Cabibbo favored hadronic decays of charmed baryons in flavor SU(3)

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Abstract

The two body Cabibbo favored hadronic decays of charmed baryons $\Lambda_c^+$, $\Xi_c^+$ and $\Xi_c^0$ into an octet or decuplet baryon and a pseudoscalar meson are examined in the SU(3) symmetry scheme. The numerical estimates for decay widths and branching ratios of some of the modes are obtained and are in good agreement with experiment.

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1 Introduction

The hyperon nonleptonic weak decays have so far evaded their complete understanding. It is expected that the hadronic decays of the charmed and heavier hadrons will be simpler and their study would help in the understanding of the nonleptonic decay processes, in general. Upto now greater part of theoretical effort to understand charm decays has been devoted to charmed mesons. Only recently, the study of hadronic two-body decays of the charmed baryons has gained serious attention [1-7]. It is primarily due to the fact that some data on these decays has started coming. The scarce data [8-10] which is available at present is already beginning to discriminate between the theoretical models. It is our hope that more and more data will become available in the near future, and this data will provide a new arena in which to study the standard model. Some very recent data [10] prompts us to make a systematic analysis of the Cabibbo allowed decays of charmed baryons in the framework of flavor SU(3) symmetry generated by $u$, $d$ and $s$ quarks.

The two-body weak decay modes of hyperons have traditionally been studied through the standard current algebra approach using the soft pion theorem. It has been shown for quite some time, that though this approach successfully reproduces the s- and p-wave amplitudes of the hyperons, and their relative sign, it fails to predict their relative magnitudes [11,12]. To have a better agreement between theory and experiment, the importance of including the factorization contributions, which vanish in the soft-pion limit, has been recognized [13].
The weak decays of charmed baryons have been analyzed [1,7] in the framework of soft-pion technique with the inclusion of factorization terms. It had actually been expected that the factorization terms would dominate. However, the observation of a few decays like \(\Lambda_c^+ \rightarrow \Delta^{++} K^- / \Sigma^0 \pi^+ / \Xi^0 K^+\) does not support this view and indicates the significance of pole diagrams for charm changing decays. Further, the calculations of both the pole terms and the factorization contribution have uncertainties associated with the many parameters that have to be estimated.

First, the soft-pion approach for the charm decays is suspect because the meson emitted in the charm decays is far from being soft as there is a lot of energy available in these decays. Second, the baryon-baryon weak transitions involved in the commutator terms as well as in the pole terms of the current algebra techniques have their own uncertainties. The evaluation of the factorization involves the knowledge of form factors which are not precisely known. The factorization contribution turns out to be too large and has to be toned down arbitrarily to give even a reasonable agreement with experiment.

These features have resulted in gross differences among the predictions of various models and with experiment. The ratio of the experimental branching ratio for \(\Lambda \pi^+\) and \(p \bar{K}^0\) modes of \(\Lambda_c^+\), for example, is about 0.4 whereas the theoretical estimates [5] are between 1 and 13. The \(\Lambda_c^+ \rightarrow \Sigma^0 \pi^+ / \Sigma^+ \pi^0\) modes do not get contribution from factorization term, while their branching ratios are comparable to that of the \(\Lambda \pi^+\) mode. Similarly, the \(\Lambda_c^+ \rightarrow \Xi^0 K^+\) mode
does not get contribution from factorization, but the ratio of its branching
fraction with that of $\Lambda\pi^+$ mode is significant. These facts indicate that weak
decays of charm baryons are more complex than those of D-mesons, since non-
spectator processes are significant here. Even by adjusting all the available
parameters, the agreement of any theoretical calculation done so far with the
experimental observations is far from satisfactory.

The symmetry approach does have a number of parameters, but has the
advantage that it lumps the effects of all dynamical processes together. Since
SU(3) is a better symmetry than SU(4) for the charm hadrons [4], it is expected
to yield more reliable results. So we investigate the Cabibbo enhanced decays
of charm =1 antitriplet baryons in flavor SU(3) which we believe would be
valid in both the s- and p-wave modes.

For $B_c \to B + P$ mode, using 6* domonance at the SU(3) level, we have three
parameters each for the s- and p-wave amplitudes. First, we use the available
data on $\Lambda_c^+ \to \Lambda\pi^+/\Sigma^+\pi^0/\Xi^0 K^+$ decays to fix the parameters and then make
predictions on the remaining branching ratios and asymmetries. Further, we
attempt to relate p-wave charm baryon decays with those of the hyperons
following the approach of Altarelli, Cabibbo and Maiani [14]. The predictions
obtained in the present analysis are consistent with the experimental values.
Particularly a small ratio of $Br(\Lambda_c^+ \to \Lambda\pi^+)/Br(\Lambda_c^+ \to p\bar{K}^0)$ can be explained.

We then extend our analysis to $B_c \to D + P$ decays. Here, by employing
the quark-line diagram approach of Kohara [3], we are able to express ampli-
tudes of all the $B_c$ decays in terms of only two reduced amplitudes. Using $B(\Lambda_c^+ \to \Delta^{++}K^-/\Xi^{*0}K^+)$ as input, branching ratio of the remaining decays are predicted.

