^{(\prime)} &\equiv E_j^{(\prime)} + 2\delta_c E_j^{(\prime)} \equiv (1 + 2\delta_c^{e_j}) E_j^{(\prime)}, \\ E_{j,vc}^{(\prime)} &\equiv E_j^{(\prime)} + \delta_v E_j^{(\prime)} + \delta_c E_j^{(\prime)} \equiv (1 + \delta_v^{e_j} + \delta_c^{e_j}) E_j^{(\prime)}, \\ E_{j,vcc}^{(\prime)} &\equiv E_j^{(\prime)} + \delta_v E_j^{(\prime)} + 2\delta_c E_j^{(\prime)} \equiv (1 + \delta_v^{e_j} + 2\delta_c^{e_j}) E_j^{(\prime)}, \end{aligned} \quad (11)$$

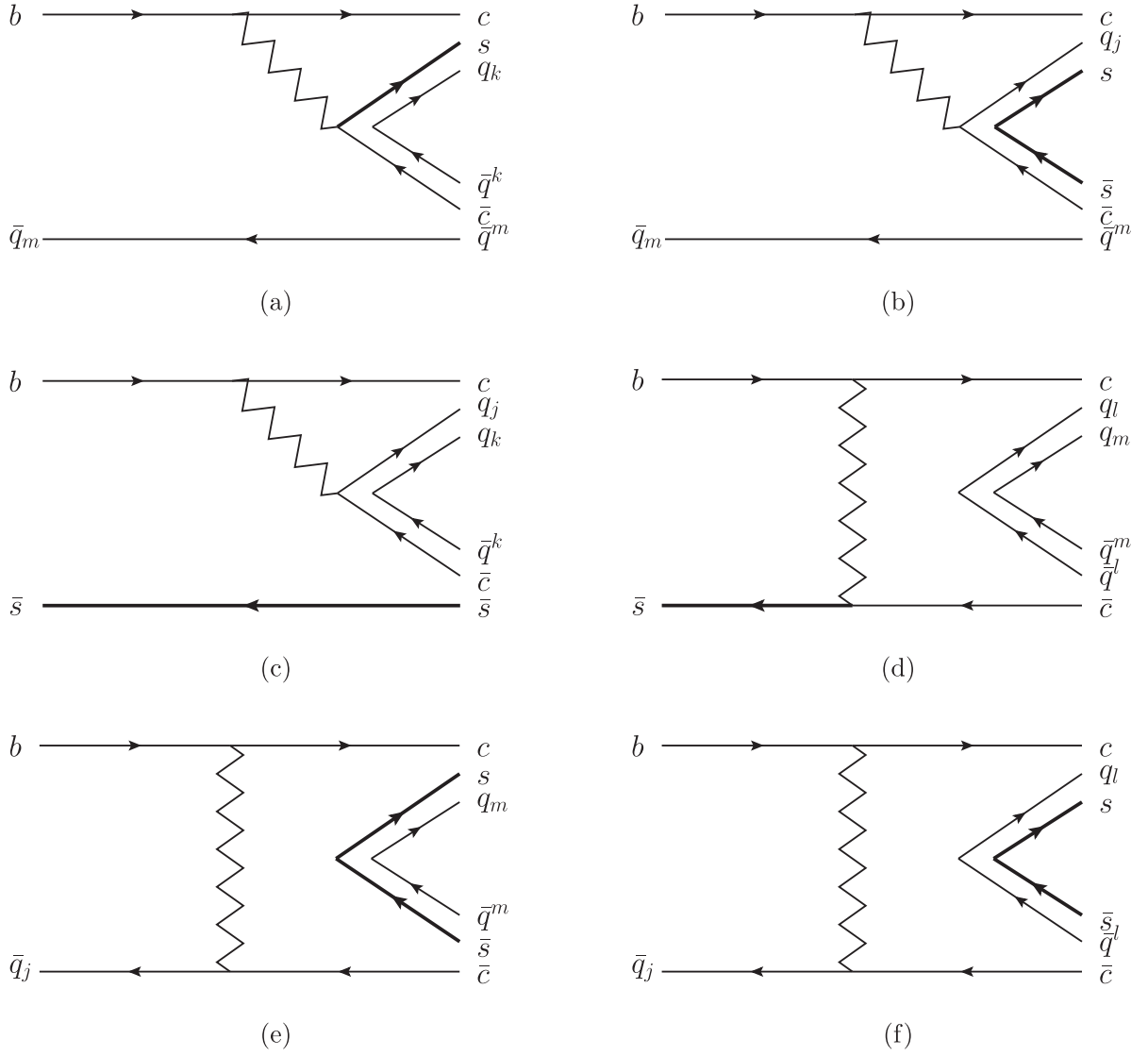


FIG. 2. Internal W -tree diagrams containing SU(3)-breaking effects, in (a) vertex line, (b) pair creation line, and (c) spectator line; W -exchange diagrams containing SU(3)-breaking effects, in (d) vertex line and (e), (f) pair creation lines.

for $j = 1, 4$. These $\delta_v^{c_i}$, $\delta_s^{c_i}$, $\delta_c^{e_i}$, $\delta_v^{e_i}$, and $\delta_c^{e_i}$ parameters should be the measures of the degree of the SU(3) breaking in amplitudes. As we shall see using Eq. (9), $\bar{B} \rightarrow \mathcal{B}_c \bar{\mathcal{B}}_c$ decay amplitudes can be decomposed into the above amplitudes, in addition to $C_i^{(j)}$ and $E_i^{(j)}$.

We depict in Fig. 2 some topological diagrams containing SU(3)-breaking effects. Internal W -tree diagrams containing SU(3)-breaking effects, in (a) vertex line, (b) pair creation line, and (c) spectator line, and W -exchange diagrams containing SU(3)-breaking effects, in (d) vertex line and (e)-(f) pair creation lines, are shown in the figure. When other quark lines are u, d quark lines, these diagrams can be identified as $C_{i,v}$, $C_{i,c}$, $C_{i,s}$, $E_{i,v}$, and $E_{i,c}$, where the subscripts v, c , and s , stand for vertex, pair creation, and spectator, respectively, see also Eq. (10). For example, we have

$$C_{i,v} = (1 + \delta_v^{c_i})C_i, \quad C_{i,s} = (1 + \delta_s^{c_i})C_i, \quad (12)$$

where the SU(3)-breaking parameters $\delta_v^{c_i}$ and $\delta_s^{c_i}$ occur in $C_{i,v}$ and $C_{i,s}$, respectively, as the s -quark lines are in the vertex and spectator of the internal W -tree diagrams, respectively, as shown Figs. 2(a) and 2(c), respectively.

Note that there may be more than one s -quark line in these diagrams. For example, from Eq. (10), we have

$$C_{i,vs} = (1 + \delta_v^{c_i} + \delta_s^{c_i})C_i. \quad (13)$$

It can be understood as follows. In $C_{i,vs}$, the s quarks can be in the vertex and the spectator at the same time. Hence, we have both SU(3)-breaking parameters $\delta_v^{c_i}$ and $\delta_s^{c_i}$ occurring in $C_{i,vs}$ at the same time.

III. TOPOLOGICAL AMPLITUDES AND BRANCHING RATIOS

A. Topological amplitudes

Decay amplitudes of various $\bar{B}_q \rightarrow \mathcal{B}_c \bar{\mathcal{B}}_c$ decays in $\Delta S = -1$ and $\Delta S = 0$ transitions, in terms of topological amplitudes, can be readily obtained using Eq. (9). We give the decompositions of $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay amplitudes in Table III, $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f) \bar{\mathcal{B}}_c(\bar{\mathbf{3}}_f)$ decay amplitudes in Table IV, $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decay amplitudes in Table V, and $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f) \bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decay amplitudes in Table VI. Note that, although some of the decay modes in $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f) \bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays are kinematically forbidden, their amplitudes are also listed for completeness. In fact, the $\mathcal{B}_c(\mathbf{6}_f)$ or $\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$, in a kinematically forbidden two-body decay, may participate in a multibody $\bar{B}_q$ decay virtually. Hence, the two-body decay amplitude can still be useful.

Note that the decompositions of decay amplitudes in these tables are not only valid for low-lying $\mathcal{B}_c(\bar{\mathbf{3}}_f)$ and $\mathcal{B}_c(\mathbf{6}_f)$ states. They are also applicable for excited $\mathcal{B}_c$ and/or $\bar{\mathcal{B}}_c$ final states. For example, from Table II, we see that $\Xi_c^0(2645)$ is in a $\mathbf{6}_f$ multiplet. Hence, $B^- \rightarrow \Xi_c^0(2645) \bar{\Lambda}_c^-$ decay is also a $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay with amplitude decomposition similar to those given in Table IV. Indeed, by referring to Table IV, we should have $A(B^- \rightarrow \Xi_c^0(2645) \bar{\Lambda}_c^-) = -\tilde{C}_{2,v}$, where a different notation, $\tilde{C}_{2,v}$, is used to differentiate it from the $C_{2,v}$ of the low-lying states.

