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Charm changing weak hadronic decays of triplet (C = 1) baryons emitting axial-vector mesons including factorizable and pole contributions

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We investigate the weak nonleptonic decays of Λ_c^+, Ξ_c^+, and Ξ_c^0 into the octet baryons ($J^P = 1/2^+$) and axial-vector mesons ($J^P = 1^+$) employing the factorization scheme for W-emission diagrams and the pole model for W-exchange contributions. Determining the baryon-baryon transition form factors in the nonrelativistic quark model and incorporating the constraints of heavy quark symmetry, we predict their branching ratios and asymmetry parameters.

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I. INTRODUCTION

During the last few decades, significant progress has taken place for understanding the decays of charmed baryons both at experimental [1] and theoretical [2–9] fronts. Theoretical focus has, so far, been on the pseudoscalar and vector meson emitting decays of the charm baryons. However, these baryons, being heavy, can emit p-wave mesons also. Earlier, we have investigated the branching ratios of charm baryons emitting axial-vector mesons based on the factorization scheme [10] to estimate the amplitudes arising from the W-emission diagrams. However, W-exchange diagrams can also contribute to these decays [2,3,6], which are usually calculated in the pole model framework. In fact, the only observed p-wave meson emitting decay $\Lambda_c^+ \to p f_0(980)$, which is prohibited in the factorization approach due to the vanishing decay constants of $f_0(980)$, provides evidence for such nonfactorizable contributions [11]. In this work, we extend our work to include the pole contributions for weak nonleptonic decays of Λ_c^+, Ξ_c^+, and Ξ_c^0 into the octet baryons ($J^P = 1/2^+$) and axial-vector mesons ($J^P = 1^+$) in the Cabibbo-Kobayashi-Maskawa (CKM)-favored and CKM-suppressed modes. We predict the branching ratios and asymmetry parameters of these decay modes.

The layout of this paper is as follows. In Sec. II, we give the meson spectroscopy, and Sec. III deals with the general framework for kinematical formulae, factorization, and pole contributions. Numerical results and conclusions are presented in the last section. In our analysis, we find that, like pseudoscalar/vector emitting decays of charm baryons, pole contributions are quite important for axial-vector meson emitting decays of the charm baryons.

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II. MESON SPECTROSCOPY

Experimentally, two nonets of axial-vector mesons (a_1, K_1, f_1, f_1') and $(b_1, \underline{K}_1, h_1, h_1')$ have been identified with different charge conjugations, i.e., ${}^3P_1(1^{++})$ and ${}^1P_1(1^{+-})$, in agreement with the quark model expectations. For $J^{\rm PC} = 1^{++}$, there exist three candidates, $f_1(1.285)$, $f_1(1.420)$, and $f_1(1.510)$—out of which $f_1(1.420)$ is a multiquark state in the form of a $K\bar{K}\pi$ bound state [12] or a $K\bar{K}^*$ deuteron state [13]. In the present analysis, we define mixing of the isoscalar states as

$$\begin{aligned} f_1(1.282) &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos\phi_A + (s\bar{s})\sin\phi_A, \\ f_1'(1.510) &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\sin\phi_A - (s\bar{s})\cos\phi_A. \end{aligned} \tag{1}$$

Similarly, for $J^{\rm PC}$, mixing of the isoscalars $h_1(1.170)$ and $h_1'(1.380)$ is defined as

$$\begin{aligned} h_1(1.170) &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos\phi_B + (s\bar{s})\sin\phi_B, \\ h_1'(1.380) &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\sin\phi_B - (s\bar{s})\cos\phi_B. \end{aligned} \tag{2}$$

Proximity of $a_1(1.260)$ and $f_1(1.285)$ and to a lesser extent, that of $b_1(1.235)$ and $h_1(1.170)$ favors ideal mixing for 1^{++} and 1^{+-} nonets, i.e.,

$$\phi_A = \phi_B = 0^0. \tag{3}$$

This is also supported by their decay patterns. $f_1(1.285)$ decays predominantly to 4π and $\eta\pi\pi$, while $f_1'(1.510)$ decays to $K\bar{K}\pi$. Similarly, $h_1(1.170)$ decays predominantly to $\rho\pi$, and $h_1'(1.380)$ decays to $K\bar{K}^*$ and $\bar{K}K^*$ states.

Experimentally, two axial-vector strange mesons exist, $K_1(1.270)$ and $\underline{K}_1(1.400)$. Here, SU(3) breaking allows a mixing between them:

$$K_1 = K_{1A}\sin\theta + K_{1B}\cos\theta,$$
$$\underline{K}_1 = K_{1A}\cos\theta - K_{1B}\sin\theta, \tag{4}$$

where K_{1A} and K_{1B} denote the strange partners of $a_1(1.260)$ and $b_1(1.235)$, respectively. Particle Data Group [1] assumes that the mixing is maximal, i.e., $\theta_1 = 45°$; whereas, $\tau \to K_1(1.270)/K_1(1.400) + \nu_\tau$ data yield $\theta_1 = \pm 37°$ and $\theta_1 = \pm 58°$ [14]. However, the study of $D \to K_1(1.270)\pi$, $K_1(1.400)\pi$ decays rules out positive mixing-angle solutions. Therefore, both negative mixing-angle solutions are allowed by experiment as discussed in detail in Ref. [15]. But $D \to K_1^-(1.400)\pi^+$ is very suppressed for $\theta_1 = -37°$ and favors the other solution $\theta_1 = -58°$ [15]. Hence, we take $\theta_1 = -58°$ in our analysis.