2 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

$$H_W = \frac{G_F}{\sqrt{2}} V_{ud} V_{cs} (\bar{u}d)(\bar{s}c), \quad (1)$$

where $q_1 q_2 \equiv \bar{q}_1 \gamma_\mu (1 - \gamma_5) q_2$ represents the color-singlet combination. If the QCD short distance effects are included the effective weak Hamiltonian becomes

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

where the QCD coefficients $c_1 = \frac{1}{2} (c_+ + c_-)$, $c_2 = \frac{1}{2} (c_+ - c_-)$ and $c_\pm (\mu) = \left[ \frac{\alpha_s(\mu^2)}{\alpha_s(m_W^2)} \right] d_\pm / 2b$ with $d_- = -2d_+ = 8$ and $b = 11 - \frac{2}{3} N_f$, $N_f$ being the number of effective flavors, $\mu$ the mass scale. The value of these QCD coefficients are difficult to assign, depending as they do on the mass scale and $\Lambda_{QCD}$. For the charm sector, one usually takes, $c_1 = 1.2$, $c_2 = -0.5$. The effective Hamiltonian (2) then transforms as an admixture of the $6^*$ and 15 representations of flavor SU(3).
3 \( B_c(1^+ \rightarrow B(1^+) + P(0^-)) \) decays

We construct the effective Hamiltonian for the charm baryon decaying into an octet baryon and a pseudoscalar meson by combining the final state baryon octet and meson octet multiplets into definite representations of SU(3), namely, 1, 8\(_S\), 8\(_A\) 10, 10\(^*\), 27. Then combining these representations with charmed baryon antitriplet we construct 6\(^*\) and 15 Hamiltonian. Equivalently, we may construct SU(3) irreducible representations from the product of charm baryon antitriplet and weak Hamiltonian 6\(^*\) or 15 and contract it with the irreducible representations obtained in the product of final state baryon octet and meson octet. The weak Hamiltonian is then given by

\[
H_{W}^{6^*} = \sqrt{2}g_{8S}\{\bar{B}^a_{m}P^m_{b}B^n_{b}H^b_{[n,a]} + \bar{B}^m_{b}P^a_{m}B^n_{b}H^b_{[n,a]}\}
+ \sqrt{2}g_{8A}\{\bar{B}^a_{m}P^m_{b}B^n_{b}H^b_{[n,a]} - \bar{B}^m_{b}P^a_{m}B^n_{b}H^b_{[n,a]}\}
+ \frac{\sqrt{2}}{2}g_{10^*}\{B^a_{b}P^c_{d}B^b_{c}H^d_{[a,c]} + B^c_{b}P^a_{d}B^b_{d}H^b_{[a,c]}
- \frac{1}{3}\bar{B}^a_{b}P^c_{a}B^b_{n}H^b_{[n,c]} + \frac{1}{3}\bar{B}^c_{a}P^a_{d}B^n_{d}H^b_{[n,a]}\},
\]

(3)

\[
H_{W}^{15} = \frac{\sqrt{2}}{2}h_{27}\{\bar{B}^a_{b}P^c_{d}B^b_{c}H^d_{(a,c)} + \bar{B}^a_{b}P^c_{d}B^b_{d}H^b_{(a,c)}
- \frac{1}{5}\bar{B}^a_{b}P^c_{a}B^n_{(n,c)} - \frac{1}{5}\bar{B}^c_{a}P^a_{d}B^n_{(n,a)}\}
+ \frac{\sqrt{2}}{2}h_{10}\{\bar{B}^a_{b}P^c_{d}B^b_{c}H^d_{(a,c)} - \bar{B}^a_{b}P^c_{d}B^b_{d}H^b_{(a,c)}
+ \frac{1}{3}\bar{B}^a_{b}P^c_{a}B^n_{(n,c)} - \frac{1}{3}\bar{B}^c_{a}P^a_{d}B^n_{(n,a)}\}
+ \sqrt{2}h_{8S}\{B^a_{m}P^m_{b}B^n_{b}H^b_{(n,a)} + \bar{B}^m_{b}P^a_{m}B^n_{b}H^b_{(n,a)}\}
+ \sqrt{2}h_{8A}\{B^a_{m}P^m_{b}B^n_{b}H^b_{(n,a)} - \bar{B}^m_{b}P^a_{m}B^n_{b}H^b_{(n,a)}\}.
\]

(4)
The QCD coefficients $c_1$ and $c_2$ are absorbed in the reduced amplitudes $g$’s and $h$’s.

### 3.1 The decay width and asymmetry formulas

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

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

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

$$\Gamma = C_1 |A|^2 + C_2 |B|^2,$$

where

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

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

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

$m_i$ 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

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

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

### 3.2 Decay amplitudes

Choosing $H_{13}^2$ component of the weak Hamiltonian (3) and (4), decay amplitudes for various decays of antitriplet charmed baryons are obtained and they
are listed in Table 1. The C.G. coefficients occurring in this table, are the same for PV as well as for PC modes. However, the reduced amplitudes $g$’s and $h$’s will have different values for them. Thus in all, there exist 7 parameters in each PV and PC modes. Perturbative corrections give rise to enhancement of coefficient of $H_6^6$ over that of $H_6^9$. Consequently, it is possible, in analogy with octet dominance in hyperon decays, that sextet dominance may give reasonable results [2]. So in order to reduce the number of parameters, we assume 6* dominance which gives the following relations among the amplitudes:

$$\langle \Sigma^0 \pi^+ | \Lambda_c^+ \rangle = -\langle \Sigma^+ \pi^0 | \Lambda_c^+ \rangle,$$

$$\langle p \bar{K}^0 | \Lambda_c^+ \rangle = \frac{\sqrt{6}}{2} \langle \Lambda \pi^+ | \Lambda_c^+ \rangle - \frac{1}{\sqrt{2}} \langle \Sigma^+ \pi^0 | \Lambda_c^+ \rangle,$$

$$\langle p \bar{K}^0 | \Lambda_c^+ \rangle = \langle \Xi^- \pi^+ | \Xi_c^0 \rangle,$$

$$-\langle \Sigma^0 \bar{K}^0 | \Xi_c^0 \rangle = \frac{\sqrt{3}}{2} \langle \Lambda \pi^+ | \Lambda_c^+ \rangle + \frac{1}{2} \langle \Sigma^+ \pi^0 | \Lambda_c^+ \rangle,$$

$$-\langle \Lambda \bar{K}^0 | \Xi_c^0 \rangle = \frac{1}{2} \langle \Lambda \pi^+ | \Lambda_c^+ \rangle - \frac{\sqrt{3}}{2} \langle \Sigma^+ \pi^0 | \Lambda_c^+ \rangle.$$