B. Branching ratios

In the following numerical study, we will encounter $\bar{B}_q \rightarrow \mathcal{B}_c(J = \frac{1}{2}) \bar{\mathcal{B}}_c(J = \frac{1}{2})$ and $\bar{B}_q \rightarrow \mathcal{B}_c(J = \frac{3}{2}) \bar{\mathcal{B}}_c(J = \frac{1}{2})$ decays, where $\bar{\mathcal{B}}_c(J = \frac{1}{2})$ is a spin-1/2 anticharmed baryon, while $\mathcal{B}_c(J = \frac{1}{2}, \frac{3}{2})$ are spin-1/2 and spin-3/2 charmed baryons, respectively.

For a $\bar{B}_q \rightarrow \mathcal{B}_c(1/2) \bar{\mathcal{B}}_c(1/2)$ decay, we can use the following formula for the branching ratio, see the Appendix:

$$\begin{aligned} \text{Br}\left(\bar{B}_q \rightarrow \mathcal{B}_c\left(\frac{1}{2}\right) \bar{\mathcal{B}}_c\left(\frac{1}{2}\right)\right) \\ = \tau_{B_q} \frac{p_{\text{c.m.}}}{8\pi m_{\bar{B}_q}^2} \left| A\left(\bar{B}_q \rightarrow \mathcal{B}_c\left(\frac{1}{2}\right) \bar{\mathcal{B}}_c\left(\frac{1}{2}\right)\right) \right|^2, \end{aligned} \quad (14)$$

where $|A(\bar{B}_q \rightarrow \mathcal{B}_c(\frac{1}{2}) \bar{\mathcal{B}}_c(\frac{1}{2}))|^2$ should contain various factors. For example, for $B^- \rightarrow \Xi_c^0 \bar{\Lambda}_c^-$ and $B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^-$ decays, we have (see also Table III)

$$\begin{aligned} |A(B^- \rightarrow \Xi_c^0 \bar{\Lambda}_c^-)|^2 &= |C_{1,v}|^2 = \left| \frac{G_F}{\sqrt{2}} m_{B_q} V_{cb} V_{cs}^* \right|^2 c_{1,v}^2, \\ |A(B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^-)|^2 &= |C'_{1,c}|^2 = \left| \frac{G_F}{\sqrt{2}} m_{B_q} V_{cb} V_{cd}^* \right|^2 c_{1,c}^2, \end{aligned} \quad (15)$$

with $c_{1,v} = (1 + \delta_v^{c_1})c_1$ and $c_{1,c} = (1 + \delta_c^{c_1})c_1$.

Note that the above amplitudes squared are indeed the polarization sum of $|\bar{u}(a + \gamma_5 b)v|^2$, see Eq. (A1). Indeed, we have

$$\begin{aligned} &\left| \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \right|^2 m_{B_q}^2 c_{1,v}^2 \\ &= (2m_{B_q}^2 - 2(m_{B_c} + m_{\bar{B}_c})^2) |a|^2 \\ &\quad + (2m_{B_q}^2 - 2(m_{B_c} - m_{\bar{B}_c})^2) |b|^2 \\ &= (2m_{B_q}^2 - 2(m_{B_c} - m_{\bar{B}_c})^2) \\ &\quad \times \left(|b|^2 + \frac{4p_{\text{c.m.}}^2 m_{B_q}^2}{[m_{B_q}^2 - (m_{B_c} - m_{\bar{B}_c})^2]^2} |a|^2 \right). \end{aligned} \quad (16)$$

The $|b|^2$ term is the s -wave term, while the $|a|^2$ term is the p -wave term. The latter contribution is relatively kinematically suppressed in a typical $\bar{B}_q \rightarrow \mathcal{B}_c(\frac{1}{2}) \bar{\mathcal{B}}_c(\frac{1}{2})$ decay. Consequently, the s -wave or the $|b|^2$ term is dominating. To determine s - and p -wave contributions, one needs, for example, the asymmetry α . Since only data on total rates are available presently, we use, for simplicity, a single parameter, namely, $c_{1,v}^2$, for the amplitudes squared in this study. This situation can be improved when data on asymmetries become available.

TABLE III. $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay amplitudes in $\Delta S = -1$ and $\Delta S = 0$ transitions.

Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f))$	Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f) \bar{\mathcal{B}}_c(\mathbf{3}_f))$
$B^- \rightarrow \Xi_c^0 \bar{\Lambda}_c^-$	$C_{1,v}$	$\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Lambda}_c^-$	$C_{1,v}$
$\bar{B}_s^0 \rightarrow \Xi_c^0 \bar{\Xi}_c^0$	$-C_{1,vs} - E_{1,vc}$	$\bar{B}_s^0 \rightarrow \Xi_c^+ \bar{\Xi}_c^-$	$-C_{1,vs} - E_{1,vc}$
$\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$	$-E_{1,v}$		
$B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^-$	$C'_{1,c}$	$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$	$-C'_1 - E'_1$
$\bar{B}^0 \rightarrow \Xi_c^0 \bar{\Xi}_c^0$	$-C'_{1,c} - E'_{1,c}$	$\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Xi}_c^-$	$-E'_{1,c}$
$\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Xi}_c^-$	$C'_{1,s}$		

TABLE IV. $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay amplitudes in $\Delta S = -1$ and $\Delta S = 0$ transitions.

Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f))$	Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f))$
$B^- \rightarrow \Xi_c^{\prime 0}\bar{\Lambda}_c^-$	$-C_{2,v}$	$B^- \rightarrow \Omega_c^0\bar{\Xi}_c^-$	$\sqrt{2}C_{2,vc}$
$\bar{B}^0 \rightarrow \Xi_c^{\prime +}\bar{\Lambda}_c^-$	$C_{2,v}$	$\bar{B}^0 \rightarrow \Omega_c^0\bar{\Xi}_c^0$	$-\sqrt{2}C_{2,vc}$
$\bar{B}_s^0 \rightarrow \Xi_c^{\prime +}\bar{\Xi}_c^-$	$-C_{2,vs}$	$\bar{B}_s^0 \rightarrow \Xi_c^{\prime 0}\bar{\Xi}_c^0$	$C_{2,vs}$
$B^- \rightarrow \Sigma_c^0\bar{\Lambda}_c^-$	$-\sqrt{2}C_2'$	$B^- \rightarrow \Xi_c^{\prime 0}\bar{\Xi}_c^-$	$C_{2,c}'$
$\bar{B}^0 \rightarrow \Sigma_c^+\bar{\Lambda}_c^-$	C_2'	$\bar{B}^0 \rightarrow \Xi_c^{\prime 0}\bar{\Xi}_c^0$	$-C_{2,c}'$
$\bar{B}_s^0 \rightarrow \Sigma_c^+\bar{\Xi}_c^-$	$-C_{2,s}'$	$\bar{B}_s^0 \rightarrow \Sigma_c^0\bar{\Xi}_c^0$	$\sqrt{2}C_{2,s}'$

TABLE V. $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{3}_f)\bar{\mathcal{B}}_c(\mathbf{6}_f)$ decay amplitudes in $\Delta S = -1$ and $\Delta S = 0$ transitions.

Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{3}_f)\bar{\mathcal{B}}_c(\mathbf{6}_f))$	Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{3}_f)\bar{\mathcal{B}}_c(\mathbf{6}_f))$
$B^- \rightarrow \Xi_c^+\bar{\Sigma}_c^{--}$	$\sqrt{2}C_{3,v}$	$B^- \rightarrow \Xi_c^0\bar{\Sigma}_c^-$	$-C_{3,v}$
$\bar{B}^0 \rightarrow \Xi_c^0\bar{\Sigma}_c^0$	$-\sqrt{2}C_{3,v}$	$\bar{B}^0 \rightarrow \Xi_c^+\bar{\Sigma}_c^-$	$C_{3,v}$
$\bar{B}_s^0 \rightarrow \Xi_c^0\bar{\Xi}_c^{\prime 0}$	$-C_{3,vs}$	$\bar{B}_s^0 \rightarrow \Xi_c^+\bar{\Xi}_c^{\prime -}$	$C_{3,vs}$
$B^- \rightarrow \Lambda_c^+\bar{\Sigma}_c^{--}$	$-\sqrt{2}C_3'$	$B^- \rightarrow \Xi_c^0\bar{\Xi}_c^{\prime -}$	$C_{3,c}'$
$\bar{B}^0 \rightarrow \Lambda_c^+\bar{\Sigma}_c^-$	$-C_3'$	$\bar{B}^0 \rightarrow \Xi_c^0\bar{\Xi}_c^{\prime 0}$	$C_{3,c}'$
$\bar{B}_s^0 \rightarrow \Lambda_c^+\bar{\Xi}_c^{\prime -}$	$-C_{3,s}'$	$\bar{B}_s^0 \rightarrow \Xi_c^0\bar{\Omega}_c^0$	$\sqrt{2}C_{3,cs}'$

Furthermore, although the factor $(m_{\bar{B}_q}^2 - (m_{\mathcal{B}_c} - m_{\bar{\mathcal{B}}_c})^2)$ in the above equation can introduce some SU(3)-breaking effects, in the modes studied in this work, the SU(3)-breaking effects are at most at 1% level. As we shall see, this is much less than the SU(3)-breaking effects in amplitudes introduced earlier. Hence, it is not necessary to modify the $m_{\bar{B}_q}^2$ factor before $c_{1,v}^2$.

