

# A study of weak mesonic decays of $\Lambda_c$ and $\Xi_C$ baryons on the basis of HQET results

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Received: 14 May 1998 / Revised version: 25 August 1998 / Published online: 3 December 1998

**Abstract.** We investigate two-body Cabibbo-angle enhanced weak decays of charmed baryons into octet baryon and pseudoscalar meson in the current algebra framework with inclusion of the factorization terms which are evaluated using the HQET guided baryonic form factors. We obtain the branching ratios and asymmetry parameters for various Cabibbo-enhanced decays of  $\Lambda_c^+$ ,  $\Xi_c^+$  and  $\Xi_c^0$  baryons. Sensitivity of the flavor dependence of the spatial wavefunction overlap on the branching ratios and asymmetry parameters is also investigated.

## 1 Introduction

A significant progress in the experimental determination of masses, lifetimes of charmed baryons and their decays has taken place during the last few years. Masses of the charm unity baryons have been measured within accuracy of a few percent. Charmed baryons can decay through numerous channels. However, data on their exclusive weak decays are available mainly for  $\Lambda_c^+$  baryon [1], though, a few decay modes of  $\Xi_c^+$  baryon have also been observed [2]. Recently, the asymmetry parameters of  $\Lambda_c^+ \rightarrow \Lambda\pi^+$  and  $\Lambda_c^+ \rightarrow \Sigma^+\pi^0$  decays have been measured by the CLEO collaboration [3]. In the near future a large quantity of new and more accurate data on the exclusive nonleptonic decays of heavy baryon can be expected which calls for a comprehensive analysis of these decays.

Even the meager data available for the charm baryon decays have already started to distinguish between various theoretical models. These models have been developed employing the flavor symmetries [4], factorization [5], pole model [6–8], current algebra [9, 10] frameworks. So far none of these attempts has been able to explain the available data on the nonleptonic decays of the charmed baryons. The analysis of weak hadronic decays of baryons gets complicated by their being the three quark systems. Further, it is not straightforward to estimate the strong interaction effects on their decays. Initially, it was hoped that like meson decays the spectator quark processes would dominate charm baryon decays also. However, this scheme does not seem to be supported by the experiment as the observed branching ratios of  $\Lambda_c^+ \rightarrow \Sigma^+\pi^0$ ,  $\Lambda_c^+ \rightarrow \Sigma^0\pi^+$ ,  $\Lambda_c^+ \rightarrow \Sigma^+\eta$  and  $\Lambda_c^+ \rightarrow \Xi^0 K^+$  decays, forbidden by the spectator quark process, are significantly large thereby indicating the need of the W-exchange contributions. Unlike

the mesons, W-exchange seems to play a dramatic role in the charmed baryon decays, as this mechanism is neither helicity nor color suppressed in baryon decays due to the presence of a scalar diquark system inside the baryons. Theoretically the contribution from this process has been expected to be proportional to  $|\psi(0)|^2$ , which renders it quite significant for these decays.

For two-body baryon decays, W-emission process leads to the factorization which expresses decay amplitude as coupling of weak baryon transition with the meson current. The matrix elements of the weak transition between baryon states in general involve six form factors which control the factorization contributions [5]. Fortunately, in the past few years the discovery of new flavor and spin symmetries has simplified the heavy flavor physics [11]. In the framework of Heavy Quark Effective Theory (HQET), the form factors get mutually related, though  $1/M$  corrections are certainly needed [12, 13]. At present one does not know how to carry out these corrections from first principles particularly for heavy to light baryon transitions and one takes the help of phenomenological models. Recently, Cheng and Tseng [14] have determined such corrections to the baryonic form factors in the nonrelativistic quark model, which gives excellent agreement with the experimental value for the only measured semileptonic decay  $\Lambda_c^+ \rightarrow \Lambda e^+\nu_e$ . Similar result has also been obtained by Ivanov et al. in a relativistic three quark model [15]. It is worth remarkable here that the agreement has been achieved due to the flavor-suppression factor, resulting from the HQET considerations, for the factorizable contribution. The full implications of this feature for the nonleptonic decays of the charmed baryons is yet to be considered.

In the present work, we study Cabibbo-enhanced two-body weak decays of  $\Lambda_c^+$ ,  $\Xi_c^+$  and  $\Xi_c^0$  into octet baryons ( $J^P = 1/2^+$ ) and a pseudoscalar meson ( $J^P = 0^-$ ). We

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include the factorization terms using the HQET guided form factors and the nonspectator contributions. Since current algebra is the most common approach used before for the study of the nonleptonic decays, we employ it to obtain the nonspectator contributions. Sect. 2 describes the methodology of the calculations. Sect. 3 deals with the numerical results for branching ratios and asymmetries of the charmed baryon decays and their comparison with the available data. Here, we also study the effect of flavor dependence of the  $|\psi(0)|^2$  on these decays. In our analysis, we find that all factorization, pole and equal time current commutator (ETC) terms are equally important in the charm baryon decays, though, one may dominate over other depending upon the decay channel.

## 2 Methodology

### 2.1 Weak Hamiltonian

The general weak current  $\otimes$  current weak Hamiltonian for Cabibbo enhanced ( $\Delta C = \Delta S = -1$ ) decays in terms of the quark fields is

$$H_W = \frac{G_F}{\sqrt{2}} V_{ud} V_{cs}^* [c_1 (\bar{u}d) (\bar{s}c) + c_2 (\bar{s}d) (\bar{u}c)], \quad (1)$$

where  $\bar{q}_1 q_2 \equiv \bar{q}_1 \gamma_\mu (1 - \gamma_5) q_2$  represents the color-singlet combination.  $V_{ud}$  and  $V_{cs}$  are the Cabibbo-Kobayashi-Maskawa (CKM) weak mixing matrix elements. The perturbative QCD coefficients for the charm sector,  $c_1 = \frac{1}{2}(c_+ + c_-) = 1.26 \pm 0.04$  and  $c_2 = \frac{1}{2}(c_+ - c_-) = -0.51 \pm 0.05$ , are usually taken at the charm mass scale [16].