III. GENERAL FRAMEWORK

A. Kinematics

Following the standard procedure for baryon decays [6,16], the matrix element for the $B_i(1/2^+) \to B_f(1/2^+) + A_k(1^+)$ decay process can be written as

$$\langle B_f(p_f)A_k(q)|H_W|B_i(p_i)\rangle = i\bar{u}_{B_f}(p_f)\varepsilon^{*\mu}(A_1\gamma_\mu\gamma_5 + A_2 p_{f\mu}\gamma_5 + B_1\gamma_\mu + B_2 p_{f\mu}) \times u_{B_i}(p_i),$$

where ε^μ is the polarization vector of the axial-vector meson A_k. Here, A_i's and B_i's denote the parity conserving and parity violating amplitudes, respectively. The orbital angular momentum of the final state is now an admixture of S, P, and D waves. Moreover, there are two independent P-wave amplitudes: one associated with the singlet combination of the parent and daughter baryon spins, and the other with the triplet. The basic effects of the interference between the parity violating S and D waves on one hand with the parity conserving P-wave amplitude on the other give rise to asymmetries for the daughter with respect to the spin of the parent baryon. Thus, the decay width is given by

$$\Gamma = \frac{q_\mu}{8\pi}\frac{E_f + m_f}{m_i}\Big[2(|S|^2 + |P_2|^2) + \frac{E_A^2}{m_A^2}(|S+D|^2 + |P_1|^2)\Big], \tag{5}$$

and asymmetry parameter is

$$\alpha = \frac{4m_A^2\,\mathrm{Re}(S * P_2) + 2E_A^2\,\mathrm{Re}(S+D) * P_1}{2m_A^2(|S|^2 + |P_2|^2) + E_A^2(|S+D|^2 + |P_1|^2)}, \tag{6}$$

with

$$S = -A_1,$$
$$P_1 = -\frac{q_\mu}{E_A}\left(\frac{m_i + m_f}{E_f + m_f}B_1 + m_i B_2\right),$$
$$P_2 = \frac{q_\mu}{E_f + m_f}B_1,$$
$$D = -\frac{q_\mu^2}{E_A(E_f + m_f)}(A_1 - m_i A_2),$$

and

$$|q_\mu| = \frac{1}{2m_i}\sqrt{[m_i^2 - (m_f - m_A)^2][m_i^2 - (m_f + m_A)^2]},$$

where $q_\mu = (p_i - p_f)_\mu$ is the four momentum of the axial-vector meson in the rest frame of the parent particle, m_i and m_f are the masses of the initial and final baryons, and m_A is the emitted meson mass. E_A and E_f are the energies of the axial-vector meson and the daughter baryon, respectively.

B. Weak Hamiltonian

The general current $\otimes$ current weak Hamiltonian H_W, including the short distance QCD effects, for the charm changing baryon decays is given by

$$H_W = \frac{G_F}{2\sqrt{2}}V_{ud}V_{cs}^*(c_- O_- + c_+ O_+) \tag{7}$$

for CKM-favored mode ($\Delta C = \Delta S = -1$), with $O_\pm = (\bar{u}d)(\bar{s}c) \pm (\bar{s}d)(\bar{u}c)$, where V_{ij} denote the CKM matrix elements, and $\bar{q}_1 q_2 \equiv \bar{q}_1\gamma_\mu(1-\gamma_5)q_2$ represents color singlet $V - A$ current. In the leading log approximation, QCD coefficients c_+ and c_- are given by

$$c_\pm(\mu) = \left[\frac{\alpha_s(\mu^2)}{\alpha_s(m_W^2)}\right]^{d_\pm/2b} \tag{8}$$

with $d_- = -2d_+ = 8$ and $b = 11 - \frac{2}{3}N_f$; N_f is the number of flavors, μ is the mass scale, m_W is weak boson mass, and α_s is the fine-structure constant. Though, the precise value of QCD coefficients is difficult to assign, we use

$$c_+(\mu) = 0.75, \qquad c_-(\mu) = 1.77 \text{ at } \mu \approx m_c^2,$$

fixed from $D \to K\pi$ [3]. Similarly, the weak Hamiltonian for CKM-suppressed mode ($\Delta C = -1$, $\Delta S = 0$) can be constructed.