For a $\bar{B}_q \rightarrow \mathcal{B}_c(\frac{3}{2})\bar{\mathcal{B}}_c(\frac{1}{2})$ decay, we can use the following formula for the branching ratio, see the Appendix:

$$\begin{aligned}
 Br\left(\bar{B}_q \rightarrow \mathcal{B}_c\left(\frac{3}{2}\right)\bar{\mathcal{B}}_c\left(\frac{1}{2}\right)\right) &= \tau_{B_q} \frac{p_{\text{c.m.}}}{8\pi m_{\bar{B}_q}^2} \left(\frac{p_{\text{c.m.}}}{m_{\mathcal{B}_c(3/2)}}\right)^2 \\
 &\times \left|A\left(\bar{B}_q \rightarrow \mathcal{B}_c\left(\frac{3}{2}\right)\bar{\mathcal{B}}_c\left(\frac{1}{2}\right)\right)\right|^2. \quad (17)
 \end{aligned}$$

Note that we show explicitly the additional $(p_{\text{c.m.}}/m_{\mathcal{B}_c(3/2)})^2$ factor in the above equation, as the decay

TABLE VI. $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{6}_f)$ decay amplitudes in $\Delta S = -1$ and $\Delta S = 0$ transitions.

Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{6}_f))$	Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{6}_f))$
$B^- \rightarrow \Xi_c^{\prime +}\bar{\Sigma}_c^{--}$	$\sqrt{2}C_{4,v}$	$B^- \rightarrow \Xi_c^{\prime 0}\bar{\Sigma}_c^-$	$C_{4,v}$
$B^- \rightarrow \Omega_c^0\bar{\Xi}_c^-$	$\sqrt{2}C_{4,vc}$	$\bar{B}^0 \rightarrow \Xi_c^{\prime +}\bar{\Sigma}_c^-$	$C_{4,v}$
$\bar{B}^0 \rightarrow \Xi_c^0\bar{\Sigma}_c^0$	$\sqrt{2}C_{4,v}$	$\bar{B}^0 \rightarrow \Omega_c^0\bar{\Xi}_c^0$	$\sqrt{2}C_{4,vc}$
$\bar{B}_s^0 \rightarrow \Sigma_c^{++}\bar{\Sigma}_c^{--}$	$E_{4,v}$	$\bar{B}_s^0 \rightarrow \Sigma_c^{++}\bar{\Sigma}_c^-$	$E_{4,v}$
$\bar{B}_s^0 \rightarrow \Sigma_c^0\bar{\Xi}_c^0$	$E_{4,v}$	$\bar{B}_s^0 \rightarrow \Xi_c^{\prime +}\bar{\Xi}_c^{\prime -}$	$C_{4,vs} + E_{4,vc}$
$\bar{B}_s^0 \rightarrow \Xi_c^{\prime 0}\bar{\Xi}_c^0$	$C_{4,vs} + E_{4,vc}$	$\bar{B}_s^0 \rightarrow \Omega_c^0\bar{\Omega}_c^0$	$2C_{4,vcs} + E_{4,vcc}$
$B^- \rightarrow \Sigma_c^+\bar{\Sigma}_c^{--}$	$\sqrt{2}C_4'$	$B^- \rightarrow \Sigma_c^0\bar{\Sigma}_c^-$	$\sqrt{2}C_4'$
$B^- \rightarrow \Xi_c^{\prime 0}\bar{\Xi}_c^{\prime -}$	$C_{4,c}'$	$\bar{B}^0 \rightarrow \Sigma_c^{++}\bar{\Sigma}_c^{--}$	E_4'
$\bar{B}^0 \rightarrow \Sigma_c^+\bar{\Sigma}_c^-$	$C_4' + E_4'$	$\bar{B}^0 \rightarrow \Sigma_c^0\bar{\Sigma}_c^0$	$2C_4' + E_4'$
$\bar{B}^0 \rightarrow \Xi_c^{\prime +}\bar{\Xi}_c^{\prime -}$	$E_{4,c}'$	$\bar{B}^0 \rightarrow \Xi_c^{\prime 0}\bar{\Xi}_c^0$	$C_{4,c}' + E_{4,c}'$
$\bar{B}^0 \rightarrow \Omega_c^0\bar{\Omega}_c^0$	$E_{4,cc}'$	$\bar{B}_s^0 \rightarrow \Sigma_c^+\bar{\Xi}_c^-$	$C_{4,s}'$
$\bar{B}_s^0 \rightarrow \Sigma_c^0\bar{\Xi}_c^0$	$\sqrt{2}C_{4,s}'$	$\bar{B}_s^0 \rightarrow \Xi_c^{\prime 0}\bar{\Omega}_c^0$	$\sqrt{2}C_{4,cs}'$

amplitude for a $\bar{B}_q \rightarrow \mathcal{B}_c(\frac{3}{2})\bar{\mathcal{B}}_c(\frac{1}{2})$ decay is basically $(p_{c.m.}/m_{\mathcal{B}_c(3/2)})\bar{u}_1(a + \gamma_5 b)v_2$, see Eq. (A4). Similarly, the amplitude squared, $|A(\bar{B}_q \rightarrow \mathcal{B}_c(\frac{3}{2})\bar{\mathcal{B}}_c(\frac{1}{2}))|^2$, should contain various factors. For example, for $B^- \rightarrow \Xi_c^0(2645)\bar{\Lambda}_c^-$ and $\bar{B}^0 \rightarrow \Sigma_c^+(2520)\bar{\Lambda}_c^-$ decays, similarly, we have

$$\begin{aligned} |A(B^- \rightarrow \Xi_c^0(2645)\bar{\Lambda}_c^-)|^2 &= |\tilde{C}_{2,v}|^2 \\ &= \left| \frac{G_F}{\sqrt{2}} m_{B_q} V_{cb} V_{cs}^* \right|^2 \tilde{c}_{2,v}^2, \\ |A(\bar{B}^0 \rightarrow \Sigma_c^+(2520)\bar{\Lambda}_c^-)|^2 &= |\tilde{C}_2'|^2 = \left| \frac{G_F}{\sqrt{2}} m_{B_q} V_{cb} V_{cd}^* \right|^2 \tilde{c}_2'^2, \end{aligned} \quad (18)$$

with $\tilde{c}_{2,v} = (1 + \delta_v^{\tilde{c}_2})\tilde{c}_2$. Note that $\Xi_c^0(2645)$ and $\Sigma_c^+(2520)$ are spin-3/2 charmed baryons in a $\mathbf{6}_f$ multiplet, see Table II. Hence, the decompositions of their amplitudes are similar to those given in Table IV.

Note that the $p_{c.m.}$ and $p_{c.m.}^3$ kinematic factors in Eqs. (14) and (17), respectively, provide additional SU(3)-breaking effects in rates. These effects can be sizable in some modes.

IV. NUMERICAL RESULTS

Numerical results on rates of $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{\bar{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$, $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$, and $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{\bar{3}}_f)\bar{\mathcal{B}}_c(\mathbf{\bar{6}}_f)$ decays will be presented in this section. As one can see from Tables I and II, data on the rates of some of these modes are available, while no data on $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{\bar{6}}_f)$ decays are reported yet. Hence, we do not include the latter modes in this numerical study. Masses and lifetimes of B_q mesons and masses of $\mathcal{B}_c$ baryons are taken from Ref. [1]. CKM matrix elements are from the latest fit in Ref. [30].

A. $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{\bar{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay rates

In this subsection, we give the numerical results of the branching ratios of $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{\bar{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays for low-lying $\mathcal{B}_c(\mathbf{\bar{3}}_f)$ and $\bar{\mathcal{B}}_c(\mathbf{3}_f)$, and for excited $\mathcal{B}_c(\mathbf{\bar{3}}_f)$ with $J^P = \frac{1}{2}^-$, namely, $\bar{B}_q \rightarrow \Xi_c^{0,+}(2790)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ and $\Lambda_c^+(2595)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays.

1. Low-lying case

We start with the low-lying case. Presently, we have data on rates of the following four modes, namely, $B^- \rightarrow \Xi_c^0\bar{\Lambda}_c^-$, $\bar{B}^0 \rightarrow \Xi_c^+\bar{\Lambda}_c^-$, $\bar{B}_s^0 \rightarrow \Lambda_c^+\bar{\Lambda}_c^-$, and $\bar{B}^0 \rightarrow \Lambda_c^+\bar{\Lambda}_c^-$ decays with rates shown in Table I. Their amplitudes are governed by $C_{1,v}$, $E_{1,v}$, and $C_1' + E_1'$, see Table III, which can be expressed in terms of four unknown parameters, c_1 , e_1 , $\delta_v^{c_1}$, and $\delta_v^{e_1}$. At first sight, it seems that these four unknown parameters can be fully determined from the above four experimental inputs. This is, however, not the case, as

$B^- \rightarrow \Xi_c^0\bar{\Lambda}_c^-$ and $\bar{B}^0 \rightarrow \Xi_c^+\bar{\Lambda}_c^-$ decays are isospin related, which are identical in the isospin limit, and can hardly be counted as two independent inputs. To proceed, one needs to impose a constraint on these parameters. Since $\delta_v^{c_1}$ and $\delta_v^{e_1}$ are measurements of the SU(3)-breaking effects, they are expected to be of similar size. For simplicity, we assume

$$|\delta_v^{c_1}| = |\delta_v^{e_1}|. \quad (19)$$

Note that this working assumption can be relaxed when data from more modes become available.