### 2.2 Decay width and asymmetry formulas

The matrix element for the baryon  $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+ + 0^-$  decay process is written as

$$M = -\langle B_f P | H_W | B_i \rangle = i \bar{u}_{B_f} (A - \gamma_5 B) u_{B_i} \phi_P, \quad (2)$$

where  $A$  and  $B$  represent the parity violating (PV) and the parity conserving (PC) amplitudes respectively. The decay width is computed from

$$\Gamma = C_1 [|A|^2 + C_2 |B|^2], \quad (3)$$

where

$$C_1 = \frac{|\mathbf{q}|}{8\pi} \frac{(m_i + m_f)^2 - m_P^2}{m_i^2}, \quad (4)$$

$$C_2 = \frac{(m_i - m_f)^2 - m_P^2}{(m_i + m_f)^2 + m_P^2}, \quad (5)$$

and

$$|\mathbf{q}| = \frac{1}{2m_i} \sqrt{[m_i^2 - (m_f - m_P)^2][m_i^2 - (m_f + m_P)^2]}, \quad (6)$$

is the magnitude of centre of mass three-momentum in the rest frame of the parent particle.  $m_i$  and  $m_f$  are the

masses of the initial and final baryons and  $m_P$  is the mass of the emitted meson. Asymmetry parameter is given by

$$\alpha = \frac{2\text{Re}(A\bar{B}^*)}{(|A|^2 + |B|^2)}, \quad (7)$$

where  $\bar{B} = \sqrt{C_2} B$ .

### 2.3 Decay amplitudes

It is now established that dominance of the factorizable contributions to the nonleptonic weak decays of charm baryons has lost its theoretical support. Present available data now clearly demands the introduction of the nonfactorizable terms for these decays. Generalising the current algebra (CA) framework of the hyperon decays [9, 10] to the charm sector, nonfactorizable terms for the charmed baryon decay amplitudes receive contributions from the pole diagrams involving the W-exchange process and the ETC term. Thus the nonleptonic decay amplitude may be written as

$$\langle B_f P | H_W | B_i \rangle = M_{fac} + M_{ETC} + M_{pole}. \quad (8)$$

The factorizable part  $M_{fac}$  is obtained using the standard vacuum insertion technique, which expresses it as a product of two current matrix elements which vanish in the soft meson limit. Thus it may be viewed as a correction to the current algebra framework.

It may still be noted that this is at best an empirical approach and does not answer the deeper conceptual issues, like renormalization scale dependence, for the nonleptonic weak decays. We discuss the contribution of each of these terms in the context of PC and PV amplitudes.

#### 2.3.1 Factorization contributions

The first term  $M_{fac}$  in (8), corresponding to the factorization contribution, can be obtained by inserting vacuum intermediate states, which express it as a product of two current matrix elements [5];

$$\langle P | A_\mu | 0 \rangle \langle B_f(P_f) | V^\mu - A^\mu | B_i(P_i) \rangle \quad (9)$$

where

$$\langle P | A_\mu | 0 \rangle = i f_P q_\mu \quad (10)$$

with  $q_\mu$  being the meson four momenta, and  $f_P$  is the decay constant of the meson emitted. The matrix element for the baryonic transition  $B_i \rightarrow B_f$  can be expanded as

$$\begin{aligned} \langle B_f(P_f) | V_\mu | B_i(P_i) \rangle &= \bar{u}_f(P_f) [f_1(q^2) \gamma_\mu \\ &\quad + i f_2(q^2) \sigma_{\mu\nu} q^\nu + f_3(q^2) q_\mu] u_i(P_i), \end{aligned} \quad (11)$$

$$\begin{aligned} \langle B_f(P_f) | A_\mu | B_i(P_i) \rangle &= \bar{u}_f(P_f) [g_1(q^2) \gamma_\mu \\ &\quad + i g_2(q^2) \sigma_{\mu\nu} q^\nu + g_3(q^2) q_\mu] \gamma_5 u_i(P_i), \end{aligned} \quad (12)$$

where  $f_i$ 's and  $g_i$ 's are the vector and axial vector form factors. In the HQET framework, the matrix elements can be parameterised [11] in terms of the baryon velocities  $v$  and  $v'$ ,

$$\langle B_f(v')|V_\mu|B_i(v)\rangle = \bar{u}_f[F_1(\omega)\gamma_\mu + F_2(\omega)v_\mu + F_3(\omega)v'_\mu]u_i, \quad (13)$$

$$\langle B_f(v')|A_\mu|B_i(v)\rangle = \bar{u}_f[G_1(\omega)\gamma_\mu + G_2(\omega)v_\mu + G_3(\omega)v'_\mu]\gamma_5 u_i, \quad (14)$$

with  $\omega = v \cdot v'$ . The form factors  $f_i$ 's and  $g_i$ 's are related to  $F_i$ 's and  $G_i$ 's via

$$f_1 = F_1 + \frac{1}{2}(m_i + m_f) \left( \frac{F_2}{m_i} + \frac{F_3}{m_f} \right), \quad (15)$$

$$f_2 = \frac{1}{2} \left( \frac{F_2}{m_i} + \frac{F_3}{m_f} \right), \quad (16)$$