Relation (8) follows from the isospin subgroup of SU(3). The above relations involve only two decay amplitudes $\langle \Lambda \pi^+ | \Lambda_c^+ \rangle$ and $\langle \Sigma^+ \pi^0 | \Lambda_c^+ \rangle$ on the right hand side. We now add one more to obtain:

$$\langle \Sigma^+ K^- | \Xi_c^0 \rangle = \langle \Xi^0 K^+ | \Lambda_c^+ \rangle,$$

$$\langle \Sigma^+ \eta_8 | \Lambda_c^+ \rangle = \sqrt{\frac{2}{3}} \langle \Xi^0 K^+ | \Lambda_c^+ \rangle - \frac{1}{\sqrt{3}} \langle \Sigma^+ \pi^0 | \Lambda_c^+ \rangle,$$

$$-\langle \Xi^0 \pi^0 | \Xi_c^0 \rangle = \frac{1}{\sqrt{2}} \langle \Xi^0 K^+ | \Lambda_c^+ \rangle - \langle \Sigma^+ \pi^0 | \Lambda_c^+ \rangle,$$

$$-\langle \Xi^0 \eta_8 | \Xi_c^0 \rangle = \frac{1}{\sqrt{6}} \langle \Xi^0 K^+ | \Lambda_c^+ \rangle + \frac{1}{\sqrt{3}} \langle \Sigma^+ \pi^0 | \Lambda_c^+ \rangle.$$
\[-\langle \Xi^0 \pi^+ | \Xi^+_c \rangle = \langle \Sigma^+ K^0 | \Xi^+_c \rangle = \]
\[-\langle \Xi^0 K^+ | \Lambda_c^+ \rangle + \frac{\sqrt{6}}{2} \langle \Lambda \pi^+ | \Lambda_c^+ \rangle + \frac{1}{\sqrt{2}} \langle \Sigma^+ \pi^0 | \Lambda_c^+ \rangle. \quad (17)\]

### 3.3 Results and conclusion

Experimentally, branching ratios of all the Cabibbo enhanced $\Lambda_c^+ \to B(\frac{1}{2}^+) + P(0^-)$ decays (except $\Lambda_c^+ \to \Sigma^+ \eta'$) have now been measured [8-10]. Besides the decay asymmetries of $\Lambda_c^+ \to \Lambda \pi^+ / \Sigma^+ \pi^0$ have also become available. Following sets of PV and PC amplitudes (in units of $G_F V_{ud} V_{cs} \times 10^{-2} GeV^2$) have been mentioned in a recent CLEO measurement [10],

\[
A(\Lambda_c^+ \to \Lambda \pi^+) = -3.0_{-1.2}^{+0.8} \quad \text{or} \quad -4.3_{-0.9}^{+0.8},
\]
\[
B(\Lambda_c^+ \to \Lambda \pi^+) = +12.7_{-2.5}^{+2.7} \quad \text{or} \quad +8.9_{-2.4}^{+3.4},
\]
\[
A(\Lambda_c^+ \to \Sigma^+ \pi^0) = +1.3_{-1.1}^{+0.9} \quad \text{or} \quad +5.4_{-0.7}^{+0.9},
\]
\[
B(\Lambda_c^+ \to \Sigma^+ \pi^0) = -17.3_{-2.9}^{+2.3} \quad \text{or} \quad -4.1_{-3.6}^{+3.4}. \quad (18)
\]

Relation (8) immediately implies

\[
Br(\Lambda_c^+ \to \Sigma^0 \pi^+) = Br(\Lambda_c^+ \to \Sigma^+ \pi^0). \quad (19)
\]

Experimentally [8, 10] the L. H. S is $0.87 \pm 0.20\%$ and R. H. S is $0.87 \pm 0.22\%$.

Also relation (8) gives

\[
\alpha(\Lambda_c^+ \to \Sigma^0 \pi^+) = \alpha(\Lambda_c^+ \to \Sigma^+ \pi^0) = -0.45 \pm 0.31 \pm 0.06. \quad (20)
\]
However, relations (9) to (12) would lead to different values of the branching ratios and asymmetries depending upon which set out of the four possibilities for $\Lambda_c^+ \to \Lambda \pi^+$ and $\Lambda_c^+ \to \Sigma^+ \pi^0$ amplitudes is used as input. We carry out numerical analysis for all the four choices and find branching and asymmetries for various modes in the following ranges:

$$Br(\Lambda_c^+ \to p\bar{K}^0) = 2.74 \text{ to } 3.51\%, \quad \text{(Expt. } 2.1 \pm 0.4\%) [8]$$

$$\alpha(\Lambda_c^+ \to p\bar{K}^0) = -0.72 \text{ to } -0.99; \quad (21)$$

$$Br(\Xi_c^0 \to \Lambda\bar{K}^0) = 0.69 \text{ to } 0.87\%,$$

$$\alpha(\Xi_c^0 \to \Lambda\bar{K}^0) = -0.62 \text{ to } 0.86; \quad (22)$$

$$Br(\Xi_c^0 \to \Xi^- \pi^+) = 1.30 \text{ to } 1.50\%,$$

$$\alpha(\Xi_c^0 \to \Xi^- \pi^+) = -0.75 \text{ to } -0.99; \quad (23)$$

$$Br(\Xi_c^0 \to \Sigma^0 \bar{K}^0) = 0.06 \text{ to } 0.19\%,$$

$$\alpha(\Xi_c^0 \to \Sigma^0 \bar{K}^0) = -0.67 \text{ to } -0.87 \text{ or } +0.05 \text{ to } +0.19. \quad (24)$$

This is to be remarked that SU(3) symmetry predicts a large value of branching ratio for $\Lambda_c^+ \to p\bar{K}^0$ than that of $\Lambda_c^+ \to \Lambda \pi^+$ in agreement with experiment. The present data on $Br(\Lambda_c^+ \to p\bar{K}^0)$ seems to prefer the following choice for the input:

$$A(\Lambda_c^+ \to \Sigma^+ \pi^0) = +5.4, \quad B(\Lambda_c^+ \to \Sigma^+ \pi^0) = -4.1;$$

$$A(\Lambda_c^+ \to \Lambda \pi^+) = -3.0, \quad B(\Lambda_c^+ \to \Lambda \pi^+) = +12.7. \quad (25)$$