The above constraint can be reduced to the two following cases:

$$\begin{aligned} \text{case 1: } \delta_v^{c_1} &= +\delta_v^{e_1}, \\ \text{case 2: } \delta_v^{c_1} &= -\delta_v^{e_1}. \end{aligned} \quad (20)$$

From χ^2 fit using rates of the above four modes, we obtain for the best fits,

$$\begin{aligned} \text{case 1: } c_1 &= 0.15, \quad e_1 = -0.03, \quad \delta_v^{c_1} = +\delta_v^{e_1} = 0.88, \\ \text{case 2: } c_1 &= 0.21, \quad e_1 = -0.09, \quad \delta_v^{c_1} = -\delta_v^{e_1} = 0.35, \end{aligned} \quad (21)$$

both with $\chi_{\min}^2 = 0.315$.

From these results, one can immediately see that case 1 is unfavorable, as the fit indicates a significant SU(3)-breaking effect, with 88% SU(3) breaking in amplitudes. On the contrary, the fit in case 2 needs only 35% SU(3)-breaking effects. It is more reasonable and acceptable compared to case 1. Consequently, we will proceed with case 2 in the following study of the low-lying $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{\bar{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays.

We show in Table VII the fitted values of c_1 , e_1 , $\delta_v^{c_1}$, and $\delta_v^{e_1}$ with uncertainties obtained by scanning the parameter space allowed by $\chi^2 \leq \chi_{\min}^2 + 1$. As noted, the four experimental rates are input of the fit, and they are insensitive to the other three SU(3)-breaking parameters, namely, $\delta_c^{c_1}$, $\delta_s^{c_1}$, and $\delta_c^{e_1}$. These δ 's likely have sizes similar to $\delta_v^{c_1}$ and $\delta_v^{e_1}$. We assume their values as 0 ± 0.35 independently.

TABLE VII. Parameters in $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{\bar{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ for low-lying $\mathcal{B}_c(\mathbf{\bar{3}}_f)$ and $\bar{\mathcal{B}}_c(\mathbf{3}_f)$, where c_1 , e_1 , $\delta_v^{c_1}$ are fitted parameters with a constraint on SU(3)-breaking parameters, $\delta_v^{e_1} = -\delta_v^{c_1}$. Their uncertainties are obtained by scanning parameter space with $\chi^2 \leq \chi_{\min}^2 + 1$. We assume other SU(3)-breaking parameters ($\delta_c^{c_1}$, $\delta_s^{c_1}$, $\delta_c^{e_1}$) have sizes at most as $|\delta_v^{c_1}|$ and $|\delta_v^{e_1}|$.

c_1	e_1	$\delta_v^{c_1}$	$\delta_v^{e_1} (= -\delta_v^{c_1})$
$0.209^{+0.015}_{-0.016}$	-0.091 ± 0.015	0.35 ± 0.11	-0.35 ± 0.11
$\delta_c^{c_1}$	$\delta_s^{c_1}$	$\delta_c^{e_1}$	$\chi_{\min}^2$
0 ± 0.35	0 ± 0.35	0 ± 0.35	0.315

TABLE VIII. $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay amplitudes and branching ratios (in units of 10^{-4}) in $\Delta S = -1$ and $\Delta S = 0$ transitions. Experimental results are inputs of the χ^2 fit. Results from Ref. [13] are also shown for comparison.

Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f))$	$Br(\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f))$ this work	$Br(\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f))$ Ref. [13]	Expt.
$B^- \rightarrow \Xi_c^0 \bar{\Lambda}_c^-$	$C_{1,v}$	$10.06^{+1.98}_{-2.04}$	$7.8^{+2.3}_{-2.0}$	9.51 ± 2.28 [2]
$\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Lambda}_c^-$	$C_{1,v}$	$9.34^{+1.84}_{-1.90}$	$7.2^{+2.1}_{-1.9}$	11.6 ± 4.46 [6]
$\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$	$-E_{1,v}$	$0.50^{+0.16}_{-0.15}$	$0.81^{+0.17}_{-0.15}$	0.50 ± 0.16 [5]
$\bar{B}_s^0 \rightarrow \Xi_c^0 \bar{\Xi}_c^0$	$-C_{1,vs} - E_{1,vc}$	$5.33^{+8.67}_{-4.44}$	$3.0^{+1.4}_{-1.1}$	...
$\bar{B}_s^0 \rightarrow \Xi_c^+ \bar{\Xi}_c^-$	$-C_{1,vs} - E_{1,vc}$	$5.36^{+8.72}_{-4.46}$	$3.0^{+1.4}_{-1.1}$	...
$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$	$-C'_1 - E'_1$	$0.101^{+0.031}_{-0.032}$	$0.21^{+0.10}_{-0.08}$	0.101 ± 0.032
$\bar{B}^0 \rightarrow \Xi_c^0 \bar{\Xi}_c^0$	$-C'_{1,c} - E'_{1,c}$	$0.071^{+0.227}_{-0.071}$	$0.15^{+0.07}_{-0.06}$	...
$B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^-$	$C'_{1,c}$	$0.240^{+0.261}_{-0.154}$	$0.34^{+0.10}_{-0.09}$	...
$\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Xi}_c^-$	$C'_{1,s}$	$0.297^{+0.322}_{-0.190}$	$0.39^{+0.12}_{-0.10}$	...
$\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Xi}_c^-$	$-E'_{1,c}$	$0.042^{+0.063}_{-0.030}$	0.030 ± 0.006	...

There are three implications from the fit. First, the W -exchange diagram is sizable in $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay, with the $|E_1^{(v)}|/|C_1^{(v)}|$ ratio about 44%. Neglecting the contribution from the exchange- W -tree diagram is not acceptable. Second, there is a large cancellation between the internal W -tree and the exchange- W -tree amplitudes. Third, SU(3) breaking is sizable. We find that 35% SU(3) breaking in amplitudes is needed. Furthermore, they work differently in different amplitudes. With the SU(3)-breaking effects, the internal W -tree amplitude $C_{1,v}$ is enlarged, while the exchange- W -tree amplitude $E_{1,v}$ is reduced. It remains to be seen if this pattern is followed by other internal W -tree and exchange- W -tree amplitudes, such as $C_{1,s}$, $C_{1,c}$, $C_{1,vs}$, $E_{1,s}$, and $E_{1,vc}$.

Note that some of the above observations on the low-lying case have been pointed out in Ref. [5], but in this work, more detailed information, such as the size of the ratio of the topological amplitudes, the sizes of the SU(3)-breaking effects, and different behaviors of the effects on different topological amplitudes, is provided.

Note that, in principle, the phases of E_1 and C_1 need not be the same. However, from the large cancellation of C_1 and E_1 , and the constraint of the size of E_1 from the W -exchange mode, the data support the case that they have similar phase or, more precisely, opposite phases. In other words, adding the imaginary part of E_1 does not improve the fit.

We show in Table VIII the branching ratios of $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays in $\Delta S = -1$ and $\Delta S = 0$ transitions. We also show the corresponding decay amplitudes taken from Table III for our convenience. The results in the table are obtained using the parameters in Table VII. Experimental results are inputs of the χ^2 fit. Results from Ref. [13] are also shown for comparison.

From the table, we see that the central value of the fitted $B^- \rightarrow \Xi_c^0 \bar{\Lambda}_c^-$ rate is slightly higher than the central value of the experimental result, while the case of the $\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Lambda}_c^-$ decay is the other way around. The amplitudes of these two modes are both $C_{1,v}$. Hence, the maximum of $|C_{1,v}|$ is constrained by the $B^- \rightarrow \Xi_c^0 \bar{\Lambda}_c^-$ data, while the minimum is by the $\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Lambda}_c^-$ data. For $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$ and $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$ decays, the fit reproduces the data well.

We have predictions on six other modes, namely, $\bar{B}_s^0 \rightarrow \Xi_c^0 \bar{\Xi}_c^0$, $\bar{B}_s^0 \rightarrow \Xi_c^+ \bar{\Xi}_c^-$, $\bar{B}^0 \rightarrow \Xi_c^0 \bar{\Xi}_c^0$, $B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^-$, $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Xi}_c^-$, and $\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Xi}_c^-$ decays. However, the uncertainties in these predicted rates are substantial. The reason can be traced to the poorly known SU(3)-breaking parameters, $\delta_c^{c_1}$, $\delta_s^{c_1}$, $\delta_v^{c_1}$, which are not constrained by the present data. From the amplitudes shown in the same table, these six modes indeed depend on these parameters.

