Nonleptonic Weak Decays of Charm Baryons involving Axial-Vector Mesons

Rohit Dhir
IPAP & Department of Physics
Yonsei University
Seoul

2014 Spring Yonsei Workshop on Particle Physics
(April 11, 2014)
Outline

• Motivation

• Formalism for Nonleptonic Weak decays of Baryons

• $P$-wave Meson Emitting Weak Nonleptonic Decays of Charm baryons

• Conclusions
Motivation

• In the heavy quark meson sector, a lot of work has been done. However, decays of heavy quark baryons have come under active experimental and theoretical investigation, recently

• Experimentally, several modes of $\Lambda_c$ and a few decays of $\Xi_c$ baryons have been measured. Theoretically, the main work has been done for the $s$-wave meson emitting decays of heavy baryons.

• Being heavy these $B_i(1/2^+)$ charm and bottom baryons can also emit p-wave ($0^+$-scalar and $1^+$-axial-vector) mesons in the final state.

• Only measured p-wave meson emitting decay mode is $\Lambda_c^+ \rightarrow p f_0 (980)$ and also, one bottom baryon decay $\Lambda_b^0 \rightarrow \Lambda_c^+ + a_1^-$ has been seen but not yet measured.

• In this work we obtain first estimates of non leptonic weak decays of charm baryons which would help the experimentalist for their search of these modes.
Two-body Weak Hadronic Decays of Baryons

Theoretical focus, so far, has been on the following decays of the baryons:

(i) \( B_i(1/2^+) \rightarrow B_f(1/2^+) + P(0^-) \),
(ii) \( B_i(1/2^+) \rightarrow B_f(1/2^+) + V(1^-) \).

Being heavy, \( B_i(1/2^+) \) charm and bottom baryons can also emit \( p \)-wave mesons, e.g.

(i) \( B_i(1/2^+) \rightarrow B_f(1/2^+) + S(0^+) \),
(ii) \( B_i(1/2^+) \rightarrow B_f(1/2^+) + A(1^+) \),
(iii) \( B_i(1/2^+) \rightarrow B_f(1/2^+) + T(2^+) \),

In addition to these, these baryons may also decay weakly to \( B_f(3/2^+) \) baryons.
Dynamics in Meson Decays

• Heavy flavor mesons decays are described reasonably well in terms factorizable W-emission spectator quark process.

• Three-body matrix elements reduce to product of two-body matrix elements of weak current,

\[ \langle M_1 M_2 | H_W | M \rangle \sim \langle M_1 | J | M \rangle \langle M_2 | J | 0 \rangle . \]

• These involve certain form-factors and decay constants, which contain the real dynamics.

• W-exchange terms are suppressed due to helicity and color arguments.
Dynamics in Baryon Decays

• Similar to meson decays, here also factorizable W-emission process contribute.

• Three-body matrix elements reduce to product of two-body matrix elements of weak current,

\[ < M B_f | H_w | B_i > \sim < B_f | J | B_i > < M | J | 0 > . \]

• These involve Baryon form-factors and meson decay constants.

• However, W-exchange terms are not suppressed, in fact are comparable.
Experimentally, two types of the axial-vector mesons exist i.e. $^{3}P_{1}(J^{PC} = 1^{++})$ and $^{1}P_{1}(J^{PC} = 1^{+-})$

For $1^{++}$

Isovector : $a_{1}(1.230) : a_{1}^{+}, a_{1}^{-}, a_{1}^{0}$

Isoscalars:

$$f_{1}(1.285) = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos\phi_{A} + (s\bar{s})\sin\phi_{A}$$

$$f'_{1}(1.512) = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\sin\phi_{A} - (s\bar{s})\cos\phi_{A}$$

$\chi_{c1}(3.511) = (c\bar{c})$

where

$$\phi_{A} = \theta(\text{ideal}) - \theta_{A}(\text{physical})$$
For \( 1^{+-} \)

**Isovector:**

\[ b_1(1.229) : b_1^+, b_1^-, b_1^0 \]