To predict the remaining decays, we use the $\Lambda_c^+ \to \Xi^0 K^+$. Experimentally, only its branching ratio is known, $Br(\Lambda_c^+ \to \Xi^0 K^+) \approx 0.34 \pm 0.09\% [8]$. Ig-
Ignoring the small kinematic difference, the relation (13) gives

\[ Br(\Xi^0_c \to \Sigma^+ K^-) \approx Br(\Lambda^+_c \to \Xi^0 K^+) = 0.34 \pm 0.09\%, \]
\[ \alpha(\Xi^0_c \to \Sigma^+ K^-) \approx \alpha(\Lambda^+_c \to \Xi^0 K^+). \]  

(26)

To be able to use other relations, we need the amplitude for the decay \( \Lambda^+_c \to \Xi^0 K^+ \) in both the PV and PC modes. The measured branching ratio implies

\[ |A(\Lambda^+_c \to \Xi^0 K^+)|^2 + 0.055|B(\Lambda^+_c \to \Xi^0 K^+)|^2 = 14.42. \]  

(27)

The dynamical mechanisms considered for the charm baryon decay seem to indicate that the PV mode of this decay is invariably strongly suppressed. The decay can occur neither through the factorization nor from the equal time commutator term of the current algebra framework. Even through the \( \frac{1}{2}^- \) baryon pole, it acquires a negligibly small contributions [5]. Therefore, we expect its asymmetry to be close to zero, which then gives

\[ A(\Lambda^+_c \to \Xi^0 K^+) \approx 0, \quad B(\Lambda^+_c \to \Xi^0 K^+) = \pm 16.21. \]  

(28)

Ignoring physical \( \eta - \eta' \) mixing, we then obtain

\[ Br(\Lambda^+_c \to \Sigma^+ \eta) = 0.67\%, \quad \alpha(\Lambda^+_c \to \Sigma^+ \eta) = -0.95 \text{ for +ve sign}; \]
\[ Br(\Lambda^+_c \to \Sigma^+ \eta) = 0.45\%, \quad \alpha(\Lambda^+_c \to \Sigma^+ \eta) = +0.99 \text{ for -ve sign}. \]  

(29)

where \( \Lambda^+_c \to \Lambda\pi^+ \) and \( \Lambda^+_c \to \Sigma^+\pi^0 \) have been used from (25). A recent CLEO measurement [9] gives

\[ \frac{Br(\Lambda^+_c \to \Sigma^+ \eta)}{Br(\Lambda^+_c \to pK^-\pi^+)} = 0.11 \pm 0.03 \pm 0.02. \]
This measurement is consistent with both the theoretical predictions as PDG data [8] gives $Br(\Lambda^+_c \to pK^+\pi^+) = 4.4 \pm 0.6\%$. So we give branching ratio and decay asymmetry of the charm decays for both the sets in Table 2. The values of the PC reduced amplitudes (in units of $G_F V_{ud}V_{cs} \times 10^{-2}GeV^2$) for these sets are:

Set I: $B(\Lambda^+_c \to \Xi^0K^+) = -16.21$

\[
(g_{8s})_{PC} = -1.09, \quad (g_{8A})_{PC} = -7.70, \quad (g_{10})_{PC} = +28.81,
\]
\[
(g_{8s})_{PV} = +3.76, \quad (g_{8A})_{PV} = +3.80, \quad (g_{10})_{PV} = +0.10; \quad (30)
\]

Set II: $B(\Lambda^+_c \to \Xi^0K^+) = +16.21$

\[
(g_{8s})_{PC} = -17.30, \quad (g_{8A})_{PC} = -2.29, \quad (g_{10})_{PC} = -3.61,
\]
\[
(g_{8s})_{PV} = +3.76, \quad (g_{8A})_{PV} = +3.80, \quad (g_{10})_{PV} = +0.10. \quad (31)
\]

Branching ratios of $\Xi^+_c$ decays show drastic difference between the two sets. Decay asymmetries of $\Xi^0_c \to \Xi^0 + \pi^0/\eta$, though remaining large, have different signs in the two cases.

### 3.4 Relating charm baryon decays with hyperon decays

The hyperon decays arise through

\[
H_W = \frac{G_F}{\sqrt{2}} V_{ud}V_{us}[(\bar{d}u)(\bar{u}s) - (\bar{d}c)(\bar{c}s)]. \quad (32)
\]

Under SU(3) symmetry, $H_W$ transforms like $8 \oplus 27$ representation and the short distance effects enhance octet part over the $27$ part, though the enhancement
factor falls short of experimental value. Using octet dominance for hyperon decays, Altarelli, Cabibbo and Maiani [14] related the charm baryon decays with the hyperon decays. They related the reduced amplitudes $g$’s, and $h$’s with those of the hyperon decays using CP-invariance at the SU(4) level. In our phase convention, the relations are:

\begin{equation}
(g_{8S})_{PV} = \frac{1}{2}(g_{10})_{PV} = \frac{1}{2\sqrt{6}}[A(\Sigma^+_0) + \sqrt{2}A(\Sigma^+_1)],
\end{equation}

\begin{equation}
(g_{8A})_{PV} = \frac{1}{6\sqrt{6}}[-A(\Sigma^+_0) + 5\sqrt{2}A(\Sigma^+_1)],
\end{equation}

\begin{equation}
(g_{10})_{PC} = \frac{1}{\sqrt{6}}B(\Sigma^+_1) - B(\Lambda^0),
\end{equation}

\begin{equation}
(g_{8A})_{PC} = -\frac{1}{6\sqrt{6}}B(\Sigma^+_1) - \frac{\sqrt{3}}{4}B(\Sigma^+_0) + \frac{5}{12}B(\Lambda^0) - \frac{1}{2}B(\Xi^-),
\end{equation}

\begin{equation}
(g_{8S})_{PC} = \frac{1}{2\sqrt{6}}B(\Sigma^+_1) - \frac{\sqrt{3}}{4}B(\Sigma^+_0) + \frac{3}{4}B(\Lambda^0) - \frac{1}{2}B(\Xi^-).
\end{equation}