The uncertainties in the rates of these modes simply reflect our estimates of the SU(3)-breaking parameters. As stated previously, their sizes are estimated to be at most as $|\delta_v^{c_1}|$ and $|\delta_v^{e_1}|$. This observation, in fact, identifies the opportunity to really constrain or even determine these SU(3)-breaking parameters by measuring these modes, as they are highly sensitive to them.

For example, in $B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^-$ decay, we have $A(B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^-) = C'_{1,c} = C'_1(1 + \delta_c^{c_1})$. Although the present data can effectively constrain C'_1 , see the c_1 value in Table VII, the value of $\delta_c^{c_1}$ is basically unconstrained. The predicted $B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^-$ rate has large uncertainty, giving $Br(B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^-) = (0.240^{+0.261}_{-0.154}) \times 10^{-4}$, reflecting our poor understanding on the SU(3)-breaking parameter $\delta_c^{c_1}$. Therefore, a measured $B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^-$ rate can give valuable information on $\delta_c^{c_1}$.

The comparison of our results to those obtained in Ref. [13], as shown in Table VIII, makes the above point even clearer. The uncertainties of our predicted results on $\bar{B}_s^0 \rightarrow \Xi_c^0 \bar{\Xi}_c^0$, $\bar{B}_s^0 \rightarrow \Xi_c^+ \bar{\Xi}_c^-$, $\bar{B}^0 \rightarrow \Xi_c^0 \bar{\Xi}_c^0$, $B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^-$, $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Xi}_c^-$, and $\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Xi}_c^-$ decay rates are almost always larger than those obtained in Ref. [13]. This discrepancy clearly shows the different treatments of SU(3)-breaking effects in amplitudes, which are absent in Ref. [13]. Hence, measuring these rates can constrain or even identify the underlying SU(3)-breaking effects.

2. Excited $\mathcal{B}_c(\bar{\mathbf{3}}_f)$ case

We now give the numerical results of the branching ratios of $\bar{B}_q \rightarrow \Xi_c^{0,+}(2790)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ and $\Lambda_c^+(2595)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays with $\bar{\mathcal{B}}_c(\mathbf{3}_f)$ a low-lying anticharmed state. As noted in Table II, $\Lambda_c^+(2595)$ and $\Xi_c^{0,+}(2790)$ are $J^P = \frac{1}{2}^-$ charmed baryons which form a $\bar{\mathbf{3}}_f$ multiplet. Hence, these decays are also $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays, and their decay amplitudes can be decomposed similar to those shown in Table III.

On the experimental side, presently only the $B^- \rightarrow \Xi_c^0(2790)\bar{\Lambda}_c^-$ rate is measured, see Table I. Note that the amplitude of this mode is given by

$$A(B^- \rightarrow \Xi_c^0(2790)\bar{\Lambda}_c^-) = \tilde{C}_{1,v}, \quad (22)$$

where the tilde on top of the topological amplitude is used to differentiate the internal W -tree amplitude in this case from that in the low-lying case. As this is the only mode measured, we can only have information on the internal W -tree amplitude with SU(3)-breaking effect on the vertex, namely, $\tilde{C}_{1,v} = (1 + \delta_v^{\tilde{c}_1})\tilde{C}_1$ or effectively $\tilde{c}_{1,v} = (1 + \delta_v^{\tilde{c}_1})\tilde{c}_1$. The fitted value on $\tilde{c}_{1,v}$ using the measured $B^- \rightarrow \Xi_c^0(2790)\bar{\Lambda}_c^-$ rate is given in Table IX. The uncertainty is obtained by scanning $\chi^2 \leq \chi_{\min}^2 + 1$, and

TABLE IX. Parameters in $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ for $1/2^- \mathcal{B}_c(\bar{\mathbf{3}}_f)$ and low-lying $\bar{\mathcal{B}}_c(\mathbf{3}_f)$, where $\tilde{c}_{1,v} \equiv (1 + \delta_v^{\tilde{c}_1})\tilde{c}_1$ is the fitted parameter. The uncertainty is obtained by scanning $\chi^2 \leq \chi_{\min}^2 + 1$. We assume SU(3)-breaking parameters $\delta_v^{\tilde{c}_1}$, $\delta_c^{\tilde{c}_1}$, and $\delta_s^{\tilde{c}_1}$ have sizes at most as $|\delta_v^{\tilde{c}_1}|$. Information about $\tilde{e}_1$ and its SU(3)-breaking parameters is unavailable from the present data.

$\tilde{c}_{1,v} \equiv (1 + \delta_v^{\tilde{c}_1})\tilde{c}_1$	$\delta_v^{\tilde{c}_1}$	$\delta_c^{\tilde{c}_1}$	$\delta_s^{\tilde{c}_1}$
$0.118^{+0.020}_{-0.024}$	0 ± 0.35	0 ± 0.35	0 ± 0.35
$\tilde{e}_1$	$\delta_v^{\tilde{e}_1}$	$\delta_c^{\tilde{e}_1}$	$\chi_{\min}^2$
...	...	...	0

it simply reflects the uncertainty of the measured $B^- \rightarrow \Xi_c^0(2790)\bar{\Lambda}_c^-$ rate. We assume that SU(3)-breaking parameters $\delta_v^{\tilde{c}_1}$, $\delta_c^{\tilde{c}_1}$, and $\delta_s^{\tilde{c}_1}$ have sizes at most as $|\delta_v^{\tilde{c}_1}|$ in the low-lying case. Information about $\tilde{e}_1$ and its SU(3)-breaking parameters is unavailable from the present data.

We give predictions on the rates of some related $\bar{B}_q \rightarrow \Xi_c^{0,+}(2790)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ and $\Lambda_c^+(2595)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ modes in Table X. The corresponding decay amplitudes are also shown for our convenience. Since we do not have any information on the W -exchange amplitude in these modes, the decay rates of modes containing $\tilde{E}$ and $\tilde{E}'$ cannot be predicted. Only modes governed by internal W -tree amplitudes can be predicted, namely, $\bar{B}^0 \rightarrow \Xi_c^+(2790)\bar{\Lambda}_c^-$, $B^- \rightarrow \Xi_c^0(2790)\bar{\Xi}_c^-$, and $\bar{B}_s^0 \rightarrow \Lambda_c^+(2595)\bar{\Xi}_c^-$ decays. The $\bar{B}^0 \rightarrow \Xi_c^+(2790)\bar{\Lambda}_c^-$ decay amplitude is also governed by $\tilde{C}_{1,v}$, while the other two modes are governed by $\tilde{C}'_{1,c}$ and $\tilde{C}'_{1,s}$, respectively. The $\bar{B}^0 \rightarrow \Xi_c^+(2790)\bar{\Lambda}_c^-$ mode is the isospin-related mode of $B^- \rightarrow \Xi_c^0(2790)\bar{\Lambda}_c^-$, while the amplitudes of the other two modes can be expressed in terms of $\tilde{C}'_{1,v}$, which is related to $\tilde{C}_{1,v}$ through CKM factors and SU(3)-breaking factors as follows:

TABLE X. $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay amplitudes and branching ratios (in units of 10^{-4}) in $\Delta S = -1$ and $\Delta S = 0$ transitions, where $\mathcal{B}_c(\bar{\mathbf{3}}_f)$ are $1/2^-$ states, while $\bar{\mathcal{B}}_c(\mathbf{3}_f)$ are low-lying states. The experimental result is the input of the χ^2 fit. As the information about $\tilde{e}_1$ is unavailable, there is no prediction on rates of modes involving $\tilde{E}_1^{(i)}$.

Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f))$	$Br(\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f))$	Expt.
$B^- \rightarrow \Xi_c^0(2790)\bar{\Lambda}_c^-$	$\tilde{C}_{1,v}$	1.10 ± 0.40	1.1 ± 0.4 [3]
$\bar{B}^0 \rightarrow \Xi_c^+(2790)\bar{\Lambda}_c^-$	$\tilde{C}_{1,v}$	1.02 ± 0.37	...
$\bar{B}_s^0 \rightarrow \Lambda_c^+(2595)\bar{\Lambda}_c^-$	$-\tilde{E}_{1,v}$	...	...
$\bar{B}_s^0 \rightarrow \Xi_c^0(2790)\bar{\Xi}_c^0$	$-\tilde{C}_{1,vs} - \tilde{E}_{1,vc}$	...	...
$\bar{B}_s^0 \rightarrow \Xi_c^+(2790)\bar{\Xi}_c^-$	$-\tilde{C}_{1,vs} - \tilde{E}_{1,vc}$	...	...
$B^- \rightarrow \Xi_c^0(2790)\bar{\Xi}_c^-$	$\tilde{C}'_{1,c}$	$0.018^{+0.087}_{-0.015}$	...
$\bar{B}_s^0 \rightarrow \Lambda_c^+(2595)\bar{\Xi}_c^-$	$\tilde{C}'_{1,s}$	$0.096^{+0.471}_{-0.082}$	...
$\bar{B}^0 \rightarrow \Lambda_c^+(2595)\bar{\Lambda}_c^-$	$-\tilde{C}'_1 - \tilde{E}'_1$	...	...
$\bar{B}^0 \rightarrow \Xi_c^0(2790)\bar{\Xi}_c^0$	$-\tilde{C}'_{1,c} - \tilde{E}'_{1,c}$	...	...
$\bar{B}^0 \rightarrow \Xi_c^+(2790)\bar{\Xi}_c^-$	$-\tilde{E}'_{1,c}$	...	...