C. Factorizable contribution

In the standard factorization scheme [2], the separable combination of decay amplitudes for $B_i(1/2^+) \to B_f(1/2^+) + A_k(1^+)$ is given by

$$\langle A_k(q)|A_\mu|0\rangle\langle B_f(p_f)|V^\mu + A^\mu|B_i(p_i)\rangle \tag{9}$$

apart from the scale factors. The first factor is written as

$$\langle A_k(q)|A_\mu|0\rangle = f_A m_A \varepsilon^*_\mu, \quad (10)$$

where f_A is the decay constant of the emitted axial-vector meson A_k. Matrix elements of the weak currents between baryon states are

$$\langle B_f(p_f)|V_\mu|B_i(p_i)\rangle = \bar{u}_f(p_f)\left[f_1\gamma_\mu - \frac{f_2}{m_i}i\sigma_{\mu\nu}q^\nu + \frac{f_3}{m_i}q_\mu\right]u_i(p_i), \quad (11)$$

and

$$\langle B_f(p_f)|A_\mu|B(p_i)\rangle = \bar{u}_f(p_f)\left[g_1\gamma_\mu\gamma_5 - \frac{g_2}{m_i}i\sigma_{\mu\nu}q^\nu\gamma_5 + \frac{g_3}{m_i}q_\mu\gamma_5\right]u_i(p_i). \quad (12)$$

The factorizable amplitudes are thus given by

$$A_1^{\rm fac} = -\frac{G_F}{\sqrt{2}}F_C f_A c_k m_A\left[g_1^{B_i,B_f}(m_A^2) - g_2^{B_i,B_f}(m_A^2)\frac{m_i - m_f}{m_i}\right],$$
$$A_2^{\rm fac} = \frac{G_F}{\sqrt{2}}F_C f_A c_k m_A[2g_2^{B_i,B_f}(m_A^2)/m_i],$$
$$B_1^{\rm fac} = \frac{G_F}{\sqrt{2}}F_C f_A c_k m_A\left[f_1^{B_i,B_f}(m_A^2) + f_2^{B_i,B_f}(m_A^2)\frac{m_i + m_f}{m_i}\right],$$
$$B_2^{\rm fac} = -\frac{G_F}{\sqrt{2}}F_C f_A c_k m_A[2f_2^{B_i,B_f}(m_A^2)/m_i], \quad (13)$$

where F_C contains appropriate CKM factors and Clebsch-Gordan coefficients. In the naïve vacuum-saturation approximation, c_k factors are given by

$$c_1 = (2c_+ + c_-)/3 \quad \text{and} \quad c_2 = (2c_+ - c_-)/3.$$

However, for nonleptonic decays of heavy flavor mesons, this fails particularly for color-suppressed decays [2,10,17]. Furthermore, nonfactorizable effects may modify c_1 and c_2, thereby indicating that these may be treated as free parameters. The discrepancy between theory and experiment is greatly improved in the large N_c version of the factorization approach. Hence, we use

$$c_1 = \tfrac{1}{2}(c_+ + c_-) = 1.26 \quad \text{and}$$
$$c_2 = \tfrac{1}{2}(c_+ - c_-) = -0.51$$

in this work [2].

The evaluation of the form factors and that of decay constants have already been discussed in our earlier work [10]. Determination of the baryonic form factors in the quark model is not straightforward due to their three-quark structure and several corrections, like q^2-dependence of the form factors and hard gluon QCD contributions. Moreover, the form factors for baryon-baryon transitions are expected to satisfy the constraints imposed by the heavy quark symmetry. The first estimate of the form factors for charm changing baryon to baryon transitions has been made by Perez-Marcial *et al.* [18] in the nonrelativistic quark model (NRQM). Later, H. Y. Cheng *et al.* [19] have calculated $1/M$ corrections to the form factors using the constraints of heavy quark effective theory (HQET). The calculated form factors show theoretical uncertainties in their numerical values which would obviously affect the branching ratios. We evaluate the required form factors in both the models which are given in Table I. Following our earlier work [10], we use the following decay constants:

$$f_{K_1(1.270)} = 0.175 \pm 0.019\ \text{GeV},$$
$$f_{\underline{K}_1(1.400)} = -0.087 \pm 0.010\ \text{GeV},$$
$$f_{f_1} \approx f_{a_1} = 0.203 \pm 0.018\ \text{GeV}.$$

TABLE I. Baryon to baryon transition form factors at $q^2 = 0$.