Unfortunately, the constraint (33) forbids $\Lambda^+_c \to \Lambda\pi^+$ in PV mode and so would predict $\alpha(\Lambda^+_c \to \Lambda\pi^+) = 0$. Further, the reduced amplitudes obtained from these relations give very large branching ratio for charm decays by a factor of 25 or so. In fact, $g_{8S} = \frac{1}{2}g_{10}$ for PV mode is a typical consequence of SU(4) symmetry, giving Iwasaki relation [15] for the hyperon decays,

\begin{equation}
\Lambda^0_0 : \Sigma^+_0 : \Xi^- = 1 : -\sqrt{3} : 2,
\end{equation}

which is badly violated by experiment. The reason is that SU(4) symmetry forbids factorization contributions in the PV mode, which is proportional to the mass difference of the initial and final baryons. Therefore, such relations among charm and uncharm sectors in PV mode are not reliable. However, for PC mode, the relations (35) to (37) may still have some meaning. Further,
due to the QCD modifications, the reduced amplitudes in charm sector are expected to be lower than those needed for the hyperon decays [16]. Then, lowering [16] the PC-reduced amplitudes $g_{8S}$, $g_{8A}$ and $g_{10}$ obtained from (35) to (37) by a factor of 5, we use branching ratio of $\Lambda^+_c \to \Lambda \pi^+$ and $\Lambda^+_c \to \Sigma^+ \pi^0$ as input to determine the PV-reduced amplitudes. The best set obtained for branching ratios and decay asymmetry parameters for various charm-baryon decays is given in Table 3. The values of the reduced amplitudes are:

$$(g_{8S})_{PC} = -17.72, \quad (g_{8A})_{PC} = -2.75, \quad (g_{10})_{PC} = +3.81;$$

$$(g_{8S})_{PV} = +2.92, \quad (g_{8A})_{PV} = +3.19, \quad (g_{10})_{PV} = +0.81. \quad (39)$$

These values and results obtained match well with those given in col. (4) and (5) of Table 3, and favor a positive sign of $B(\Lambda^+_c \to \Xi^0 K^+)$. 

**4 $B_c(\frac{1}{2}^+) \to D(\frac{3}{2}^+) + P(0^-)$ decays**

In this section we examine the Cabibbo-favored decays of the anti-triplet charm baryon ($B_c$) to a decuplet baryon ($D$) and a pseudoscalar meson ($P$). The matrix element for the decay being defined as

$$\langle D, P | H_W | B_c \rangle = i q_\mu \bar{u}_D (C - \gamma_5 D) u_{B_c} \phi_P, \quad (40)$$

the decay rate and the asymmetry parameter for $B(\frac{1}{2}^+) \to D(\frac{3}{2}^+) + P(0^-)$ decay are given by

$$\Gamma = \frac{|q|^2 m_1 (m_2 + E_2)}{6\pi m_2^2} [ |C|^2 + |D|^2 ], \quad (41)$$
\[ \alpha = \frac{2 \text{Re}(C \bar{D}^*)}{(|C|^2 + |\bar{D}|^2)}, \tag{42} \]

where
\[ \bar{D} = \rho D, \quad \rho = [(E_2 - m_2)/(E_2 + m_2)]^{1/2}. \]

C and D are the p-wave (parity-conserving) and d-wave (parity-violating) amplitudes respectively. \( w_\mu \) is the Rarita-Schwinger spinor representing the spin \( 3/2 \) baryon and \( q_\mu \) is the four momentum of the emitted meson.

Following a procedure similar to that used for \( B(1^+) \to B(1^+) + P(0^-) \) decays, we construct the following Hamiltonian for decuplet baryon emitting decays:
\[ H^6_{W} = \sqrt{2} j_8 (\epsilon_{mdb} \bar{D}^{mnc} P^n B^d H^b_{[a,c]}), \tag{43} \]
\[ H^{15}_{W} = \sqrt{2} k_8 (\epsilon_{mpb} \bar{D}^{mna} P^n B^c H^b_{(a,c)}) \]
\[ + \sqrt{2} k_{10} (\epsilon_{mnd} \bar{D}^{mac} P^n B^d H^b_{(a,c)} - \epsilon_{mn} \bar{D}^{mac} P^n B^d H^b_{(a,c)} - \epsilon_{mn} \bar{D}^{mac} P^n B^d H^b_{(a,c)} + \epsilon_{mn} \bar{D}^{mac} P^n B^d H^b_{(a,c)}) \]
\[ + \sqrt{2} k_{27} (\epsilon_{mnd} \bar{D}^{mac} P^n B^d H^b_{(a,c)} + \epsilon_{mn} \bar{D}^{mac} P^n B^d H^b_{(a,c)} - \epsilon_{mn} \bar{D}^{mac} P^n B^d H^b_{(a,c)}) \]
\[ - \frac{2}{3} \epsilon_{mn} \bar{D}^{mdc} P^n B^a H^b_{(a,c)}), \tag{44} \]

where \( \epsilon_{abc} \) is the Levi-Civita symbol and \( D_{abc} \) represents totally symmetric decuplet baryons. Choosing \( H^2_{13} \) component of \( H^b_{[a,c]} \) and \( H^b_{(a,c)} \) tensors, we obtain the decay amplitudes for various decay modes. These are shown in the Table 4. In all there are 4 reduced amplitudes for each of the PV and PC modes. Dynamically, these decays are relatively simpler than the ones considered in the last section. It has been shown by Xu and Kamal [7] that
factorization terms do not contribute to these decays and that these decays arise only through W-exchange diagrams. In fact, performing a quark diagram analyses, Kohara [3] has observed that most of the quark diagrams, allowed for \( B(\frac{1}{2}^+) \to B(\frac{1}{2}^+) + P(0^-) \) decays are forbidden for \( B(\frac{1}{2}^+) \to D(\frac{3}{2}^+) + P(0^-) \) decays due to the symmetry property of the decuplet baryons. There exist only two independent diagrams, which are expressed as:

\[
A = d_1 \bar{D}^{1ab} B_{[2,a]} M_b^3 + d_2 \bar{D}^{3ab} B_{[2,a]} M_b^1, \tag{45}
\]

where \( B_{[a,b]} \) represents the \( 3^* \) baryon. In our notation, it amounts to the following constraints:

\[
k_8 = \frac{1}{3} k_{10}, \quad k_{27} = 0. \tag{46}
\]