TABLE XI. Parameters in $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays for low-lying $\mathcal{B}_c(\mathbf{6}_f)$ and $\bar{\mathcal{B}}_c(\mathbf{3}_f)$, where $c_{2,v} \equiv (1 + \delta_v^{c_2})c_2$ is a fitted parameter. The uncertainty is obtained by scanning $\chi^2 \leq \chi_{\min}^2 + 1$. We assume SU(3)-breaking parameters ($\delta_v^{c_2}$, $\delta_c^{c_2}$, $\delta_s^{c_2}$) have sizes at most as $|\delta_v^{c_1}|$.

$c_{2,v} \equiv (1 + \delta_v^{c_2})c_2$	$\delta_v^{c_2}$	$\delta_c^{c_2}$	$\delta_s^{c_2}$	$\chi_{\min}^2$
$0.173^{+0.045}_{-0.062}$	0 ± 0.35	0 ± 0.35	0 ± 0.35	0

$$\begin{aligned}\tilde{C}'_{1,c} &= (1 + \delta_c^{c_1})\tilde{C}'_1 = \frac{1 + \delta_c^{c_1}}{1 + \delta_v^{c_1}}\tilde{C}'_{1,v}, \\ \tilde{C}'_{1,s} &= (1 + \delta_s^{c_1})\tilde{C}'_1 = \frac{1 + \delta_s^{c_1}}{1 + \delta_v^{c_1}}\tilde{C}'_{1,v}.\end{aligned}\quad (23)$$

With our estimations on these SU(3)-breaking factors and the measured $B^- \rightarrow \Xi_c^0(2790)\bar{\Lambda}_c^-$ rate, the decay rates of these three decay modes are obtained accordingly and are shown in Table X.

B. $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay rates

We consider $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays for low-lying $\mathcal{B}_c(\mathbf{6}_f)$ and $\bar{\mathcal{B}}_c(\mathbf{3}_f)$ and for excited $\mathcal{B}_c(\mathbf{6}_f)$ in this subsection.

1. Low-lying case

We start with the numerical results of $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays for low-lying $\mathcal{B}_c(\mathbf{6}_f)$ and $\bar{\mathcal{B}}_c(\mathbf{3}_f)$ baryons. Note that, as forbidden by charge conservation, we do not have the $\bar{B}_q \rightarrow \Sigma_c^{++}\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay. The amplitudes are governed by internal W -tree amplitudes, which may contain SU(3)-breaking effects, see Table IV. So far only the measurement of the $B^- \rightarrow \Xi_c^0\bar{\Lambda}_c^-$ rate among these modes is reported, see Table I. Its amplitude is given by

$A(\bar{B}^0 \rightarrow \Xi_c^+\bar{\Lambda}_c^-) = C_{2,v}$. Hence, only $|C_{2,v}|$ or, equivalently, $|c_{2,v}| = |(1 + \delta_v^{c_2})c_2|$ can be constrained by data. The fitted parameter is given in Table XI.

By assuming SU(3)-breaking parameters ($\delta_v^{c_2}$, $\delta_c^{c_2}$, $\delta_s^{c_2}$) have sizes at most as $|\delta_v^{c_1}|$, results of other $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay rates can be obtained and are shown in Table XII. Their amplitudes are also shown for our convenience. Note that $\bar{B}^0 \rightarrow \Xi_c^+\bar{\Lambda}_c^-$ decay is the isospin-related mode to the measured mode, the uncertainty in rates originated from the uncertainty of the measured $B^- \rightarrow \Xi_c^0\bar{\Lambda}_c^-$ rate. Other modes have large uncertainties in their rates. This simply reflects our poor understanding of the SU(3)-breaking parameters $\delta_v^{c_2}$, $\delta_c^{c_2}$, and $\delta_s^{c_2}$. Hence, measurements of these rates can provide valuable information about these SU(3)-breaking parameters.

2. Excited $\mathcal{B}_c(\mathbf{6}_f)$ case

We now turn to the numerical results of $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays for low-lying $\bar{\mathcal{B}}_c(\mathbf{3}_f)$ charmed baryons, but with excited $\mathcal{B}_c(\mathbf{6}_f)$ anticharmed baryons. Namely, we will discuss $\bar{B}_q \rightarrow \Sigma_c^{0,+}(2520)\bar{\mathcal{B}}_c(\mathbf{3}_f)$, $\Xi_c^{0,+}(2645)\bar{\mathcal{B}}_c(\mathbf{3}_f)$, and $\Omega_c^0(2770)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays. As shown in Table II, these charmed baryons are $J^P = \frac{3}{2}^+$ members of a $\mathbf{6}_f$ multiplet. Note that, as forbidden by charge conservation, we do not have the $\bar{B}_q \rightarrow \Sigma_c^{++}(2520)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay. The amplitudes of these modes are governed by internal W -tree amplitudes and can be expressed similar to those in Table IV. For example, we have

$$A(B^- \rightarrow \Xi_c^0(2645)\bar{\Lambda}_c^-) = -\tilde{C}_{2,v}, \quad (24)$$

where the tilde on top of the topological amplitude is to differentiate from the amplitudes of the low-lying case.

TABLE XII. $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay amplitudes and branching ratios (in units of 10^{-4}) in $\Delta S = -1$ and $\Delta S = 0$ transitions. The experimental result is the input of the χ^2 fit.

Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f))$	$Br(\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f))$	Expt.
$B^- \rightarrow \Xi_c^0\bar{\Lambda}_c^-$	$-C_{2,v}$	3.40 ± 2.00	3.4 ± 2.0 [3]
$\bar{B}^0 \rightarrow \Xi_c^+\bar{\Lambda}_c^-$	$C_{2,v}$	3.15 ± 1.85	...
$B^- \rightarrow \Omega_c^0\bar{\Xi}_c^-$	$\sqrt{2}C_{2,vc}$	$3.66^{+10.10}_{-3.34}$	...
$\bar{B}^0 \rightarrow \Omega_c^0\bar{\Xi}_c^0$	$-\sqrt{2}C_{2,vc}$	$3.35^{+9.25}_{-3.06}$	...
$\bar{B}_s^0 \rightarrow \Xi_c^+\bar{\Xi}_c^-$	$-C_{2,vs}$	$2.81^{+7.75}_{-2.56}$	...
$\bar{B}_s^0 \rightarrow \Xi_c^0\bar{\Xi}_c^0$	$C_{2,vs}$	$2.80^{+7.70}_{-2.55}$	...
$B^- \rightarrow \Sigma_c^0\bar{\Lambda}_c^-$	$-\sqrt{2}C'_2$	$0.41^{+1.14}_{-0.32}$	...
$\bar{B}^0 \rightarrow \Sigma_c^+\bar{\Lambda}_c^-$	C'_2	$0.19^{+0.53}_{-0.15}$	...
$B^- \rightarrow \Xi_c^0\bar{\Xi}_c^-$	$C'_{2,c}$	$0.14^{+0.80}_{-0.12}$	...
$\bar{B}^0 \rightarrow \Xi_c^0\bar{\Xi}_c^0$	$-C'_{2,c}$	$0.13^{+0.74}_{-0.11}$	...
$\bar{B}_s^0 \rightarrow \Sigma_c^+\bar{\Xi}_c^-$	$-C'_{2,s}$	$0.18^{+1.03}_{-0.16}$	...
$\bar{B}_s^0 \rightarrow \Sigma_c^0\bar{\Xi}_c^0$	$\sqrt{2}C'_{2,s}$	$0.35^{+2.05}_{-0.32}$	...

TABLE XIII. Parameters in $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ for low-lying $\bar{\mathcal{B}}_c(\mathbf{3}_f)$ and excited $(3/2)^+ \mathcal{B}_c(\mathbf{6}_f)$ states, where $\tilde{c}_{2,v} \equiv (1 + \delta_v^{c_2})\tilde{c}_2$ is a fitted parameter. The uncertainty is obtained by scanning $\chi^2 \leq \chi_{\min}^2 + 1$. We assume SU(3)-breaking parameters $(\delta_v^{c_2}, \delta_c^{c_2}, \delta_s^{c_2})$ have sizes at most as $|\delta_v^{c_1}|$.

$\tilde{c}_{2,v} \equiv (1 + \delta_v^{c_2})\tilde{c}_2$	$\delta_v^{c_2}$	$\delta_c^{c_2}$	$\delta_s^{c_2}$	$\chi_{\min}^2$
$0.579^{+0.141}_{-0.189}$	0 ± 0.35	0 ± 0.35	0 ± 0.35	0

On the experimental side, so far, the measurement of the $B^- \rightarrow \Xi_c^0(2645)\bar{\Lambda}_c^-$ rate among these decays is reported, see Table I. Hence, only information about $|\tilde{C}_{2,v}|$ or, equivalently, $|\tilde{c}_{2,v}| = |(1 + \delta_v^{c_2})\tilde{c}_2|$ can be obtained. The fitted result of this parameter is shown in Table XIII. By assuming SU(3)-breaking parameters $(\delta_v^{c_2}, \delta_c^{c_2}, \delta_s^{c_2})$ have sizes at most as $|\delta_v^{c_1}|$, results of other $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay rates can be obtained and are shown in Table XIV. We also show their amplitudes for our convenience.