**Isoscalars:**

\[ h_1(1.170) = \frac{1}{\sqrt{2}} (uu + dd) \cos \phi_{A'} + (ss) \sin \phi_{A'} \]

\[ h_1'(1.380) = \frac{1}{\sqrt{2}} (uu + dd) \sin \phi_{A'} - (ss) \cos \phi_{A'} \]

\[ h_{c1}(3.526) = (cc) \]

where

\[ \phi_{A'} = \theta(\text{ideal}) - \theta_{A'}(\text{physical}) \]

with

\[ \phi_A = \phi_{A'} = 0^\circ \]
MIXING IN STRANGE AND CHARM AXIAL-VECTOR MESONS

\[ A(1^{++}) \quad A'(1^{+-}) \quad \text{and} \]

Mixing of Strange states

\[ K_1(1.270) = K_{1A} \sin \theta_1 + K_{1A'} \cos \theta_1, \]
\[ K_{1}(1.400) = K_{1A} \cos \theta_1 - K_{1A'} \sin \theta_1. \]
\[ \theta_1 = -58^0 (-37^0) \]

Mixing of Charmed and Strange Charmed states

\[ D_1(2.427) = D_{1A} \sin \theta_{D_1} + D_{1A'} \cos \theta_{D_1}, \]
\[ D_{1}(2.422) = D_{1A} \cos \theta_{D_1} - D_{1A'} \sin \theta_{D_1}, \]
\[ & \quad \& \]
\[ D_{s1}(2.460) = D_{s1A} \sin \theta_{D_{s1}} + D_{s1A'} \cos \theta_{D_{s1}}, \]
\[ D_{s1}(2.535) = D_{s1A} \cos \theta_{D_{s1}} - D_{s1A'} \sin \theta_{D_{s1}}, \]
However, in the heavy quark limit, the physical mass eigenstates with $J^P = 1^+$ are $P_{1}^{3/2}$ and $P_{1}^{1/2}$ rather than $^3P_1$ and $^1P_1$ states as the heavy quark spin decouples from the other degrees of freedom so that

$$| P_{1}^{1/2} > = -\sqrt{\frac{1}{3}} | ^1P_1 > + \sqrt{\frac{2}{3}} | ^3P_1 >,$$

$$| P_{1}^{3/2} > = \sqrt{\frac{2}{3}} | ^1P_1 > + \sqrt{\frac{1}{3}} | ^3P_1 >.$$

**Mixing of Charmed states**

$$D_1(2.427) = D_1^{1/2} \cos \theta_2 + D_1^{3/2} \sin \theta_2,$$

$$\overline{D}_1(2.422) = - D_1^{1/2} \sin \theta_2 + D_1^{3/2} \cos \theta_2.$$

**Mixing of strange-Charmed states**

$$D_{s1}(2.460) = D_{s1}^{1/2} \cos \theta_3 + D_{s1}^{3/2} \sin \theta_3,$$

$$\overline{D}_{s1}(2.535) = - D_{s1}^{1/2} \sin \theta_3 + D_{s1}^{3/2} \cos \theta_3.$$  

with

$$\theta_2 = (-5.7 \pm 2.4)^\circ \quad \theta_3 \approx 7^\circ$$
The decay constants for axial-vector mesons \( <A | J_\mu | 0> = f_A m_A \varepsilon_\mu^* \)

Since the weak axial-vector current transfers as \( (A_\mu)_a \rightarrow (A_\mu)_b \) under charge conjugation,

\[
f_A (^{1}P_1) \rightarrow 0 \quad \text{(SU(3) flavor limit)} \quad \text{[PRD 47, 1252 (1993); 55, 2840 (1997)]}.
\]

Experimental information gives:

\[
f_{K_1} (1270) = 0.175 \pm 0.019 \text{ GeV} \quad \text{[HYC, PRD 67, 094007 (2003)]},
\]

Using \( f_{K_1} (1.400)/f_{K_1} (1.270) = \cot \theta_1 \)

\[
f_{K_1} (1.400) = (-0.109 \pm 0.12) \text{ GeV},
\]

for \( \theta_1 = -37^\circ \) used in the present work.