Following relations are obtained for PV as well as PC modes,

\[
\langle \Xi^0 \pi^+ | \Xi_c^+ \rangle = \langle \Sigma^+ \bar{K}^0 | \Xi_c^+ \rangle = 0, \tag{47}
\]

\[
\langle \Delta^{++} K^- | \Lambda_c^+ \rangle = \sqrt{3} \langle \Delta^+ K^- | \Xi_c^+ \rangle = \sqrt{3} \langle \Sigma^+ K^- | \Xi_c^+ \rangle = \sqrt{6} \langle \Sigma^0 K^0 | \Xi_c^+ \rangle, \tag{48}
\]

\[
\sqrt{3} \langle \Xi^0 K^+ | \Lambda_c^+ \rangle = \sqrt{6} \langle \Sigma^+ \pi^0 | \Lambda_c^+ \rangle = \sqrt{6} \langle \Sigma^0 \pi^+ | \Lambda_c^+ \rangle
\]

\[
= \sqrt{6} \langle \Xi^0 \pi^0 | \Xi_c^+ \rangle = \sqrt{3} \langle \Xi^* - \pi^+ | \Xi_c^+ \rangle = \langle \Omega^- K^+ | \Xi_c^+ \rangle, \tag{49}
\]

\[
\langle \Sigma^{**} \eta_8 | \Lambda_c^+ \rangle = \langle \Xi^0 \eta_8 | \Xi_c^+ \rangle = \frac{1}{\sqrt{6}} \langle \Xi^0 K^+ | \Lambda_c^+ \rangle - \frac{2}{3\sqrt{2}} \langle \Delta^{++} K^- | \Lambda_c^+ \rangle. \tag{50}
\]

Since W-exchange diagram contributions to the PV mode are generally small and PV mode is suppressed due to the centrifugal barrier, we ignore them in the present analysis. Experimentally [8], the following branching ratios are
known:

\[ Br(\Lambda_c^+ \to \Delta^{++}K^-) = 0.7 \pm 0.4\%, \quad (51) \]
\[ Br(\Lambda_c^+ \to \Xi^{*0}K^+) = 0.23 \pm 0.09\%, \quad (52) \]
\[ Br(\Lambda_c^+ \to \Sigma^{*+}\eta) = 0.75 \pm 0.24\%. \quad (53) \]

The last value has been taken from a recent CLEO measurements [9].

\[ Br(\Lambda_c^+ \to \Sigma^{*+}\eta)/Br(\Lambda_c^+ \to pK^-\pi^+) = 0.17 \pm 0.04 \pm 0.03, \quad (54) \]

with

\[ Br(\Lambda_c^+ \to pK^-\pi^+) = 4.4 \pm 0.6\% \]

from PDG [8]. We employ \( Br(\Lambda_c^+ \to \Delta^{++}K^-) \) and \( Br(\Lambda_c^+ \to \Xi^{*0}K^+) \) as input to fix,

\[ j_8 = -77.14, \quad k_8 = +9.10 \ (\text{in units of } G_F V_{ud} V_{cs} \times 10^{-2} GeV^2), \]

which in turn give all other branching ratios. These are tabulated in Table 5. For \( \Lambda_c^+ \), we expect \( \Lambda_c^+ \to \Sigma^*\pi \) modes to be dominant and for \( \Xi_c^0 \) decay \( \Xi_c^0 \to \Xi^{*0}\pi/\Omega K \) modes are predicted to be dominant. Like in other theoretical models, \( \Xi_c^+ \) decays in the present analysis are also forbidden. Their observations would indicate the presence of decay mechanism other than the W-exchange process. Like \( B(\frac{1}{2}^+) \to B(\frac{1}{2}^+) + P(0^-) \) decays, here also one may like to relate these decays with decays of \( \Omega^- \) hyperon. Since \( \Omega^- \) decays do not involve W-exchange process, that comparison is not expected to work.
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Table 1: $\Delta C = \Delta S = -1$ decay amplitudes for charmed baryons.