Decay	R. Perez-Marcial *et al.* [18] NRQM				Cheng and Tseng [19] HQET			
	f_1	f_2	g_1	g_2	f_1	f_2	g_1	g_2
$c \to s$ transition								
$\Lambda_c^+ \to \Lambda$	0.35	0.09	0.58	−0.03	0.29	0.14	0.36	0.04
$\Lambda_c^+ \to \Sigma^0$	0	0	0	0	0	0	0	0
$\Xi_c^+ \to \Xi^0$	−0.48	−0.08	−0.73	0.04	−0.37	−0.22	−0.46	−0.07
$\Xi_c^0 \to \Xi^-$	−0.48	−0.08	−0.73	0.04	−0.37	−0.22	−0.46	−0.07
$c \to d$ transition								
$\Lambda_c^+ \to n$	−0.22	−0.11	−0.57	0.04	−0.25	−0.14	−0.38	−0.08
$\Xi_c^+ \to \Sigma^0$	0.22	0.06	0.45	−0.03	0.21	0.16	0.31	0.10
$\Xi_c^+ \to \Lambda$	0.10	0.03	0.23	−0.02	0.10	0.07	0.16	0.04
$\Xi_c^0 \to \Sigma^-$	0.32	0.08	0.63	−0.04	0.30	0.23	0.44	0.14
$c \to u$ transition								
$\Lambda_c^+ \to p$	0.22	0.11	0.56	−0.04	0.25	0.14	0.38	0.08
$\Xi_c^+ \to \Sigma^+$	0.32	0.08	0.63	−0.04	0.30	0.23	0.44	0.14
$\Xi_c^0 \to \Sigma^0$	0.22	0.06	0.44	−0.03	0.21	0.16	0.31	0.10
$\Xi_c^0 \to \Lambda$	−0.10	−0.03	−0.23	0.02	−0.10	−0.07	−0.16	−0.04

D. Pole contribution

For the $B_i(1/2^+) \to B_f(1/2^+) + A_k(1^+)$ decay process in s and u channels, intermediate baryon, $B_n(1/2^+)$, poles give rise to the following terms:

$$A_1^{\text{pole}} = -\sum_n \left[\frac{g_{B_f B_n A_k} a_{ni}}{m_i - m_n} + \frac{a_{fn} g_{B_n B_i A_k}}{m_f - m_n} \right],$$
$$B_1^{\text{pole}} = \sum_n \left[\frac{g_{B_f B_n A_k} b_{ni}}{m_i + m_n} + \frac{b_{fn} g_{B_n B_i A_k}}{m_f + m_n} \right], \quad (14)$$
$$A_2^{\text{pole}} = B_2^{\text{pole}} = 0,$$

where g_{ijk} are the strong baryon-axial-vector meson coupling constants. Weak baryon-baryon matrix elements a_{ij} and b_{ij} are defined as

$$\langle B_i | H_W | B_j \rangle = \bar{u}_{B_i}(a_{ij} + \gamma_5 b_{ij}) u_{B_j}. \quad (15)$$

It is well known that the matrix elements b_{ij} vanish for the hyperons in the SU(3) limit [16]. In the case of the charm decays also, it has been shown [2] that $b_{ij} \ll a_{ij}$. Moreover, the sum of baryon masses appear in the denominator for B_1^{pole}, thereby suppressing the parity violating pole contributions, which are ignored in this work.

It is worth remarking here that, in addition to the low-lying positive-parity intermediate baryon poles ($J^P = 1/2^+$), the negative-parity intermediate baryon ($J^P = 1/2^-$) may also contribute to these processes. Unfortunately, there is no information available about the axial-vector meson strong coupling constants for the negative-parity baryons. Furthermore, these contributions are expected to be suppressed because of their large masses. Therefore, we been have restricted to the leading terms for estimation of the pole contributions.

1. Axial-vector meson coupling with baryons

Strong baryon-axial-vector meson couplings can be obtained from the following contractions:

$$H_{\text{strong}} = \sqrt{2} g_F (\tfrac{1}{2} \bar{B}^{[a,b]d} B_{[a,b]c} A_d^c - \bar{B}^{[d,a]b} B_{[a,c]b} A_d^c) + \sqrt{2} g_D (\tfrac{1}{2} \bar{B}^{[a,b]d} B_{[a,b]c} A_d^c + \bar{B}^{[d,a]b} B_{[a,c]b} A_d^c), \quad (16)$$

where $B_{[a,b]c}$, $\bar{B}^{[a,b]d}$, and A_d^c denote the baryon, antibaryon, and axial-vector meson tensors, respectively, and $g_D(g_F)$ are conventional D-type and F-type parameters [20]. In the absence of experimental values for these parameters, we use the Goldberger-Treiman relation

$$g_{NNa_1} = \frac{\sqrt{2} g_A m_N}{f_{a_1}} = 8.36 \pm 0.74 \quad (17)$$

for $g_A = 1.28$ given by β decay [16]. Following the analysis of G. Erkol [21], g_D and g_F are determined as

$$g_D = 6.02 \pm 0.77 \quad \text{and} \quad g_F = 2.34 \pm 0.20, \quad (18)$$

for $g_F/(g_F + g_D) = 0.28$. Axial-vector meson-baryon coupling constants relevant for our calculation have been given in Table II.

TABLE II. Axial-vector meson-baryon strong coupling constants.