Note that, as these are $\bar{B}_q \rightarrow \mathcal{B}_c(J = \frac{3}{2})\bar{\mathcal{B}}_c(J = \frac{1}{2})$ decays, the decay rates are proportional to their center of mass momenta cubed, $p_{\text{c.m.}}^3$, see Eq. (17). These factors provide large suppressions on rates for heavy final states. For example, the $B^- \rightarrow \Omega_c^0(2770)\bar{\Xi}_c^-$ and $\bar{B}^0 \rightarrow \Omega_c^0(2770)\bar{\Xi}_c^0$ rates are much smaller than other $\Delta S = -1$ modes. This is even more prominent by comparing this situation to those of $B^- \rightarrow \Omega_c^0\bar{\Xi}_c^-$ and $\bar{B}^0 \rightarrow \Omega_c^0\bar{\Xi}_c^0$ rates given in Table XII, where the suppression is much milder as they are $\bar{B}_q \rightarrow \mathcal{B}_c(J = \frac{1}{2})\bar{\mathcal{B}}_c(J = \frac{1}{2})$ decays instead.

Except for $\bar{B}^0 \rightarrow \Xi_c^+(2645)\bar{\Lambda}_c^-$, which is the isospin-related mode of $B^- \rightarrow \Xi_c^0(2645)\bar{\Lambda}_c^-$, all other modes have large uncertainties in their rates. This simply reflects our poor understanding of the SU(3)-breaking parameters $\delta_v^{c_2}$,

TABLE XV. Parameters in $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays for low-lying $\mathcal{B}_c(\bar{\mathbf{3}}_f)$ and $\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$, where $c_{3,v} \equiv (1 + \delta_v^{c_3})c_3$ is a fitted parameter. The uncertainty is obtained by scanning $\chi^2 \leq \chi_{\min}^2 + 1$. We assume SU(3)-breaking parameters $(\delta_v^{c_3}, \delta_c^{c_3}, \delta_s^{c_3})$ have sizes at most as $|\delta_v^{c_1}|$.

$c_{3,v} \equiv (1 + \delta_v^{c_3})c_3$	$\delta_v^{c_3}$	$\delta_c^{c_3}$	$\delta_s^{c_3}$	$\chi_{\min}^2$
$0.159^{+0.017}_{-0.020}$	0 ± 0.35	0 ± 0.35	0 ± 0.35	0.035

$\delta_c^{c_2}$, and $\delta_s^{c_2}$. Hence, measurements of these rates can provide valuable information about these SU(3)-breaking parameters.

C. $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decay rates

Finally, we discuss the numerical results of $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decay rates with low-lying charmed and anticharmed baryons. These modes are governed by internal W -tree amplitudes as shown in Table V. Presently, we have measurements on the rates of two of these modes, namely, $B^- \rightarrow \Xi_c^+\bar{\Sigma}_c^{--}$ and $\bar{B}^0 \rightarrow \Xi_c^0\bar{\Sigma}_c^0$ decays, see Table I. These two modes are isospin related and are governed by $C_{3,v}$. Hence, we have information on $|C_{3,v}|$ or, equivalently, $|c_{3,v}| = |(1 + \delta_v^{c_3})c_3|$. The fitted result of this parameter is shown in Table XV.

By assuming SU(3)-breaking parameters $\delta_v^{c_3}, \delta_c^{c_3}$, and $\delta_s^{c_3}$ have sizes at most as $|\delta_v^{c_1}|$, rates of these modes can be obtained and are shown in Table XVI. We see that the experimental data on $B^- \rightarrow \Xi_c^+\bar{\Sigma}_c^{--}$ and $\bar{B}^0 \rightarrow \Xi_c^0\bar{\Sigma}_c^0$ decay rates can be reasonably reproduced. Note that, in the fit, the central value of the $B^- \rightarrow \Xi_c^+\bar{\Sigma}_c^{--}$ rate is slightly lower than that in data, while the situation in $\bar{B}^0 \rightarrow \Xi_c^0\bar{\Sigma}_c^0$ decay is the other way around. Hence, the minimum of $|C_{3,v}|$ is

TABLE XIV. $\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decay amplitudes and branching ratios (in units of 10^{-4}) in $\Delta S = -1$ and $\Delta S = 0$ transitions, where $\mathcal{B}_c(\bar{\mathbf{3}}_f)$ are low-lying $(1/2)^+$ states, while $\mathcal{B}_c(\mathbf{6}_f)$ are excited $(3/2)^+$ states. The experimental result is the input of the χ^2 fit.

Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f))$	$Br(\bar{B}_q \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f))$	Expt.
$B^- \rightarrow \Xi_c^0(2645)\bar{\Lambda}_c^-$	$-\tilde{C}_{2,v}$	4.40 ± 2.40	4.4 ± 2.4 [3]
$\bar{B}^0 \rightarrow \Xi_c^+(2645)\bar{\Lambda}_c^-$	$\tilde{C}_{2,v}$	4.09 ± 2.23	...
$\bar{B}_s^0 \rightarrow \Xi_c^+(2645)\bar{\Xi}_c^-$	$-\tilde{C}_{2,vs}$	$2.67^{+7.08}_{-2.41}$	...
$\bar{B}_s^0 \rightarrow \Xi_c^0(2645)\bar{\Xi}_c^0$	$\tilde{C}_{2,vs}$	$2.61^{+6.89}_{-2.36}$	...
$B^- \rightarrow \Omega_c^0(2770)\bar{\Xi}_c^-$	$\sqrt{2}\tilde{C}_{2,vc}$	$0.40^{+1.07}_{-0.36}$	...
$\bar{B}^0 \rightarrow \Omega_c^0(2770)\bar{\Xi}_c^0$	$-\sqrt{2}\tilde{C}_{2,vc}$	$0.34^{+0.91}_{-0.31}$	...
$B^- \rightarrow \Sigma_c^0(2520)\bar{\Lambda}_c^-$	$-\sqrt{2}\tilde{C}'_2$	$0.81^{+2.17}_{-0.61}$	...
$\bar{B}^0 \rightarrow \Sigma_c^+(2520)\bar{\Lambda}_c^-$	$\tilde{C}'_2$	$0.38^{+1.01}_{-0.28}$	...
$\bar{B}_s^0 \rightarrow \Sigma_c^+(2520)\bar{\Xi}_c^-$	$-\tilde{C}'_{2,s}$	$0.28^{+1.61}_{-0.25}$	...
$\bar{B}_s^0 \rightarrow \Sigma_c^0(2520)\bar{\Xi}_c^0$	$\sqrt{2}\tilde{C}'_{2,s}$	$0.56^{+3.17}_{-0.50}$	...
$B^- \rightarrow \Xi_c^0(2645)\bar{\Xi}_c^-$	$\tilde{C}'_{2,c}$	$0.08^{+0.45}_{-0.07}$	...
$\bar{B}^0 \rightarrow \Xi_c^+(2645)\bar{\Xi}_c^0$	$-\tilde{C}'_{2,c}$	$0.07^{+0.41}_{-0.06}$	...

TABLE XVI. Branching ratios (in units of 10^{-4}) of $\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays to low-lying charmed baryon final states in $\Delta S = -1$ and $\Delta S = 0$ transitions. Experimental results are inputs of the χ^2 fit giving $\chi^2_{\min} = 0.035$.

Mode	$A(\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f))$	$Br(\bar{B}_q \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f))$	Expt.
$B^- \rightarrow \Xi_c^+ \bar{\Sigma}_c^{--}$	$\sqrt{2}C_{3,v}$	5.38 ± 1.24	5.74 ± 2.33 [4]
$\bar{B}^0 \rightarrow \Xi_c^0 \bar{\Sigma}_c^{0-}$	$-\sqrt{2}C_{3,v}$	4.96 ± 1.14	4.83 ± 1.35 [4]
$B^- \rightarrow \Xi_c^0 \bar{\Sigma}_c^{--}$	$-C_{3,v}$	$2.68^{+0.62}_{-0.62}$	...
$\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Sigma}_c^{--}$	$C_{3,v}$	2.49 ± 0.57	...
$\bar{B}_s^0 \rightarrow \Xi_c^0 \bar{\Xi}_c^{0-}$	$-C_{3,vs}$	$2.37^{+4.53}_{-1.98}$	...
$\bar{B}_s^0 \rightarrow \Xi_c^+ \bar{\Xi}_c^{--}$	$C_{3,vs}$	$2.38^{+4.56}_{-1.99}$	...
$B^- \rightarrow \Lambda_c^+ \bar{\Sigma}_c^{--}$	$-\sqrt{2}C'_3$	$0.35^{+0.67}_{-0.20}$	...
$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Sigma}_c^{--}$	$-C'_3$	$0.16^{+0.31}_{-0.09}$	...
$B^- \rightarrow \Xi_c^0 \bar{\Xi}_c^{--}$	$C'_{3,c}$	$0.12^{+0.50}_{-0.10}$	...
$\bar{B}^0 \rightarrow \Xi_c^0 \bar{\Xi}_c^{0-}$	$C'_{3,c}$	$0.11^{+0.46}_{-0.09}$	...
$\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Xi}_c^{--}$	$-C'_{3,s}$	$0.16^{+0.68}_{-0.13}$	...
$\bar{B}_s^0 \rightarrow \Xi_c^0 \bar{\Omega}_c^{0-}$	$\sqrt{2}C'_{3,cs}$	$0.20^{+1.50}_{-0.19}$	...

constrained by the former mode, while the maximum is by the latter mode.