$$f_3 = \frac{1}{2} \left( \frac{F_2}{m_i} - \frac{F_3}{m_f} \right), \quad (17)$$

$$g_1 = G_1 - \frac{1}{2}(\Delta m) \left( \frac{G_2}{m_i} + \frac{G_3}{m_f} \right), \quad (18)$$

$$g_2 = \frac{1}{2} \left( \frac{G_2}{m_i} + \frac{G_3}{m_f} \right), \quad (19)$$

$$g_3 = \frac{1}{2} \left( \frac{G_2}{m_i} - \frac{G_3}{m_f} \right), \quad (20)$$

where  $\Delta m = m_i - m_f$ . Employing the nonrelativistic quark model framework, Cheng and Tseng [14] have calculated these form factors at maximum  $q^2$ ,

$$\begin{aligned} \frac{f_1(q_m^2)}{N_{fi}} &= 1 - \frac{\Delta m}{2m_i} + \frac{\Delta m}{4m_i m_f} \left( 1 - \frac{\bar{\Lambda}}{2m_f} \right) \\ &\quad \times (m_i + m_f - \eta \Delta m) \\ &\quad - \frac{\Delta m}{8m_i m_f} \frac{\bar{\Lambda}}{m_Q} (m_i + m_f + \eta \Delta m), \end{aligned} \quad (21)$$

$$\frac{g_1(q_m^2)}{N'_{fi}} = 1 + \frac{\Delta m \bar{\Lambda}}{4} \left( \frac{1}{m_i m_q} - \frac{1}{m_f m_Q} \right), \quad (22)$$

where  $\eta = N'_{fi}/N_{fi}$ ,  $\bar{\Lambda} = m_f - m_q$  and  $q_m^2 = (\Delta m)^2$  denotes the maximum  $q^2$  transfer.  $N_{fi}$  and  $N'_{fi}$  are the flavor factors,

$$N_{fi} = \text{flavor-spin} \langle B_f | b_q^\dagger b_Q | B_i \rangle_{\text{flavour-spin}}, \quad (23)$$

$$N'_{fi} = \text{flavor-spin} \langle B_f | b_q^\dagger \sigma_z^Q b_Q | B_i \rangle_{\text{flavour-spin}}, \quad (24)$$

for the heavy quark  $Q$  in the parent baryon  $B_i$  transiting into the light quark  $q$  in the daughter baryon  $B_f$ .  $m_Q$  and  $m_q$  denote masses of these heavy and light quarks respectively. The light diquark present in the parent baryon behaves as spectator. In the absence of a direct evaluation,  $q^2$  dependence of the baryonic form factors can be realized by assuming a pole dominance of the form,

$$f(q^2) = \frac{f(0)}{\left(1 - \frac{q^2}{m_V^2}\right)^n}, \quad (25)$$

$$g(q^2) = \frac{g(0)}{\left(1 - \frac{q^2}{m_A^2}\right)^n}, \quad (26)$$

where  $m_V$  and  $m_A$  denote, respectively, pole masses of the vector meson and axial-vector meson having the quantum numbers of the current involved. Generally for the baryons, one takes  $n = 2$ .

Upto the first order of parameterization, the factorization amplitudes are given by

$$A_{fac} = -\frac{G_F}{\sqrt{2}} F_C f_P a_k (m_i - m_f) f_1^{B_i B_f}(m_P^2), \quad (27)$$

$$B_{fac} = \frac{G_F}{\sqrt{2}} F_C f_P a_k (m_i + m_f) g_1^{B_i B_f}(m_P^2). \quad (28)$$

$F_C$  is the CKM factor.  $a$ 's are the two undetermined coefficients assigned to the effective charged current,  $a_1$ , and the effective neutral current,  $a_2$ , parts of the weak Hamiltonian given in (1). Values of these parameters can be related to the QCD coefficients as

$$a_{1,2} = c_{1,2} + \zeta c_{2,1}, \quad (29)$$

where  $\zeta = 1/N_{color}$ . The values

$$a_1 = 1.26, \quad a_2 = -0.51, \quad (30)$$

give the best fit to the experimental data on charm meson decays corresponding to  $\zeta \rightarrow 0$  [16]. In this approach, the quark currents of weak Hamiltonian are considered as interpolating meson fields generating a  $q\bar{q}$  state. The factorization contributions, being proportional to the meson momenta, can be considered as the correction to the decay amplitudes obtained in the CA framework which employs the soft meson limit.

### 2.3.2 ETC and pole contributions

The second term  $M_{ETC}$  in (8), corresponding to the equal time current commutator (ETC), is given by the matrix element of  $H_W$  between the initial and the final state baryons,

$$\langle B_f | H_W | B_i \rangle = \bar{u}_f(P_f)(a_{if} - b_{if}\gamma_5)u_i(P_i). \quad (31)$$

It is well known that the PV matrix elements  $b_{if}$  vanish for the hyperons due to C-parity null theorem [9] in the flavor symmetry limit. In the case of the charm baryon decays, in analogy with hyperons, it has been shown that  $b_{if} \ll a_{if}$ . Hence, the ETC term enters only in the s-wave (PV) amplitudes;

$$A^{ETC} = \frac{1}{f_k} \langle B_f | [Q_k^5, H_w^{PV}] | B_i \rangle = \frac{1}{f_k} \langle B_f | [Q_k, H_w^{PC}] | B_i \rangle, \quad (32)$$

where  $Q_k$  and  $Q_k^5$  denote the vector and axial vector charges respectively. The p-wave (PC) decay amplitudes are then described by the  $J^P = 1/2^+$  pole terms ( $M_{pole}$ ).