$B \to BA$	Coupling constant
$p \to pa_1^0$	8.36 ± 0.74
$p \to pf_1$	1.20 ± 0.92
$\Sigma^+ \to \Sigma^+ a_1^0$	4.68 ± 0.40
$\Sigma^+ \to \Lambda a_1^+$	6.92 ± 0.23
$\Sigma^0 \to pK_1^-$	-3.13 ± 0.67
$\Sigma^0 \to pK_{-1}^-$	1.95 ± 0.41
$\Lambda \to \Lambda a_1^0$	0
$\Lambda \to pK_1^-$	-6.39 ± 0.47
$\Lambda \to pK_{-1}^-$	3.99 ± 0.30
$\Lambda \to \Lambda f_1$	-3.38 ± 1.10
$\Xi^0 \to \Lambda \bar{K}_1^0$	0.57 ± 0.47
$\Xi^0 \to \Sigma^0 \bar{K}_1^0$	-7.09 ± 0.67
$\Lambda_c^+ \to \Sigma_c^0 a_1^+$	-6.95 ± 0.89
$\Lambda_c^+ \to \Lambda_c^+ a_1^0$	0
$\Lambda_c^+ \to \Lambda_c^+ f_1$	-3.35 ± 1.10
$\Lambda_c^+ \to \Xi_c^+ K_1^0$	2.00 ± 0.66
$\Lambda_c^+ \to \Xi_c^+ K_{-1}^0$	-1.25 ± 0.40
$\Lambda_c^+ \to \Xi_c^{\prime +} K_1^0$	-4.17 ± 0.53
$\Lambda_c^+ \to \Xi_c^{\prime +} K_{-1}^0$	2.60 ± 0.31
$\Xi_c^+ \to \Xi_c^+ a_1^0$	-1.69 ± 0.55
$\Xi_c^+ \to \Xi_c^{\prime +} a_1^0$	-3.47 ± 0.44
$\Xi_c^+ \to \Sigma_c^+ \bar{K}_1^0$	-4.17 ± 0.53
$\Xi_c^+ \to \Sigma_c^+ \bar{K}_{-1}^0$	2.60 ± 0.33

2. Weak transitions

In tensor notation, the weak Hamiltonian in (7) and (8) is given by

TABLE III. Weak baryon-baryon transition amplitudes.

Weak transition	Transition amplitude ($\times a_W$)
CKM-favored mode	
$\Lambda_c^+ \to \Sigma^+$	$-\sqrt{3/2}$
$\Sigma_c^+ \to \Sigma^+$	$3/\sqrt{2}$
$\Sigma_c^0 \to \Sigma^0$	$3/\sqrt{2}$
$\Sigma_c^0 \to \Lambda$	$\sqrt{3/2}$
$\Xi_c^0 \to \Xi^0$	$-\sqrt{3/2}$
$\Xi_c^{\prime 0} \to \Xi^0$	$-3/\sqrt{2}$
CKM-suppressed mode	
$\Lambda_c^+ \to p$	$-\sqrt{3/2}$
$\Sigma_c^+ \to p$	$3/\sqrt{2}$
$\Sigma_c^0 \to n$	-3
$\Xi_c^+ \to \Sigma^+$	$-\sqrt{3/2}$
$\Xi_c^{\prime +} \to \Sigma^+$	$3/\sqrt{2}$
$\Xi_c^0 \to \Sigma^0$	$-\sqrt{3}/2$
$\Xi_c^{\prime 0} \to \Sigma^0$	$3/2$
$\Xi_c^0 \to \Lambda$	$-3/2$
$\Xi_c^{\prime 0} \to \Lambda$	$-\sqrt{3}/2$

TABLE IV. Decay amplitudes for CKM-favored decays having both factorization and pole contributions (in units of $\frac{G_F}{\sqrt{2}} V_{ud} V_{cs}^* \text{GeV}^2$).

Decay	$A_1^{\text{fac a}}$	$A_2^{\text{fac a}}$	$B_1^{\text{fac a}}$	$B_2^{\text{fac a}}$	A_1^{pole}
$\Lambda_c^+ \to p\bar{K}_1^0$	0.14 ± 0.02	0.0078 ± 0.0008	-0.13 ± 0.01	0.032 ± 0.003	-0.87 ± 0.02
	0.076 ± 0.008	-0.015 ± 0.002	-0.15 ± 0.02	0.043 ± 0.001	
$\Xi_c^+ \to \Sigma^+\bar{K}_1^0$	0.15 ± 0.02	0.0073 ± 0.0008	-0.14 ± 0.02	0.021 ± 0.002	0.16 ± 0.03
	0.083 ± 0.009	-0.026 ± 0.003	-0.21 ± 0.03	0.063 ± 0.007	
$\Xi_c^0 \to \Lambda\bar{K}_1^0$	0.054 ± 0.006	0.0036 ± 0.0004	-0.047 ± 0.005	0.0079 ± 0.0009	0.084 ± 0.020
	-0.031 ± 0.003	0.0079 ± 0.0009	0.069 ± 0.008	-0.020 ± 0.002	
$\Xi_c^0 \to \Sigma^0\bar{K}_1^0$	0.10 ± 0.01	0.0054 ± 0.0006	-0.10 ± 0.01	0.016 ± 0.002	0.042 ± 0.011
	0.059 ± 0.006	-0.017 ± 0.002	-0.15 ± 0.02	0.044 ± 0.005	