Numerous analysis based on phenomenological studies indicate that strange axial vector meson states mixing angle \( \theta_K \) lies in the vicinity of \( \sim 35^\circ \) and \( \sim 55^\circ \). Recently, it has been pointed out [H.Y. Cheng, PLB 707, 116 (2012)] that mixing angle \( \theta_1 \sim 35^\circ \) is preferred over \( \sim 55^\circ \), we use \( \theta_1 = -37^\circ \) in our numerical calculations. It is based on the observation that choice of angle for \( f - f' \) and \( h - h' \) mixing schemes (which are close to ideal mixing) are intimately related to choice of mixing angle \( \theta_1 \).
In case of non-strange axial vector mesons, Nardulli and Pham [36]:

\[ f_{a_1} = 0.223 \text{ GeV} \quad \text{with} \quad f_{f_1} \approx f_{a_1} \quad \text{(SU(3) symmetry)} \]

Charge conjugation invariance \((^1P_1)\): \( b_0, h_1(1.235), h_f(1.170), \) and \( h'_f(1.380) \rightarrow \) vanish.

G-parity conservation: \( f_{b_1} \rightarrow 0. \)

**SUMMARY OF DECAY CONSTANTS** (in \( \text{GeV} \))

\[
\begin{align*}
    f_{K_1(1270)} & = 0.175, & f_{K_1(1.400)} & = -0.087, \\
    f_{a_1} & = 0.203, & f_{f_1} & \approx f_{a_1}, \\
    f_{D_{1A}} & = -0.127, & f_{D_{1B}} & = 0.045, \\
    f_{D_{s1A}} & = -0.121, & f_{D_{s1B}} & = 0.038, \\
    f_{\chi_{c1}} & \approx -0.160.
\end{align*}
\]
Kinematics

• Following the standard procedure for baryon decays, $B_i(1/2+) \rightarrow B_f(1/2+) \ A(1+)$

\[<B_f(p_f)A_k(q)|H_w|B_i(p_i)> = i\bar{u}_{B_i}(p_i)\gamma^\mu(A_1\gamma_\mu\gamma_5 + A_2p_\mu\gamma_5 + B_1\gamma_\mu + B_2p_\mu)u_{B_f}(p_f)\]

Here $A_i$'s and $B_i$'s denote the parity conserving (PC) and parity violating (PV) amplitudes, respectively.

• Decay width is given by

\[\Gamma = \frac{q_\mu}{8\pi} \frac{E_f + m_f}{m_i} \left|2(|S|^2 + |P_2|^2) + \frac{E_A^2}{m_A^2}(|S + D|^2 + |P_1|^2)\right|\]

• Asymmetry parameter is

\[\alpha = \frac{4m_A^2 \text{Re}(S*P_2) + 2E_A^2 \text{Re}(S + D)*P_1}{2m_A^2(|S|^2 + |P_2|^2) + E_A^2(|S + D|^2 + |P_1|^2)}\]
With

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

In the standard factorization scheme, the separable combination of decay amplitudes (apart from scale factors) for \( B_i (1/2+) \to B_f (1/2+) + A (1+) \) is expressed by

\[ < A_k (q) | A_\mu | 0 > < B_f (p_f) | V^- A^\mu | B_i (p_i) > \]

Here the first factor involves the decay constant of axial-vector meson \( A \) as

\[ < A_k (q) | (\overline{q}_1 q_2) | 0 > = f_A m_A \varepsilon_\mu \]
Matrix elements of the weak currents between baryon states are