The rates of two other isospin-related modes, namely, $B^- \rightarrow \Xi_c^0 \bar{\Sigma}_c^{--}$ and $\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Sigma}_c^{--}$ can be predicted with relatively small uncertainties. The uncertainties in rates of other modes are much larger. This simply reflects our poor understanding of the SU(3)-breaking parameters δ_v^{c3} , δ_c^{c3} , and δ_s^{c3} . Hence, measurements of these rates can provide valuable information about these SU(3)-breaking parameters.

V. CONCLUSION

We study the rates of two-body charmed-anticharmed baryonic $\bar{B} \rightarrow \mathcal{B}_c \bar{\mathcal{B}}_c$ decays using the topological amplitude approach. All amplitudes of $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$, $\mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$, $\mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$, and $\mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays are decomposed topologically. SU(3)-breaking effects on these amplitudes, depending on the position of the s -quark line, are modeled. Note that the numerical results of this work rely on several working assumptions. They can be relaxed when more data become available. For example, our estimate of some SU(3)-breaking parameters can be relaxed, and the relative contributions from s - and p -wave parts can be determined with the information of the asymmetry α .

Using existing data as input, we obtained the following results:

- (i) In the low-lying $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays, experimental results on $B^- \rightarrow \Xi_c^0 \bar{\Lambda}_c^{--}$, $\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Lambda}_c^{--}$, $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^{--}$, and $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^{--}$ decay rates can be reasonably reproduced, and predictions on other rates are given. We find that the exchange diagram is sizable, giving $|E_1^{(l)}|/|C_1^{(l)}|$ ratio about 44%. Furthermore, there is a large cancellation in internal

W -tree and exchange- W -tree amplitudes. The SU(3) breaking is sizable, 35% SU(3)-breaking effects are needed, and they work differently in different amplitudes. Namely, the internal W -tree amplitude $C_{1,v}$ is enlarged, while the exchange- W -tree amplitude $E_{1,v}$ is reduced. It remains to be seen if this pattern is followed by other internal W -tree and exchange- W -tree amplitudes, such as $C_{1,s}$, $C_{1,c}$, $C_{1,vs}$, $E_{1,s}$, and $E_{1,vc}$. The rates of $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays with excited $\mathcal{B}_c(\bar{\mathbf{3}}_f)$, such as $\Lambda_c(2595)^+$, $\Xi_c(2790)^{+,0}$, are also studied. The experimental result on the $B^- \rightarrow \Xi_c^0(2790)\bar{\Lambda}_c^{--}$ rate can be reproduced with predictions on rates of some similar modes. Note that some of the above observations on the low-lying case have been pointed out in [5], but, in this work, we provide more detailed information, such as the size of the ratio of the topological amplitudes, the sizes of the SU(3)-breaking effects, and different behaviors of the effects on different topological amplitudes.

- (ii) The $\bar{B} \rightarrow \mathcal{B}_c(\mathbf{6}_f)\bar{\mathcal{B}}_c(\mathbf{3}_f)$ decays, with low-lying $\bar{\mathcal{B}}_c(\mathbf{3}_f)$ and low-lying and excited $\mathcal{B}_c(\mathbf{6}_f)$ baryons, such as $\Sigma_c(2520)^{+,0}$, $\Xi_c(2645)^{+,0}$, $\Omega_c(2770)^0$, are studied. Since these decays are governed by a single internal W -tree amplitude in the SU(3) limit, they are highly related. Adding SU(3) breaking can easily modify their relations. Experimental results on $B^- \rightarrow \Xi_c^0 \bar{\Lambda}_c^{--}$ and $B^- \rightarrow \Xi_c^0(2645)\bar{\Lambda}_c^{--}$ decays can be reproduced with predictions on other rates obtained. Note that the excited states are spin-3/2 states. Therefore, some of their rates are highly suppressed by the kinematic factor ($p_{c.m.}^3$).
- (iii) The $\bar{B} \rightarrow \mathcal{B}_c(\bar{\mathbf{3}}_f)\bar{\mathcal{B}}_c(\bar{\mathbf{6}}_f)$ decays with low-lying charmed-anticharmed baryons are studied. Since these decays are governed by a single internal

W -tree amplitude in the SU(3) limit, they are highly related. Adding SU(3) breaking can easily modify their relations. The experimental data on $B^- \rightarrow \Xi_c^+ \bar{\Sigma}_c^{--}$ and $\bar{B}^0 \rightarrow \Xi_c^0 \bar{\Sigma}_c^0$ decay rates can be reasonably reproduced with predictions on other rates given.

- (iv) Uncertainties in most predicted rates are large, reflecting our current poor understanding of the related SU(3)-breaking effects. Measuring these rates can provide very useful information about these effects.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [1–6].

APPENDIX: FORMULA FOR DECAY RATES

The decay $\bar{B}_q \rightarrow \mathcal{B}_c(J=1/2)\bar{\mathcal{B}}_c(J=1/2)$ and $\mathcal{B}_c(J=3/2)\bar{\mathcal{B}}_c(J=1/2)$ have the following forms [31]:

$$\begin{aligned} A\left(\bar{B}_q \rightarrow \mathcal{B}_c\left(\frac{1}{2}\right)\bar{\mathcal{B}}_c\left(\frac{1}{2}\right)\right) &= \bar{u}_1(a + \gamma_5 b)v_2, \\ A\left(\bar{B}_q \rightarrow \mathcal{B}_c\left(\frac{3}{2}\right)\bar{\mathcal{B}}_c\left(\frac{1}{2}\right)\right) &= i \frac{q^\mu}{m_{B_q}} \bar{u}_1^\mu(a + \gamma_5 b)v_2, \end{aligned} \quad (\text{A1})$$

where $q = p_1 - p_2$ is the difference of the momenta of the charmed and anticharmed baryons and u^μ, v^μ are the Rarita-Schwinger vector spinors [32],

$$\begin{aligned} u_\mu\left(\pm\frac{3}{2}\right) &= \epsilon_\mu(\pm 1)u\left(\pm\frac{1}{2}\right) \\ u_\mu\left(\pm\frac{1}{2}\right) &= \frac{1}{\sqrt{3}}\left(\epsilon_\mu(\pm 1)u\left(\mp\frac{1}{2}\right) + \sqrt{2}\epsilon_\mu(0)u\left(\pm\frac{1}{2}\right)\right), \end{aligned} \quad (\text{A2})$$

with $\epsilon_\mu(\lambda)$ the polarization vector. Using the following identity:

$$q \cdot \epsilon(\lambda) = -\delta_{\lambda,0} \frac{m_{B_q} p_{\text{c.m.}}}{m_{\mathcal{B}_c(3/2)}}, \quad (\text{A3})$$

with $p_{\text{c.m.}}$ the baryon momentum in the center of mass frame, we have

$$A\left(\bar{B}_q \rightarrow \mathcal{B}_c\left(\frac{3}{2}\right)\bar{\mathcal{B}}_c\left(\frac{1}{2}\right)\right) = -i\sqrt{\frac{2}{3}} \frac{p_{\text{c.m.}}}{m_{\mathcal{B}_c(3/2)}} \bar{u}_1(a + \gamma_5 b)v_2. \quad (\text{A4})$$

It is straightforward to obtain the decay rates giving

$$\Gamma\left(\bar{B}_q \rightarrow \mathcal{B}_c\left(\frac{1}{2}\right)\bar{\mathcal{B}}_c\left(\frac{1}{2}\right)\right) = \frac{p_{\text{c.m.}}}{8\pi m_{B_q}^2} [(2m_{B_q}^2 - 2(m_{B_c} + m_{\bar{B}_c})^2)|a|^2 + (2m_{B_q}^2 - 2(m_{B_c} - m_{\bar{B}_c})^2)|b|^2], \quad (\text{A5})$$

and

$$\Gamma\left(\bar{B}_q \rightarrow \mathcal{B}_c\left(\frac{3}{2}\right)\bar{\mathcal{B}}_c\left(\frac{1}{2}\right)\right) = \frac{p_{\text{c.m.}}}{8\pi m_{B_q}^2} \frac{2}{3} \left(\frac{p_{\text{c.m.}}}{m_{\mathcal{B}_c(3/2)}}\right)^2 [(2m_{B_q}^2 - 2(m_{B_c} + m_{\bar{B}_c})^2)|a|^2 + (2m_{B_q}^2 - 2(m_{B_c} - m_{\bar{B}_c})^2)|b|^2]. \quad (\text{A6})$$

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