[a]The upper value corresponds to factorizable contributions calculated using the form factors evaluated in NRQM [18], and the lower value corresponds to that calculated on the basis of HQET modified picture [19].

$$H_W = \frac{G_F}{\sqrt{2}} V_{il} V_{jm}^* [c_-(m_c) H_{[i,j]}^{[l,m]} + c_+(m_c) H_{(i,j)}^{(l,m)}], \quad (19)$$

where $c_- = c_1 + c_2$ and $c_+ = c_1 - c_2$ and the brackets [,] and parentheses (,), respectively, denote the antisymmetrization and symmetrization among the indices. However, for baryon-baryon weak transitions [22], it has been shown that the part of the Hamiltonian $H_{(i,j)}^{(l,m)}$, being symmetric in color indices also, does not contribute. Thus, we obtain weak baryon-baryon matrix elements (a_{ij}) by choosing the $H_{[1,3]}^{[2,4]}$, $H_{[1,3]}^{[3,4]} - H_{[1,2]}^{[2,4]}$ components for CKM-favored and CKM-suppressed modes, respectively, in the following contraction:

$$H_W = a_W [\bar{B}^{[i,j]k} B_{[l,m]k} H_{[i,j]}^{[l,m]}], \quad (20)$$

which are given in Table III.

IV. NUMERICAL RESULTS AND CONCLUSIONS

A quick estimate of the pole terms in the quark model [23] can be obtained by relating $a_{\Lambda_c^+ \to \Sigma^+}$ with $a_{\Sigma^+ \to p} (= 1.2 \times 10^{-7}\ \text{GeV})$ as given below:

$$\langle \Sigma^+ | H_W^{\text{PC}} | \Lambda_c^+ \rangle = \frac{1}{\sqrt{6}} \frac{c_-(m_c)}{c_-(m_s)} \frac{V_{cs}}{V_{us}} \langle p | H_W^{\text{PC}} | \Sigma^+ \rangle, \quad (21)$$

TABLE V. Decay amplitudes for CKM-suppressed decays having both factorization and pole contributions (in units of $\frac{G_F}{\sqrt{2}} V_{ud} V_{cd}^* \text{GeV}^2$).

Decay	$A_1^{\text{fac a}}$	$A_2^{\text{fac a}}$	$B_1^{\text{fac a}}$	$B_2^{\text{fac a}}$	A_1^{pole}
$\Lambda_c^+ \to pa_1^0$	-0.098 ± 0.009	-0.0057 ± 0.0005	0.087 ± 0.008	-0.022 ± 0.002	0.037 ± 0.010
	-0.055 ± 0.005	-0.011 ± 0.001	0.10 ± 0.01	-0.029 ± 0.003	
$\Lambda_c^+ \to pf_1$	0.12 ± 0.01	0.0068 ± 0.0006	-0.11 ± 0.01	0.028 ± 0.002	-0.071 ± 0.005
	0.066 ± 0.006	-0.013 ± 0.001	-0.13 ± 0.01	0.038 ± 0.003	
$\Lambda_c^+ \to na_1^+$	-0.34 ± 0.03	-0.020 ± 0.002	0.30 ± 0.03	-0.077 ± 0.007	-0.052 ± 0.014
	0.19 ± 0.02	-0.039 ± 0.003	-0.37 ± 0.03	0.10 ± 0.01	
$\Xi_c^+ \to \Lambda a_1^+$	-0.14 ± 0.01	-0.0092 ± 0.0008	0.12 ± 0.01	-0.019 ± 0.002	-0.21 ± 0.04
	-0.078 ± 0.007	0.020 ± 0.002	0.17 ± 0.02	-0.048 ± 0.004	
$\Xi_c^+ \to \Sigma^+ a_1^0$	-0.11 ± 0.01	-0.0053 ± 0.0005	0.10 ± 0.01	-0.015 ± 0.001	-0.015 ± 0.005
	-0.060 ± 0.005	0.019 ± 0.002	0.15 ± 0.01	-0.044 ± 0.004	
$\Xi_c^+ \to \Sigma^0 a_1^+$	-0.27 ± 0.02	-0.014 ± 0.001	0.25 ± 0.02	-0.039 ± 0.004	-0.015 ± 0.005
	-0.15 ± 0.01	0.045 ± 0.004	0.37 ± 0.03	-0.11 ± 0.01	
$\Xi_c^0 \to \Lambda a_1^0$	-0.039 ± 0.004	-0.0026 ± 0.0002	0.033 ± 0.003	-0.0056 ± 0.0005	0.15 ± 0.03
	0.023 ± 0.002	-0.0058 ± 0.0005	-0.049 ± 0.004	0.014 ± 0.001	
$\Xi_c^0 \to \Lambda f_1$	0.047 ± 0.004	0.0032 ± 0.0003	-0.042 ± 0.004	0.0070 ± 0.0006	-0.0049 ± 0.0040
	-0.027 ± 0.002	0.0069 ± 0.0006	0.061 ± 0.005	-0.018 ± 0.002	
$\Xi_c^0 \to \Sigma^0 a_1^0$	-0.076 ± 0.007	-0.0039 ± 0.0003	0.071 ± 0.006	-0.011 ± 0.001	0.089 ± 0.015
	-0.043 ± 0.004	0.013 ± 0.001	0.11 ± 0.01	-0.031 ± 0.003	
$\Xi_c^0 \to \Sigma^- a_1^+$	-0.038 ± 0.033	-0.018 ± 0.002	0.35 ± 0.03	-0.052 ± 0.005	0.078 ± 0.018
	-0.21 ± 0.02	0.065 ± 0.006	0.53 ± 0.05	-0.15 ± 0.01	