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

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

The factorizable amplitudes are thus given by

\[ A_1^{fac} = -\frac{G_F}{\sqrt{2}} F_c f_A c_k m_A \left[ g_1^{B_i,B_f} (m_A^2) - g_2^{B_i,B_f} (m_A^2) \frac{m_i - m_f}{m_i} \right] \]

\[ A_2^{fac} = \frac{G_F}{\sqrt{2}} F_c f_A c_k m_A \left[ 2 g_2^{B_i,B_f} (m_A^2) / m_i \right] \]

\[ B_1^{fac} = \frac{G_F}{\sqrt{2}} F_c f_A c_k m_A \left[ f_1^{B_i,B_f} (m_A^2) + f_2^{B_i,B_f} (m_A^2) \frac{m_i + m_f}{m_i} \right] \]

\[ B_2^{fac} = -\frac{G_F}{\sqrt{2}} F_c f_A c_k m_A \left[ 2 f_2^{B_i,B_f} (m_A^2) / m_i \right] \]

where \( F_c \) contains appropriate CKM factors and Clebsch-Gordan (CG) coefficients.
### Baryon to baryon transition form factors at $q^2=0$

<table>
<thead>
<tr>
<th>Decay</th>
<th>R. Perez Marcial <em>et al.</em></th>
<th>Cheng and Tseng</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NRQM</td>
<td>HQET</td>
</tr>
<tr>
<td></td>
<td>$f_1$ $f_2$ $g_1$ $g_2$</td>
<td>$f_1$ $f_2$ $g_1$ $g_2$</td>
</tr>
<tr>
<td>$c \to s$ transition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^+ \to \Lambda$</td>
<td>0.35 0.09 0.58 -0.03</td>
<td>0.29 0.14 0.36 0.04</td>
</tr>
<tr>
<td>$\Lambda_c^+ \to \Sigma^0$</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
</tr>
<tr>
<td>$\Xi_c^+ \to \Xi^0$</td>
<td>-0.48 -0.08 -0.73 0.04</td>
<td>-0.37 -0.22 -0.46 -0.07</td>
</tr>
<tr>
<td>$\Xi_c^0 \to \Xi^-$</td>
<td>-0.48 -0.08 -0.73 0.04</td>
<td>-0.37 -0.22 -0.46 -0.07</td>
</tr>
<tr>
<td>$c \to d$ transition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^+ \to n$</td>
<td>-0.22 -0.11 -0.57 0.04</td>
<td>-0.25 -0.14 -0.38 -0.08</td>
</tr>
<tr>
<td>$\Xi_c^+ \to \Sigma^0$</td>
<td>0.22 0.06 0.45 -0.03</td>
<td>0.21 0.16 0.31 0.10</td>
</tr>
<tr>
<td>$\Xi_c^+ \to \Lambda$</td>
<td>0.10 0.03 0.23 -0.02</td>
<td>0.10 0.07 0.16 0.04</td>
</tr>
<tr>
<td>$\Xi_c^0 \to \Sigma^-$</td>
<td>0.32 0.08 0.63 -0.04</td>
<td>0.30 0.23 0.44 0.14</td>
</tr>
<tr>
<td>$c \to u$ transition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^+ \to p$</td>
<td>0.22 0.11 0.56 -0.04</td>
<td>0.25 0.14 0.38 0.08</td>
</tr>
<tr>
<td>$\Xi_c^+ \to \Sigma^+$</td>
<td>0.32 0.08 0.63 -0.04</td>
<td>0.30 0.23 0.44 0.14</td>
</tr>
<tr>
<td>$\Xi_c^0 \to \Sigma^0$</td>
<td>0.22 0.06 0.44 -0.03</td>
<td>0.21 0.16 0.31 0.10</td>
</tr>
<tr>
<td>$\Xi_c^0 \to \Lambda$</td>
<td>-0.10 -0.03 -0.23 0.02</td>
<td>-0.10 -0.07 -0.16 -0.04</td>
</tr>
</tbody>
</table>
W-exchange Processes: Pole Model
Pole Contributions