The baryon pole terms, arising from s- and u-channels contributions to PC decay amplitude, are given by

$$B_{pole} = \frac{g_{\ell f k} a_{i\ell}}{m_i - m_\ell} \frac{m_i + m_f}{m_\ell + m_f} + \frac{g_{i\ell' k} a_{\ell' f}}{m_f - m_{\ell'}} \frac{m_i + m_f}{m_i + m_{\ell'}}, \quad (33)$$

where  $g_{ijk}$  are the strong baryon-baryon coupling constants,  $\ell$  and  $\ell'$  are the intermediate states – corresponding to the respective s- and u-channels. This pole contribution differs from the simple pole model calculations due to the appearance of extra mass factors. This term is actually a modified pole term and contains the contributions from the surface term, the soft-meson Born-term contraction and the baryon-pole term [9], combined in a well-defined way. It has been pointed out by Karlsen and Scadron [10] that in this way this term accounts for the large momentum dependence away from the soft pion limit as occurs in the charmed baryon decays. The weak matrix elements  $a_{ij}$  for baryonic transition  $B_i \rightarrow B_f$  are evaluated in the constituent quark model following the work of Riazuddin and Fayyazuddin [17]. For the strong baryon-meson coupling constants  $g_{ijk}$ , we introduce SU(4) breaking effects [18] through

$$g_{BB'P} = \frac{M_B + M_{B'}}{2M_N} g_{BB'P}^{sym}, \quad (34)$$

where  $g_{BB'P}^{sym}$  denotes the SU(4) symmetric coupling.

### 3 Numerical calculations and discussion of results

We first determine the factorizable contributions to the Cabibbo-angle enhanced decays of  $\Lambda_c^+$  baryon using the HQET guided form factors, which have been calculated earlier in the nonrelativistic quark model framework [14];

$$f_1^{\Lambda_c \Lambda} = 0.50 N_{\Lambda_c \Lambda}, \quad g_1^{\Lambda_c \Lambda} = 0.65 N_{\Lambda_c \Lambda}; \quad (35)$$

$$f_1^{\Lambda_c p} = 0.34 N_{\Lambda_c p}, \quad g_1^{\Lambda_c p} = 0.53 N_{\Lambda_c p}, \quad (36)$$

where the flavor-spin factors are

$$N'_{\Lambda_c \Lambda} = N_{\Lambda_c \Lambda} = \frac{1}{\sqrt{3}}; \quad N'_{\Lambda_c p} = N_{\Lambda_c p} = \frac{1}{\sqrt{2}}. \quad (37)$$

Reliability of these form factors has been well tested by computing decay width of the semileptonic mode  $\Lambda_c^+ \rightarrow \Lambda^+ \nu_e$ ,

$$\Gamma(\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e) = 7.1 \times 10^{10} \text{ s}^{-1} \quad (38)$$

which is consistent with the experimental value [1]. It is worth pointing that the flavor factors  $N_{\Lambda_c \Lambda}$  plays a crucial role for the agreement. Earlier theoretical models [19] have given quite large values for this semileptonic decay rate. The weak Hamiltonian (1) allows only  $\Lambda_c^+ \rightarrow p \bar{K}^0 / \Lambda \pi^+$  decays to receive the factorization contributions. For these decays, the form factors given in (35) and (36) yield the following branching ratios and asymmetries:

$$Br(\Lambda_c^+ \rightarrow p \bar{K}^0) = 0.48\% \quad ((2.2 \pm 0.4)\% \text{ Expt.}), \quad (39)$$

$$\alpha(\Lambda_c^+ \rightarrow p \bar{K}^0) = -0.94, \quad (40)$$

$$Br(\Lambda_c^+ \rightarrow \Lambda \pi^+) = 1.29\% \quad ((0.79 \pm 0.18)\% \text{ Expt.}), \quad (41)$$

$$\alpha(\Lambda_c^+ \rightarrow \Lambda \pi^+) = -0.97 \quad (-0.94 \pm 0.29 \text{ Expt.}). \quad (42)$$

Though, the asymmetry of  $\Lambda_c^+ \rightarrow \Lambda \pi^+$  is in good agreement with experiment, its branching ratio is rather large. In contrast, branching ratio of  $\Lambda_c^+ \rightarrow p \bar{K}^0$ , is much less than the experimental value. Thus, the spectator contributions alone cannot explain even these decays. The branching ratio of  $\pi^+$  emitting mode is greater than that of the  $\bar{K}^0$  emitting mode due to the color enhancement factor  $(a_1/a_2)^2$ . However, in a typical  $\pi^+$  emitting decay  $\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$ , the factorization term vanishes due to the Clebsch-Gordon coefficient. It proceeds only through the nonspectator processes, which are also responsible for the remaining  $\Lambda_c^+$  decays where the factorization terms do not appear. Accurate experimental measurements of these decays can clearly determine the relative strength of the nonspectator terms in the charmed baryon decays.