[a]The upper value corresponds to factorizable contributions calculated using the form factors evaluated in NRQM [18], and the lower value corresponds to that calculated on the basis of HQET modified picture [19].

TABLE VI. Decay amplitudes for decays acquiring pole contributions only.

Decay	$A_1^{\rm pole}$
CKM-favored mode	
(in units of $\frac{G_F}{\sqrt{2}} V_{ud} V_{cs}^* \ {\rm GeV}^2$)	
$\Xi_c^0 \to \Sigma^+ K_1^-$	-0.10 ± 0.01
CKM-suppressed mode	
(in units of $\frac{G_F}{\sqrt{2}} V_{ud} V_{cd}^* \ {\rm GeV}^2$)	
$\Xi_c^+ \to p \bar{K}_1^0$	-0.21 ± 0.03
$\Xi_c^+ \to p \bar{K}_{-1}^0$	0.13 ± 0.03
$\Xi_c^0 \to p K_1^-$	0.091 ± 0.012
$\Xi_c^0 \to p K_{-1}^-$	-0.057 ± 0.007
$\Xi_c^0 \to n \bar{K}_1^0$	0.12 ± 0.03
$\Xi_c^0 \to n \bar{K}_{-1}^0$	-0.073 ± 0.018
$\Xi_c^0 \to \Sigma^+ a_1^-$	-0.098 ± 0.013

where $c_-(m_c) = 1.77$ and $c_-(m_s) = 2.23$. The factorizable contributions in both the models and the pole contributions to the weak decay amplitudes are given in Tables IV, V, and VI for CKM-favored as well as CKM-suppressed modes. Because of the uncertainties with the hadronic factors, particularly the axial-vector meson decay constants and strong coupling constants g_D and g_F, we have also shown resulting errors in the factorizable and pole amplitudes. Combining them, branching ratios and asymmetry parameters are predicted as shown in Table VII for CKM-favored and CKM-suppressed modes. In Table VIII, we have given results for those decays which acquire pole contributions only. We observe the following:

(1) We find that the decays $\Lambda_c^+ \to p \bar{K}_1^0$, $\Xi_c^0 \to \Sigma^+ K_1^-$ in CKM-favored mode and $\Lambda_c^+ \to n a_1^+$, $\Xi_c^+ \to \Lambda a_1^+ / \Sigma^0 a_1^+ / p \bar{K}_1^0 / p \bar{K}_{-1}^0$, $\Xi_c^0 \to \Sigma^- a_1^+$ decays in CKM-suppressed mode are the dominant ones having branching ratios in the range 0.1–3.0%.

(2) In our earlier work involving factorizable contributions only [10], it has been observed that, though the decays $\Lambda_c^+ \to n a_1^+$, $\Xi_c^+ \to \Sigma^0 a_1^+ / \Lambda a_1^+$, and $\Xi_c^0 \to \Sigma^- a_1^+$ are CKM-suppressed, they compete well with CKM-favored decays. This happens because the latter occur through color-suppressed diagrams, and the former are generated by color-favored diagrams. This trend also remains valid in the presence of pole diagrams.

(3) Branching ratios of $\Lambda_c^+ \to p \bar{K}_1^0$ decay in the CKM-favored mode and $\Lambda_c^+ \to p a_1 / p f_1$ and of $\Xi_c^+ \to \Lambda a_1^+ / \Sigma^+ a_1^0 / \Sigma^0 a_1^+$ decays in CKM-suppressed modes increase on the inclusion of pole contributions; however, the branching ratios of Ξ_c that decay in the CKM-favored mode reduce due to the destructive interference between the factorizable and pole contributions.

(4) It is found that pole contributions compare well with the factorizable term, which is evident from the branching ratios of $\Xi_c^0 \to \Sigma^+ K_1^-$ and $\Xi_c^+ \to p \bar{K}_1^0 / p \bar{K}_{-1}^0$ decays. Observation of such decays would provide a clear test for W-exchange effects in these decays.