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

\[
A_i^{\text{pole}} = -\sum_n \left[ \frac{g_{B_j B_n A_k} a_{ni}}{m_i - m_n} + \frac{a_{fn} g_{B_n B_i A_k}}{m_f - m_n} \right]
\]

\[
B_1^{\text{pole}} = \sum_n \left[ \frac{g_{B_j B_n A_k} b_{ni}}{m_i + m_n} + \frac{b_{fn} g_{B_n B_i A_k}}{m_f + m_n} \right]
\]

\[
A_2^{\text{pole}} = B_2^{\text{pole}} = 0
\]

Weak baryon baryon matrix elements $a_{ij}$ and $b_{ij}$ are defined as

\[
\langle B_i \mid H_W \mid B_j \rangle = \bar{u}_{B_i} (a_{ij} + \gamma_5 b_{ij}) u_{B_j}
\]

Matrix elements $b_{ij}$ vanish for hyperons in $SU(3)$ limit.

It is believed that $b_{ij} \ll a_{ij}$ for heavy baryon decays. Moreover, sum of baryon masses appear in the denominator for $B_1^{\text{pole}}$, thereby suppressing the PV pole contributions, which are ignored in this work.
Axial-vector meson coupling with baryons

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

\[ H_{\text{strong}} = \sqrt{2} g_F \left( \frac{1}{2} \bar{B}^{[a,b]d} B_{[a,b]c} A^c_d - \bar{B}^{[d,a]b} B_{[a,c]b} A^c_d \right) \]

\[ + \sqrt{2} g_D \left( \frac{1}{2} \bar{B}^{[a,b]d} B_{[a,b]c} A^c_d + \bar{B}^{[d,a]b} B_{[a,c]b} A^c_d \right) \]

where \( B_{[a,b]c} \), \( B^{[a,b]d} \) and \( A^c_d \) denote the baryon, anti-baryon, and axial-vector meson tensors respectively.

\( g_D \) (\( g_F \)) are conventional D-type and F-type parameters [Z. Phys. C 1, 69 (1979); ibid. 55, 659 (1992); Phys. Rev. D 49, 5921 (1994)].

In the absence of experimental values for these parameters, we use the Goldberger-Treiman relation

\[ g_{N\alpha_i} = \frac{\sqrt{2} g_A m_N}{f_{\alpha_i}} = 8.36 \pm 0.74 \]

for \( g_A = 1.28 \) given by beta-decay [Phys. Rev. D 8, 2190 (1973)].

Following the analysis of G. Erkol [Thesis, 2006] and \( g_F \) are determined as \( g_D = 6.02 \pm 0.77 \), and \( g_F = 2.34 \pm 0.20 \), for \( g_F/(g_F+g_D) = 0.28 \).
### Axial-vector meson-baryon strong coupling constants