In our framework, nonspectator ETC and pole terms involve the matrix elements of the kind  $\langle B_f | H_W^{PC} | B_i \rangle$ . We evaluate such matrix elements following the scheme of Riazuddin and Fayyazuddin [17], which gives the nonrelativistic reduction of the PC-Hamiltonian,

$$H_W^{PC} = c_-(m_c)(s^\dagger c u^\dagger d - s^\dagger \sigma c \cdot u^\dagger \sigma d) \delta^3(\mathbf{r}). \quad (43)$$

Note that only  $c_-$  appears in this limit, because the part of Hamiltonian corresponding to  $c_+$  is symmetric in the color indices. We take the QCD enhancement at the charm mass scale  $c_-(m_c) = 1.75$ , which is lower than  $c_-(m_s) = 2.23$  used in the hyperon sector. To reduce the number of free parameters, we determine the scale for the ETC and pole terms using

$$\langle \psi_\Lambda | \delta^3(r) | \psi_{\Lambda_c^+} \rangle \approx \langle \psi_p | \delta^3(r) | \psi_{\Sigma^+} \rangle. \quad (44)$$

Combining all the ingredients of PV and PC decay amplitudes, we compute the branching ratios and asymmetries for various decays. These are given in the Table 1. Experimentally measured [1] masses, lifetimes, and decay constants have been used in the present analysis. Comparing the theoretical values with those obtained in the pure factorization case, we find that inclusion of the nonspectator terms modifies the branching ratios in the desired direction without affecting the asymmetry parameters. We make the following observations:

**1.** The branching fraction for  $\Lambda_c^+ \rightarrow p \bar{K}^0$  increases from 0.48% to 1.23% bringing it closer to the experiment. The increase in the branching ratio occurs due to constructive interference between the ETC and factorization terms, comparable in magnitude, in the PV mode. Similarly for the PC mode also, the pole and factorization terms interfere constructively, though the pole contribution is around 30% only. We predict its asymmetry  $\alpha(\Lambda_c^+ \rightarrow p \bar{K}^0) = -0.99$ .

**2.** For the decay  $\Lambda_c^+ \rightarrow \Lambda \pi^+$ , the branching ratio decreases from 1.29% to 1.17% in the right direction. For this decay, the ETC contribution vanishes, so its PV amplitude is given only by the factorization term. For its PC amplitude, there exists a destructive interference between the pole and factorization contributions for the choice of the form factors given in (35). We wish to remark that even if the pole and factorization terms interfere constructively, its branching ratio would hardly be raised to 1.44%.

**Table 1.** Branching ratios and asymmetries of charmed baryon decays ( $r = 1$ )

Decay	Br.(%)	Expt. Br. (%)	$\alpha$	Expt. $\alpha$
$\Lambda_c^+ \rightarrow p\bar{K}^0$	1.23	$2.2 \pm 0.4$	-0.99	
$\Lambda_c^+ \rightarrow \Lambda\pi^+$	1.17	$0.79 \pm 0.18$	-0.99	$-0.94 \pm 0.24$
$\Lambda_c^+ \rightarrow \Sigma^+\pi^0$	0.69	$0.88 \pm 0.22$	-0.31	$-0.45 \pm 0.31$
$\Lambda_c^+ \rightarrow \Sigma^+\eta$	$0.25^a (0.21^b)$	$0.48 \pm 0.17$	$-0.99^a (-0.96^b)$	
$\Lambda_c^+ \rightarrow \Sigma^+\eta'$	$0.08^a (0.11^b)$		$+0.44^a (+0.20^b)$	
$\Lambda_c^+ \rightarrow \Sigma^0\pi^+$	0.69	$0.88 \pm 0.20$	-0.31	
$\Lambda_c^+ \rightarrow \Xi^0 K^+$	0.07	$0.34 \pm 0.09$	0.00	
$\Xi_c^+ \rightarrow \Xi^0\pi^+$	1.08	$1.2 \pm 0.5 \pm 0.3$	-0.74	
$\Xi_c^+ \rightarrow \Sigma^+\bar{K}^0$	0.08		-0.38	
$\Xi_c^0 \rightarrow \Xi^0\pi^0$	0.44		-0.80	
$\Xi_c^0 \rightarrow \Xi^0\eta$	$0.07^a (0.04^b)$		$-0.45^a (-0.37^b)$	
$\Xi_c^0 \rightarrow \Xi^0\eta'$	$0.05^a (0.07^b)$		$+0.65^a (+0.56^b)$	
$\Xi_c^0 \rightarrow \Xi^-\pi^+$	1.99		-0.99	
$\Xi_c^0 \rightarrow \Sigma^+K^-$	0.06		0.00	
$\Xi_c^0 \rightarrow \Sigma^0\bar{K}^0$	0.08		-0.15	
$\Xi_c^0 \rightarrow \Lambda\bar{K}^0$	0.34		-0.85	

$$a = \phi_{\eta-\eta'} = -10^\circ, \quad b = \phi_{\eta-\eta'} = -23^\circ$$

This is due to the reason that the pole terms in s- and u-channels tend to cancel each other thereby reducing the pole strength to around 10% of the factorization. We obtain its asymmetry  $\alpha(\Lambda_c^+ \rightarrow \Lambda\pi^+) = -0.99$  in nice agreement with the experimental value

$$\alpha(\Lambda_c^+ \rightarrow \Lambda\pi^+) = -0.94_{-0.06}^{+0.21} {}_{-0.06}^{+0.12}$$

recently measured by the CLEO collaboration [3]. By combining this value with the previously measured decay rate [1]:

$$\Gamma(\Lambda_c^+ \rightarrow \Lambda\pi^+) = (0.40 \pm 0.11) \times 10^{11} \text{ s}^{-1}$$

the followings sets of PV and PC amplitudes (in the units of  $G_F V_{ud} V_{cs}^* \times 10^{-2} \text{ GeV}^2$ ) are given by the CLEO collaboration [3]:

$$\begin{aligned} \text{Set I} : A(\Lambda_c^+ \rightarrow \Lambda\pi^+) &= -3.0_{-1.2}^{+0.8}, \\ B(\Lambda_c^+ \rightarrow \Lambda\pi^+) &= +12.7_{-2.5}^{+2.7}; \end{aligned} \quad (45)$$

$$\begin{aligned} \text{Set II} : A(\Lambda_c^+ \rightarrow \Lambda\pi^+) &= -4.3_{-0.9}^{+0.8}, \\ B(\Lambda_c^+ \rightarrow \Lambda\pi^+) &= +8.9_{-2.4}^{+3.4}. \end{aligned} \quad (46)$$

Our analysis gives

$$A(\Lambda_c^+ \rightarrow \Lambda\pi^+) = -4.6, \quad B(\Lambda_c^+ \rightarrow \Lambda\pi^+) = +15.8, \quad (47)$$

which seem to favor the first set. As this decay occurs largely through the spectator quark process, the present data seems to demand lower values of the form factors involved, or more accurate measurement is desired to clarify the situation.