| Decay                      | $H_{W}^{0}$                          | $H_{W}^{15}$                          |
|----------------------------|--------------------------------------|---------------------------------------|
| $\Lambda_{c}^{+} \rightarrow pK^{0}$ | $-g_{8S} - g_{8A} + \frac{1}{3}g_{10}$ | $h_{8S} + h_{8A} + \frac{1}{3}h_{10} + \frac{2}{5}h_{27}$ |
| $\Lambda_{c}^{+} \rightarrow \Lambda\pi^{+}$ | $\frac{1}{\sqrt{6}}(-2g_{8S} + g_{10})$ | $\frac{1}{\sqrt{6}}(2h_{8S} - h_{10} - \frac{6}{5}h_{27})$ |
| $\Lambda_{c}^{+} \rightarrow \Sigma^{+}\pi^{0}$ | $\frac{1}{\sqrt{2}}(2g_{8A} + \frac{1}{3}g_{10})$ | $\frac{1}{\sqrt{2}}(-2h_{8A} + \frac{1}{3}h_{10})$ |
| $\Lambda_{c}^{+} \rightarrow \Sigma^{+}\eta_{8}$ | $\frac{1}{\sqrt{6}}(-2g_{8S} - g_{10})$ | $\frac{1}{\sqrt{6}}(2h_{8S} + h_{10} - \frac{6}{5}h_{27})$ |
| $\Lambda_{c}^{+} \rightarrow \Sigma^{0}\pi^{+}$ | $\frac{1}{\sqrt{2}}(-2g_{8A} - \frac{1}{3}g_{10})$ | $\frac{1}{\sqrt{2}}(2h_{8A} - \frac{1}{3}h_{10})$ |
| $\Lambda_{c}^{+} \rightarrow \Xi^{0}K^{+}$ | $-g_{8S} + g_{8A} - \frac{1}{7}g_{10}$ | $h_{8S} - h_{8A} - \frac{1}{3}h_{10} + \frac{2}{5}h_{27}$ |
| $\Xi_{c}^{+} \rightarrow \Xi^{0}\pi^{+}$ | $-g_{10}$ | $h_{27}$ |
| $\Xi_{c}^{+} \rightarrow \Sigma^{+}\bar{K}^{0}$ | $g_{10}$ | $h_{27}$ |
| $\Xi_{c}^{0} \rightarrow \Xi^{0}\pi^{0}$ | $\frac{1}{\sqrt{2}}(g_{8S} + g_{8A} + \frac{2}{3}g_{10})$ | $\frac{1}{\sqrt{2}}(h_{8S} + h_{8A} + \frac{1}{3}h_{10} - \frac{3}{5}h_{27})$ |
| $\Xi_{c}^{0} \rightarrow \Xi^{0}\eta_{8}$ | $\frac{1}{\sqrt{6}}(g_{8S} - 3g_{8A})$ | $\frac{1}{\sqrt{6}}(h_{8S} - 3h_{8A} + h_{10} - \frac{3}{5}h_{27})$ |
| $\Xi_{c}^{0} \rightarrow \Xi^{-}\pi^{+}$ | $-g_{8S} - g_{8A} + \frac{1}{7}g_{10}$ | $-h_{8S} - h_{8A} - \frac{1}{3}h_{10} - \frac{2}{5}h_{27}$ |
| $\Xi_{c}^{0} \rightarrow \Sigma^{+}K^{-}$ | $-g_{8S} + g_{8A} - \frac{1}{3}g_{10}$ | $-h_{8S} + h_{8A} + \frac{1}{3}h_{10} - \frac{2}{5}h_{27}$ |
| $\Xi_{c}^{0} \rightarrow \Sigma^{0}\bar{K}^{0}$ | $\frac{1}{\sqrt{2}}(g_{8S} - g_{8A} - \frac{2}{3}g_{10})$ | $\frac{1}{\sqrt{2}}(h_{8S} - h_{8A} - \frac{1}{3}h_{10} - \frac{3}{5}h_{27})$ |
| $\Xi_{c}^{0} \rightarrow \Lambda\bar{K}^{0}$ | $\frac{1}{\sqrt{6}}(g_{8S} + 3g_{8A})$ | $\frac{1}{\sqrt{6}}(h_{8S} + 3h_{8A} - h_{10} - \frac{3}{5}h_{27})$ |
Table 2: Branching ratios and decay asymmetries of charmed baryons.

| Decay                  | Br. (%) | Asymmetry $\alpha$ | Br. (%) | Asymmetry $\alpha$ |
|------------------------|---------|---------------------|---------|---------------------|
| $\Lambda_c^+ \to p\bar{K}^0$ | 2.74    | $-0.99$             | 2.74    | $-0.99$             |
| $\Lambda_c^+ \to \Lambda\pi^+$  | $0.79^\dagger$ | $-0.94^\dagger$   | $0.79^\dagger$ | $-0.94^\dagger$   |
| $\Lambda_c^+ \to \Sigma^+\pi^0$ | 0.87$^\dagger$ | $-0.45^\dagger$   | 0.87$^\dagger$ | $-0.45^\dagger$   |
| $\Lambda_c^+ \to \Sigma^+\eta$ | 0.45    | $+0.99$             | 0.67    | $-0.95$             |
| $\Lambda_c^+ \to \Sigma^0\pi^+$ | 0.87    | $-0.45$             | 0.87    | $-0.45$             |
| $\Lambda_c^+ \to \Xi^0\bar{K}^+$ | 0.34$^\dagger$ | 0.00               | 0.34$^\dagger$ | $-0.00$             |
| $\Xi_c^+ \to \Xi^0\pi^+$ | 4.05    | $+0.02$             | 0.06    | $-0.19$             |
| $\Xi_c^+ \to \Sigma^+\bar{K}^0$ | 4.23    | $+0.02$             | 0.07    | $-0.17$             |
| $\Xi_c^0 \to \Xi^0\pi^0$ | 0.51    | $+0.71$             | 0.77    | $-0.99$             |
| $\Xi_c^0 \to \Xi^0\eta$ | 0.20    | $-0.97$             | 0.14    | $+0.65$             |
| $\Xi_c^0 \to \Xi^-\pi^+$ | 1.31    | $-0.96$             | 1.31    | $-0.96$             |
| $\Xi_c^0 \to \Sigma^+\bar{K}^-$ | 0.38    | 0.00                | 0.38    | 0.00                |
| $\Xi_c^0 \to \Sigma^0\bar{K}^0$ | 0.11    | $+0.05$             | 0.11    | $+0.05$             |
| $\Xi_c^0 \to \Lambda\bar{K}^0$ | 0.69    | $-0.86$             | 0.69    | $-0.86$             |

$^\dagger$ input
Table 3: Branching ratios and asymmetries of charmed baryons using hyperon PC amplitudes as input.