<table>
<thead>
<tr>
<th>$B \rightarrow BA$</th>
<th>Coupling constant</th>
<th>$B \rightarrow BA$</th>
<th>Coupling constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow p a_1^0$</td>
<td>$8.36 \pm 0.74$</td>
<td>$\Lambda_c^+ \rightarrow \Sigma^0 a_1^+$</td>
<td>$-6.95 \pm 0.89$</td>
</tr>
<tr>
<td>$p \rightarrow pf_1$</td>
<td>$1.20 \pm 0.92$</td>
<td>$\Lambda_c^+ \rightarrow \Lambda_c^+ a_1^0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\Sigma^+ \rightarrow \Sigma^+ a_1^0$</td>
<td>$4.68 \pm 0.40$</td>
<td>$\Lambda_c^+ \rightarrow \Lambda_c^+ f_1$</td>
<td>$-3.35 \pm 1.10$</td>
</tr>
<tr>
<td>$\Sigma^+ \rightarrow \Lambda a_1^+$</td>
<td>$6.92 \pm 0.23$</td>
<td>$\Lambda_c^+ \rightarrow \Xi^+ K_1^0$</td>
<td>$2.00 \pm 0.66$</td>
</tr>
<tr>
<td>$\Sigma^0 \rightarrow p K_1^-$</td>
<td>$-3.13 \pm 0.67$</td>
<td>$\Lambda_c^+ \rightarrow \Xi_c^+ K_1^0$</td>
<td>$-1.25 \pm 0.40$</td>
</tr>
<tr>
<td>$\Sigma^0 \rightarrow p K_{-1}^-$</td>
<td>$1.95 \pm 0.41$</td>
<td>$\Lambda_c^+ \rightarrow \Xi_{c}^+ K_{-1}^0$</td>
<td>$-4.17 \pm 0.53$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow \Lambda a_1^0$</td>
<td>$0$</td>
<td>$\Lambda_c^+ \rightarrow \Xi_c^+ K_{-1}^0$</td>
<td>$2.60 \pm 0.31$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow p K_1^-$</td>
<td>$-6.39 \pm 0.47$</td>
<td>$\Xi_c^+ \rightarrow \Xi_c^+ a_1^0$</td>
<td>$-1.69 \pm 0.55$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow p K_{-1}^-$</td>
<td>$3.99 \pm 0.30$</td>
<td>$\Xi_c^+ \rightarrow \Xi_c^+ a_1^0$</td>
<td>$-3.47 \pm 0.44$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow \Lambda f_1$</td>
<td>$-3.38 \pm 1.10$</td>
<td>$\Xi_c^+ \rightarrow \Sigma_c^+ K_1^0$</td>
<td>$-4.17 \pm 0.53$</td>
</tr>
<tr>
<td>$\Xi^0 \rightarrow \Lambda \bar{K}_1^0$</td>
<td>$0.57 \pm 0.47$</td>
<td>$\Xi_c^+ \rightarrow \Sigma_c^+ \bar{K}_{-1}^0$</td>
<td>$2.60 \pm 0.33$</td>
</tr>
<tr>
<td>$\Xi^0 \rightarrow \Sigma^0 \bar{K}_1^0$</td>
<td>$-7.09 \pm 0.67$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Weak Transitions

In tensor notation, the weak Hamiltonian is given as

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

where \( c_- = c_1 + c_2 \) and \( c_+ = c_1 - c_2 \).

It has been shown that for baryon-baryon weak transitions the symmetric (,) part of the Hamiltonian, being symmetric in color indices also, does not contribute.

Thus we obtain weak baryon-baryon matrix element \( (a_{ij}) \) by choosing the components in the contraction:

\[ H^{[2,4]}_{[1,3]}, \ H^{[3,4]}_{[1,3]} - H^{[2,4]}_{[1,2]} \]

\[ H_W = a_W [\overline{B}^{[i,j]k} B^{[l,m]k} H^{[l,m]}_{[i,j]}] \]