**3.** The same CLEO experiment [3] has measured the asymmetry of  $\Lambda_c^+ \rightarrow \Sigma^+\pi^0$  decay,

$$\alpha(\Lambda_c^+ \rightarrow \Sigma^+\pi^0) = -0.45 \pm 0.31, \quad (48)$$

which is in good agreement with our prediction,

$$\alpha(\Lambda_c^+ \rightarrow \Sigma^+\pi^0) = -0.31. \quad (49)$$

In contrast, earlier theoretical efforts [6–8] have given large positive value, ranging from 0.78 to 0.92, for this asymmetry parameter. The calculated branching ratio in our analysis,

$$Br(\Lambda_c^+ \rightarrow \Sigma^+\pi^0) = 0.69\% ((0.88 \pm 0.22)\% \text{ Expt.}), \quad (50)$$

also matches well the experimental value. Considering the PV and PC amplitudes explicitly, the CLEO collaboration [3] gives the following values (in the units of  $G_F V_{ud} V_{cs}^* \times 10^{-2} \text{ GeV}^2$ ):

$$\begin{aligned} \text{Set I} : A(\Lambda_c^+ \rightarrow \Sigma^+\pi^0) &= +1.3_{-1.1}^{+0.9}, \\ B(\Lambda_c^+ \rightarrow \Sigma^+\pi^0) &= -17.3_{-2.9}^{+2.3}; \end{aligned} \quad (51)$$

$$\begin{aligned} \text{Set II} : A(\Lambda_c^+ \rightarrow \Sigma^+\pi^0) &= +5.4_{-0.7}^{+0.9}, \\ B(\Lambda_c^+ \rightarrow \Sigma^+\pi^0) &= -4.1_{-3.0}^{+3.4}. \end{aligned} \quad (52)$$

For these decay amplitudes, we obtain,

$$A(\Lambda_c^+ \rightarrow \Sigma^+\pi^0) = +5.4; \quad B(\Lambda_c^+ \rightarrow \Sigma^+\pi^0) = -2.7, \quad (53)$$

consistent with the second set.

**4.** For  $\Lambda_c^+ \rightarrow \Sigma^0\pi^+$  decay, our analysis yields,

$$Br(\Lambda_c^+ \rightarrow \Sigma^0\pi^+) = 0.69\% ((0.88 \pm 0.20)\% \text{ Expt.}), \quad (54)$$

agreeing well with the experiment, and the asymmetry  $\alpha(\Lambda_c^+ \rightarrow \Sigma^0\pi^+) = -0.31$ , i.e. the same as that of the  $\Lambda_c^+ \rightarrow \Sigma^+\pi^0$ , as expected from the isospin symmetry arguments.

**Table 2.** Branching ratios and asymmetries of charmed baryons ( $r = 1.4$ )

Decay	Br.(%)	Expt. Br. (%)	$\alpha$	Expt. $\alpha$
$\Lambda_c^+ \rightarrow p\bar{K}^0$	1.64	$2.2 \pm 0.4$	-0.98	
$\Lambda_c^+ \rightarrow \Lambda\pi^+$	1.12	$0.79 \pm 0.18$	-0.99	$-0.94 \pm 0.24$
$\Lambda_c^+ \rightarrow \Sigma^+\pi^0$	1.34	$0.88 \pm 0.22$	-0.31	$-0.45 \pm 0.31$
$\Lambda_c^+ \rightarrow \Sigma^+\eta$	$0.49^a (0.41^b)$	$0.48 \pm 0.17$	$-0.99^a (-0.97^b)$	
$\Lambda_c^+ \rightarrow \Sigma^+\eta'$	$0.16^a (0.21^b)$		$+0.44^a (+0.20^b)$	
$\Lambda_c^+ \rightarrow \Sigma^0\pi^+$	1.34	$0.88 \pm 0.20$	-0.31	
$\Lambda_c^+ \rightarrow \Xi^0 K^+$	0.13	$0.34 \pm 0.09$	0.00	
$\Xi_c^+ \rightarrow \Xi^0\pi^+$	0.53	$1.2 \pm 0.5 \pm 0.3$	-0.27	
$\Xi_c^+ \rightarrow \Sigma^+\bar{K}^0$	0.04		+0.54	
$\Xi_c^0 \rightarrow \Xi^0\pi^0$	0.87		-0.80	
$\Xi_c^0 \rightarrow \Xi^0\eta$	$0.14^a (0.09^b)$		$-0.45^a (-0.37^b)$	
$\Xi_c^0 \rightarrow \Xi^0\eta'$	$0.11^a (0.14^b)$		$+0.66^a (+0.56^b)$	
$\Xi_c^0 \rightarrow \Xi^-\pi^+$	2.46		-0.97	
$\Xi_c^0 \rightarrow \Sigma^+K^-$	0.12		0.00	
$\Xi_c^0 \rightarrow \Sigma^0\bar{K}^0$	0.07		+0.48	
$\Xi_c^0 \rightarrow \Lambda\bar{K}^0$	0.54		-0.79	