| Decay       | Br. ratio (%) | Asymmetry α |
|-------------|---------------|-------------|
| $\Lambda_c^+ \to pK^0$ | 2.70          | −0.93       |
| $\Lambda_c^+ \to \Lambda\pi^+$ | 0.97†         | −0.66       |
| $\Lambda_c^+ \to \Sigma^+\pi^0$ | 0.65†         | −0.38       |
| $\Lambda_c^+ \to \Sigma^+\eta$ | 0.48          | −0.96       |
| $\Lambda_c^+ \to \Sigma^0\pi^+$ | 0.65          | −0.38       |
| $\Lambda_c^+ \to \Xi^0\bar{K}^+$ | 0.24          | 0.00        |
| $\Xi_c^+ \to \Xi^0\pi^+$ | 0.11          | +0.94       |
| $\Xi_c^+ \to \Sigma^+\bar{K}^0$ | 0.10          | +0.92       |
| $\Xi_c^0 \to \Xi^0\pi^0$ | 0.55          | −0.98       |
| $\Xi_c^0 \to \Xi^0\eta$ | 0.11          | +0.67       |
| $\Xi_c^0 \to \Xi^-\pi^+$ | 1.15          | −0.99       |
| $\Xi_c^0 \to \Sigma^+K^-$ | 0.27          | 0.00        |
| $\Xi_c^0 \to \Sigma^0\bar{K}^0$ | 0.22          | +0.28       |
| $\Xi_c^0 \to \Lambda\bar{K}^0$ | 0.55          | −0.96       |

† input
Table 4: $\Delta C = \Delta S = -1$ decay amplitudes of $B_c(\frac{1}{2})^+ \to D(\frac{3}{2})^+ + P(0^-)$ decays.

| Decay                     | $H_W^{6^+}$  | $H_W^{15}$          |
|----------------------------|--------------|---------------------|
| $\Lambda_c^+ \to \Delta^{++}K^-$ | $j_1$        | $-k_8 - \frac{2}{3}k_{10} + \frac{2}{3}k_{27}$ |
| $\Lambda_c^+ \to \Delta^0\bar{K}^0$ | $j_1/\sqrt{3}$ | $(-k_8 - \frac{2}{3}k_{10} + \frac{2}{3}k_{27})/\sqrt{3}$ |
| $\Lambda_c^+ \to \Sigma^{*+}\pi^0$ | $-j_1/\sqrt{6}$ | $(k_8 - \frac{4}{3}k_{10} - \frac{12}{5}k_{27})/\sqrt{6}$ |
| $\Lambda_c^+ \to \Sigma^{*+}\eta_8$ | $-j_1/\sqrt{2}$ | $(k_8 + \frac{8}{5}k_{27})/\sqrt{2}$ |
| $\Lambda_c^+ \to \Sigma^{*0}\pi^+$ | $-j_1/\sqrt{6}$ | $(k_8 - \frac{4}{3}k_{10} - \frac{12}{5}k_{27})/\sqrt{6}$ |
| $\Lambda_c^+ \to \Xi^{*0}K^+$ | $-j_1/\sqrt{3}$ | $(k_8 - \frac{4}{3}k_{10} + \frac{2}{3}k_{27})/\sqrt{3}$ |
| $\Xi_c^+ \to \Sigma^{*+}K^0$ | 0            | $(-4k_{27})/\sqrt{3}$ |
| $\Xi_c^+ \to \Xi^{*0}\pi^+$ | 0            | $(4k_{27})/\sqrt{3}$ |
| $\Xi_c^0 \to \Sigma^{*+}K^-$ | $j_1/\sqrt{3}$ | $(k_8 - \frac{4}{3}k_{10} + \frac{8}{5}k_{27})/\sqrt{3}$ |
| $\Xi_c^0 \to \Sigma^{*0}\bar{K}^0$ | $j_1/\sqrt{6}$ | $(k_8 - \frac{4}{3}k_{10} - \frac{12}{5}k_{27})/\sqrt{6}$ |
| $\Xi_c^0 \to \Xi^{*0}\pi^0$ | $-j_1/\sqrt{6}$ | $(-k_8 - \frac{2}{3}k_{10} - \frac{18}{5}k_{27})/\sqrt{6}$ |
| $\Xi_c^0 \to \Xi^{*0}\eta_8$ | $-j_1/\sqrt{2}$ | $(-k_8 + \frac{2}{3}k_{10} + \frac{2}{5}k_{27})/\sqrt{2}$ |
| $\Xi_c^0 \to \Xi^{*-}\pi^+$ | $-j_1/\sqrt{3}$ | $(-k_8 - \frac{2}{3}k_{10} + \frac{2}{5}k_{27})/\sqrt{3}$ |
| $\Xi_c^0 \to \Omega^-K^+$ | $-j_1$        | $-k_8 - \frac{2}{3}k_{10} + \frac{2}{5}k_{27}$ |
Table 5: Branching ratios of $B_c(\frac{1}{2})^+ \rightarrow D(\frac{3}{2})^+ + P(0^-)$ decays.

| Decay                  | Branching ratio (%) |
|------------------------|---------------------|
| $\Lambda_c^+ \rightarrow \Delta^{++} K^-$ | 0.70$^\dagger$    |
| $\Lambda_c^+ \rightarrow \Delta^+ \bar{K}^0$ | 0.23                |
| $\Lambda_c^+ \rightarrow \Sigma^{*+} \pi^0$ | 0.46                |
| $\Lambda_c^+ \rightarrow \Sigma^{*+} \eta$ | 0.30                |
| $\Lambda_c^+ \rightarrow \Sigma^{*0} \pi^+$ | 0.46                |
| $\Lambda_c^+ \rightarrow \Xi^{*0} K^+$ | 0.23$^\dagger$    |
| $\Xi_c^+ \rightarrow \Sigma^{*+} \bar{K}^0$ | 0.0                 |
| $\Xi_c^+ \rightarrow \Xi^{*0} \pi^+$ | 0.0                 |
| $\Xi_c^0 \rightarrow \Sigma^{*+} K^-$ | 0.13                |
| $\Xi_c^0 \rightarrow \Sigma^{*0} \bar{K}^0$ | 0.06                |
| $\Xi_c^0 \rightarrow \Xi^{*0} \pi^0$ | 0.26                |
| $\Xi_c^0 \rightarrow \Xi^{*0} \eta$ | 0.17                |
| $\Xi_c^0 \rightarrow \Xi^{*-} \pi^+$ | 0.51                |
| $\Xi_c^0 \rightarrow \Omega^- K^+$ | 0.46                |

$^\dagger$ input