(5) The decay $\Xi_c^0 \to \Sigma^+ K_1^-$, in spite of being CKM-favored, acquires a smaller branching ratio than that

TABLE VII. Branching ratios and asymmetries for decays having both factorizable and pole contributions.[a]

Decay	Branching ratio (a) (%)	Asymmetry (a) "α"	Branching ratio (b) (%)	Asymmetry (b) "α"
CKM-favored and color-suppressed mode				
$\Lambda_c^+ \to p \bar{K}_1^0$	2.82 ± 1.40	0.014	1.54 ± 0.62	0.030
$\Xi_c^+ \to \Sigma^+ \bar{K}_1^0$	0.010 ± 0.002	0.038	0.24 ± 0.06	-0.029
$\Xi_c^0 \to \Lambda \bar{K}_1^0$	0.038 ± 0.011	0.028	0.51 ± 0.30	0.018
$\Xi_c^0 \to \Sigma^0 \bar{K}_1^0$	0.039 ± 0.008	-0.006	0.0032 ± 0.0008	0.082
CKM-suppressed mode				
(i) Color-favored mode				
$\Lambda_c^+ \to n a_1^+$	0.35 ± 0.12	0.017	0.26 ± 0.08	0.036
$\Xi_c^+ \to \Lambda a_1^+$	1.20 ± 0.24	-0.012	0.84 ± 0.25	0.014
$\Xi_c^+ \to \Sigma^0 a_1^+$	0.48 ± 0.10	-0.016	0.18 ± 0.04	0.048
$\Xi_c^0 \to \Sigma^- a_1^+$	0.14 ± 0.10	-0.024	0.033 ± 0.010	0.071
(ii) Color-suppressed mode				
$\Lambda_c^+ \to p a_1^0$	0.072 ± 0.014	0.011	0.035 ± 0.024	0.029
$\Lambda_c^+ \to p f_1$	0.10 ± 0.06	0.014	0.054 ± 0.043	0.032
$\Xi_c^+ \to \Sigma^+ a_1^0$	0.095 ± 0.019	-0.018	0.037 ± 0.007	0.045
$\Xi_c^0 \to \Lambda a_1^0$	0.0040 ± 0.0012	-0.028	0.076 ± 0.022	0.007
$\Xi_c^0 \to \Lambda f_1$	0.0034 ± 0.0007	-0.013	0.0021 ± 0.0004	0.051
$\Xi_c^0 \to \Sigma^0 a_1^0$	0.00044 ± 0.00035	0.072	0.0035 ± 0.0021	-0.057

[a]Factorizable contributions are calculated, respectively, using the form factors (Table I) evaluated in (a) NRQM and (b) on the basis of HQET considerations.

TABLE VIII. Branching ratios of decays acquiring pole contributions only.

Decay	Branching ratio (%)
CKM-favored mode	
$\Xi_c^0 \to \Sigma^+ K_1^-$	0.13 ± 0.03
CKM-suppressed mode	
$\Xi_c^+ \to p\bar{K}_1^0$	0.56 ± 0.19
$\Xi_c^+ \to p\bar{K}_{-1}^0$	0.14 ± 0.05
$\Xi_c^0 \to pK_1^-$	0.028 ± 0.007
$\Xi_c^0 \to pK_{-1}^-$	0.0068 ± 0.0017
$\Xi_c^0 \to n\bar{K}_1^0$	0.045 ± 0.020
$\Xi_c^0 \to n\bar{K}_{-1}^0$	0.011 ± 0.005
$\Xi_c^0 \to \Sigma^+ a_1^-$	0.016 ± 0.004

of CKM-suppressed $\Xi_c^+ \to p\bar{K}_1^0/p\bar{K}_{-1}^0$ decays. This is because the $\Xi_c^0 \to \Sigma^+ K_1^-$ decay suffers from kinematical suppression, since the momentum available is small.

(6) All of the decays involving b_1 and h_1 mesons in the final state remain forbidden in the isospin limit. However, the isospin breaking may generate $\Lambda_c^+ \to nb_1^+$, $\Xi_c^+ \to \Lambda b_1^+/\Sigma^0 b_1^+$, and $\Xi_c^0 \to \Sigma^- b_1^+$ decays in the CKM-suppressed mode, which in our analysis are found to have branching ratios of the order of $10^{-6}\%$.

(7) Because of the uncertainties in the hadronic factors, particularly the axial-vector meson decay constants and strong coupling constants, we find that the predicted branching ratios show 20%–60% variation depending on the relative strengths of the factorizable and pole contributions and their constructive or destructive interference.

(8) In general, asymmetry parameters for all of the decays are vanishingly small and are essentially unaffected due to the uncertainties of the hadronic factors. However, asymmetry of most of the Ξ_c decays, receiving factorizable contributions, show change in sign in the two models used to determine the baryon-baryon form factors.

(9) Naively, weak decays emitting axial-vector mesons are expected to be suppressed kinematically. However, we conclude that the branching ratios of the dominant modes in both CKM-favored and CKM-suppressed modes compete well with the measured values of the pseudoscalar/vector meson emitting decays of the charmed baryons. Therefore, efforts should be made to search for these decays experimentally.

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