$$a = \phi_{\eta-\eta'} = -10^\circ, \quad b = \phi_{\eta-\eta'} = -23^\circ$$

5. For  $\eta - \eta'$  emitting decays, we calculate:

$$Br(\Lambda_c^+ \rightarrow \Sigma^+\eta) = 0.25\% ((0.48 \pm 0.17)\% \text{ Expt.}), \quad (55)$$

$$\alpha(\Lambda_c^+ \rightarrow \Sigma^+\eta) = -0.99; \quad (56)$$

$$Br(\Lambda_c^+ \rightarrow \Sigma^+\eta') = 0.08\%, \quad (57)$$

$$\alpha(\Lambda_c^+ \rightarrow \Sigma^+\eta') = +0.44; \quad (58)$$

for the  $\eta - \eta'$  physical mixing angle  $-10^\circ$ . Here the branching ratio of  $\Lambda_c^+ \rightarrow \Sigma^+ + \eta$  decay remains small for another choice of the mixing angle ( $-23^\circ$ ).

6. The decay  $\Lambda_c^+ \rightarrow \Xi^0 K^+$  is theoretically the cleanest of all the  $\Lambda_c^+$  decays as it acquires only p-wave contribution to its decay amplitude and has null asymmetry. For this mode, we obtain

$$Br(\Lambda_c^+ \rightarrow \Xi^0 K^+) = 0.07\% ((0.34 \pm 0.09)\% \text{ Expt.}), \quad (59)$$

which is smaller than the experimental value.

7. Among the  $\Xi_c^+$  decays, there are only two possible modes. Recently, the branching ratio of  $\Xi_c^+ \rightarrow \Xi^0\pi^+$  decay has also been measured in a CLEO experiment [2], for which our analysis yields,

$$Br(\Xi_c^+ \rightarrow \Xi^0\pi^+) = 1.08\% ((1.2 \pm 0.5 \pm 0.3)\% \text{ Expt.}), \quad (60)$$

in excellent agreement with experiment. It may be remarked that though, both the  $\Xi_c^+$  modes get contributions from the factorization, pole, and ETC terms, yet the decay ( $\Xi_c^+ \rightarrow \Xi^0\pi^+$ ) dominates over ( $\Xi_c^+ \rightarrow \Sigma^+\bar{K}^0$ ) by an order of magnitude

$$\frac{Br(\Xi_c^+ \rightarrow \Xi^0\pi^+)}{Br(\Xi_c^+ \rightarrow \Sigma^+\bar{K}^0)} = 13.2. \quad (61)$$

8. Among  $\Xi_c^0$  decays, we find that the dominant mode is  $\Xi_c^0 \rightarrow \Xi^-\pi^+$  which has branching ratio around 2% in our model.

### 3.1 Variation of $|\psi(0)|^2$

So far, we have taken the scale  $|\psi(0)|^2$  for the nonspectator terms same as that of the hyperon sector. However, this being a dimensional quantity, it may be incorrect to ignore its variation with flavor. Unfortunately, evaluation of  $|\psi(0)|^2$  is as yet uncertain for the baryons and more complicated, because unlike mesons these are three body systems. Experimental hyperfine splitting may provide a reliable measure of the wave function at the origin of the ground state baryon. The hyperfine splitting is given by the matrix element of the spin-spin interaction,

$$\Delta E_{HFS} = \frac{4\pi\alpha_s}{9m_1m_2} |\psi(0)|^2 \langle \sigma_1 \cdot \sigma_2 \rangle. \quad (62)$$

Using the constituent quark model developed by De Rújula et al. [20], we obtain the following ratio of the hyperfine splitting in the strange and charm sectors;

$$\frac{\Sigma_c - \Lambda_c}{\Sigma - \Lambda} = \frac{|\psi(0)|_c^2}{|\psi(0)|_s^2} \frac{\alpha_s(m_c)}{\alpha_s(m_s)} \frac{m_s(m_c - m_u)}{m_c(m_s - m_u)}. \quad (63)$$

For the choice  $\alpha_s(m_c)/\alpha_s(m_s) \approx 0.53$ , we obtain,  $r \equiv |\psi(0)|_c^2/|\psi(0)|_s^2 \approx 2.1$ . However, we do not expect this ratio to hold for the weak decays considered in the present work, as the weak baryon transitions occurring in the charmed baryon decays involve  ${}_s\langle \psi | \delta^3(\mathbf{r}) | \psi \rangle_c$  for which  $r$  should lie between 1 and 2. We have investigated the implications of this scale ratio, varying from 1 to 2, on the branching ratios and asymmetry parameters. We make the following observations:

1. Asymmetry of all the decays, except those of  $\Xi_c \rightarrow \Sigma + \bar{K}^0$ , remain almost unaffected and stay in good agreement with the experiment. Asymmetry of the  $\Xi_c \rightarrow \Sigma + \bar{K}^0$  decays show change in sign if scale parameter is increased.

2. Branching ratios of  $\Lambda_c^+ \rightarrow p\bar{K}^0/\Lambda\pi^+/\Xi^0 K^+$  decays are found to require this ratio on the higher side (1.5 to 2.1) for better agreement with the experiment, whereas the  $\Lambda_c^+ \rightarrow \Sigma\pi/\eta$  decays prefer a small enhancement ratio (1.1 to 1.3).
3. Ratio of the decay rates,

$$\frac{Br(\Lambda_c^+ \rightarrow \Lambda\pi^+)}{Br(\Lambda_c^+ \rightarrow p\bar{K}^0)} = (0.92 \text{ to } 0.40), \quad (64)$$

for the chosen range ( $r = 1$  to  $2$ ) approaching the experimental value  $0.36 \pm 0.10$ . It may be noticed that this ratio has been theoretically estimated to be as high as 13 in some of the earlier models due to the expected color enhancement.