for CKM-favored and CKM-suppressed modes.
<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching ratio (%)</th>
<th>Asymmetry '$\alpha'$</th>
<th>Branching ratio (%)</th>
<th>Asymmetry '$\alpha'$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Factorizable + Pole</strong></td>
<td>NRQM</td>
<td>HQET</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CKM-favored <em>and</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color suppressed mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^+ \to p\bar{K}_1^0$</td>
<td>2.82 ± 1.40</td>
<td>0.014</td>
<td>1.54 ± 0.62</td>
<td>0.030</td>
</tr>
<tr>
<td>$\Xi_c^+ \to \Sigma^+\bar{K}_1^0$</td>
<td>0.010 ± 0.002</td>
<td>0.038</td>
<td>0.24 ± 0.06</td>
<td>-0.029</td>
</tr>
<tr>
<td>$\Xi_c^0 \to \Lambda\bar{K}_1^0$</td>
<td>0.038 ± 0.011</td>
<td>0.028</td>
<td>0.51 ± 0.30</td>
<td>0.018</td>
</tr>
<tr>
<td>$\Xi_c^0 \to \Sigma^0\bar{K}_1^0$</td>
<td>0.039 ± 0.008</td>
<td>-0.006</td>
<td>0.0032 ± 0.0008</td>
<td>0.082</td>
</tr>
<tr>
<td><strong>CKM-suppressed mode</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(i) Color-favored mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^+ \to na_1^+$</td>
<td>0.35 ± 0.12</td>
<td>0.017</td>
<td>0.26 ± 0.08</td>
<td>0.036</td>
</tr>
<tr>
<td>$\Xi_c^+ \to \Lambda a_1^+$</td>
<td>1.20 ± 0.24</td>
<td>-0.012</td>
<td>0.84 ± 0.25</td>
<td>0.014</td>
</tr>
<tr>
<td>$\Xi_c^+ \to \Sigma^0 a_1^+$</td>
<td>0.48 ± 0.10</td>
<td>-0.016</td>
<td>0.18 ± 0.04</td>
<td>0.048</td>
</tr>
<tr>
<td>$\Xi_c^0 \to \Sigma^- a_1^+$</td>
<td>0.14 ± 0.10</td>
<td>-0.024</td>
<td>0.033 ± 0.010</td>
<td>0.071</td>
</tr>
<tr>
<td>(ii) Color-suppressed mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^+ \to pa_1^0$</td>
<td>0.072 ± 0.014</td>
<td>0.011</td>
<td>0.035 ± 0.024</td>
<td>0.029</td>
</tr>
<tr>
<td>$\Lambda_c^+ \to pf_1$</td>
<td>0.10 ± 0.06</td>
<td>0.014</td>
<td>0.054 ± 0.043</td>
<td>0.032</td>
</tr>
<tr>
<td>$\Xi_c^+ \to \Sigma^+ a_1^0$</td>
<td>0.095 ± 0.019</td>
<td>-0.018</td>
<td>0.037 ± 0.007</td>
<td>0.045</td>
</tr>
<tr>
<td>$\Xi_c^0 \to \Lambda a_1^0$</td>
<td>0.0040 ± 0.0012</td>
<td>-0.028</td>
<td>0.076 ± 0.022</td>
<td>0.007</td>
</tr>
<tr>
<td>$\Xi_c^0 \to \Lambda f_1$</td>
<td>0.0034 ± 0.0007</td>
<td>-0.013</td>
<td>0.0021 ± 0.0004</td>
<td>0.051</td>
</tr>
<tr>
<td>$\Xi_c^0 \to \Sigma^0 a_1^0$</td>
<td>0.00044 ± 0.00035</td>
<td>0.072</td>
<td>0.0035 ± 0.0021</td>
<td>-0.057</td>
</tr>
<tr>
<td>Decay</td>
<td>Branching ratio (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------------</td>
<td>---------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CKM-favored mode</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Xi_c^0 \rightarrow \Sigma^+ K_1^-$</td>
<td>0.13 ± 0.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CKM-suppressed mode</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Xi^+_c \rightarrow p \bar{K}_1^0$</td>
<td>0.56 ± 0.19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Xi^+_c \rightarrow p \bar{K}<em>1^-</em>{-1}$</td>
<td>0.14 ± 0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Xi^0_c \rightarrow p K_1^-$</td>
<td>0.028 ± 0.007</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Xi^0_c \rightarrow p K^-_{-1}$</td>
<td>0.0068 ± 0.0017</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Xi^0_c \rightarrow n \bar{K}_1^0$</td>
<td>0.045 ± 0.020</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Xi^0_c \rightarrow n \bar{K}<em>1^-</em>{-1}$</td>
<td>0.011 ± 0.005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Xi_c^0 \rightarrow \Sigma^+ a_1^-$</td>
<td>0.016 ± 0.004</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

• Unlike meson decays, W-exchange diagrams play significant role in weak hadronic decays of heavy flavor baryons.

• Factorization scheme and Pole model approaches work reasonably well in evaluating W-emission and W-exchange processes respectively.

• P-wave meson emitting decays of charm baryons compete well with s-wave meson emitting counterparts.

• Experimental searches should be made for these decays, which would decide the relative strengths of W-emission and W-exchange terms.