4. The scale ratio certainly increases the branching ratio of  $\Lambda_c^+ \rightarrow \Xi^0 K^+$  as desired by the experiment. Since all the decays  $\Lambda_c^+ \rightarrow \Sigma^+\pi^0/\Sigma^0\pi^+$ ,  $\Lambda_c^+ \rightarrow \Sigma^+\eta/\Sigma^+\eta'$  and  $\Lambda_c^+ \rightarrow \Xi^0 K^+$  occur only through the nonspectator terms, their relative ratios remain independent of the scale factor in our analysis.

5. We expect the ratio  $r$  to lie close to 1.4 using the following ansatz:

$$({}_s\langle\psi|\delta^3(\mathbf{r})|\psi\rangle_c)^2 \approx {}_s\langle\psi|\delta^3(\mathbf{r})|\psi\rangle_s \times {}_c\langle\psi|\delta^3(\mathbf{r})|\psi\rangle_c. \quad (65)$$

Though this ansatz may not be strictly true, it may acquire credence in the light of the relations derived for quarkonium wavefunction at the origin using the nonrelativistic potential model [21]. To show the trends of the results, we give corresponding values of the branching ratios and asymmetry parameter of the charmed baryon decays in the Table 2.

## 4 Summary and conclusions

We have studied the two-body Cabibbo-angle favored decays of the charmed baryons  $\Lambda_c^+$ ,  $\Xi_c^+$ , and  $\Xi_c^0$  into the octet baryons and pseudoscalar mesons. It is now established that factorization alone cannot explain the available data as the branching ratio of  $\Lambda_c^+ \rightarrow \Sigma\pi/\eta$  and  $\Lambda_c^+ \rightarrow \Xi^0 K^+$  decays, forbidden in the factorization scheme, have been measured to be comparable to that of  $\Lambda_c^+ \rightarrow \Lambda\pi^+$ . Hence the nonspectator processes, like W-exchange diagram, seem to play a significant role in understanding these decays. Further,  $\Lambda_c^+ \rightarrow p\bar{K}^0$  decay which receives color-suppressed factorization has branching ratio greater than that of the color-favored decay  $\Lambda_c^+ \rightarrow \Lambda\pi^+$  by a factor of 2.5.

In the absence of a direct method for calculating the nonspectator terms, we have employed the standard current algebra framework to estimate their strength. The factorization contributions, being proportional to the meson momentum, provide corrections to this framework. We have evaluated the factorization terms using the HQET guided baryonic form factors.

In fact the form factors are calculated in the non-relativistic quark model and the  $q^2$ -dependence is assumed conventionally. Thus our analysis becomes model dependent.

One expects these form factors to be obtained through the angular correlation measurements in the semileptonic  $\Lambda_c$  decays, though it is not an easy task to completely disentangle their structure. However, recent measurements on the polarization of the  $\Lambda$  in  $\Lambda_c \rightarrow \Lambda + \ell^+ + \nu_\ell$  and their interpretation in terms of HQET yield confidence in the theoretical estimates.

We have obtained branching ratios and asymmetry parameters for these decays, which are found to be consistent with the experimental data. We observe that inclusion of the nonspectator contributions increases  $Br(\Lambda_c^+ \rightarrow p\bar{K}^0)$  from 0.48% to 1.23% and decreases  $Br(\Lambda_c^+ \rightarrow \Lambda\pi^+)$  from 1.29% to 1.17% in the desired directions. Further, branching ratios of  $\Lambda_c^+ \rightarrow \Sigma^+\pi^0/\Sigma^0\pi^+/\Sigma^+\eta$  and the only measured  $\Xi_c^+ \rightarrow \Xi^0\pi^+$  decay, obtained in the present analysis, are in good agreement with the experiment. The experimentally available asymmetries of  $\Lambda_c^+$  decays are also found in nice agreement with our results. However, branching ratio of  $\Lambda_c^+ \rightarrow \Xi^0 K^+$  decay is found to be much less than the observed value. Theoretically, one expects  $\Lambda_c^+ \rightarrow \Xi^0 K^+$  to be the cleanest of all the modes as neither factorization nor ETC term contributes to this process, so it should provide a measure of the pole terms.

We have also investigated the effects, due to flavor dependence of  $|\psi(0)|^2$  as is evident by  $\Sigma_c$  and  $\Lambda_c$  mass splitting, on these decays. It can result into the desired enhancement of  $\Lambda_c^+ \rightarrow \Xi^0 K^+$  but simultaneously it would increase the decay rates of  $\Lambda_c^+ \rightarrow \Sigma\pi/\eta$ , as these bear fixed ratios in our model. Though we find that a small scale enhancement is acceptable to the present level of data on charmed baryon decays, it needs some new physics. Small branching ratio for  $\Lambda_c \rightarrow \Xi^0 K^+$  decay in fact results due to near cancellation of the pole terms in the s- and u-channels, which involve antitriplet ( $C = 1$ ) to octet baryon and sextet ( $C = 1$ ) to octet baryon transition respectively. We expect that the HQET considerations may differentiate between the two types of the transitions. Further, final state interactions (FSI), well known to substantially alter the decay rates of the charm mesons, may also affect the charm baryon decays by feeding one decay mode into the other.

*Acknowledgements.* One of the authors (R.C.V.) gratefully acknowledges the financial support from the Department of Science and Technology, New Delhi, India.

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