Two-body charmed-baryon weak decays

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We explore two-body charmed-baryon weak decays to examine the relevance of pole-term contributions to the total amplitude. As in the hyperon sector, the importance of the pole term in the charm sector should not be overlooked. The decay $\Lambda_c^+ \to \Xi^0 K^+$ may provide a positive test for the pole model.

I. INTRODUCTION

In recent years, numerous efforts have been made to study the weak decays of charmed baryons.[1–4] The relatively simple picture of strangeness-changing weak decays encounters difficulties when applied to D-meson decays. Additional mechanisms are being searched for to explain the observed discrepancies. Quark-annihilation contributions,[5] QCD effects,[6] and final-state interactions[7] may be important to resolve the problem.

A similar situation exists in the baryon sector. Generalizing the theory of hyperon decays to the charm sector, the charmed-baryon decay amplitudes receive contribution from commutator (s-wave) and ground-state pole (p-wave) approximations added up by the separable contributions. However, of late, the factorization approximation alone is being considered as of vital importance,[8] in analogy with the analysis of charmed-meson decays. The equal-time commutator (ETC) term may or may not be added.[4,8] In this paper, we explore the relevance of pole-term contributions to the total amplitude of charmed-baryon decays and find that these contributions are relevant. As the bulk of the nonleptonic charm decays consist of Cabibbo-favored channels, we consider here $\Delta C = \Delta S = 1$ decays only. For definiteness, we choose the processes $\Lambda_c^+ \to \Lambda\pi^+$, $p\bar{K}^0$, $\Sigma^0\pi^+$, $\Xi^0 K^+$, and $\Xi_c'^0 \to \Xi^-\pi^+$. The effective weak Hamiltonian belongs dominantly to 20″. We compare our results for the decays $\Lambda_c^+ \to \Lambda\pi^+, p\bar{K}^0$ with the recent calculations made by Pakvasa, Rosen, and Tuan[4] excluding the pole term.

In Sec. II we define the effective weak Hamiltonian and outline our basic contributions in Sec. III. Details of numerical calculations are given in Sec. IV, followed by the discussion of weak amplitudes and general results in Sec. V. We summarize our conclusions in Sec. VI.

II. WEAK HAMILTONIAN

The effective weak Hamiltonian including the QCD corrections and SU(4)-flavor-symmetry breaking has the form

$$H_w^{\text{eff}}(\Delta S=1,\Delta C=1)=\left[\frac{G_F\cos^2\theta_c}{\sqrt{2}}\right][C_1(\bar{u}d)_L(\bar{s}c)_L + C_2(\bar{s}d)_L(\bar{u}c)_L] , \tag{1}$$

where the notation $(\bar{q}q)_L$ means $\frac{1}{2}\bar{q}\gamma_\mu(1-\gamma_5)q$. Quark and color exchange effects between quark currents are absorbed in the real coefficients C_1 and C_2. They are related to the QCD short-distance coefficients C_+ and C_- as

$$\begin{aligned} C_+ &= C_1 - C_2, \quad C_- = C_1 + C_2 , \\ C_1 &= \tfrac{1}{2}(C_+ + C_-), \quad C_2 = \tfrac{1}{2}(C_- - C_+) . \end{aligned} \tag{2}$$

The values of C_1 and C_2 range from 1.1 to 1.4 and 0.4 to 0.7, respectively.

III. DYNAMICS

The dynamics of the charm sector follows in analogy with the hyperon sector. The matrix element for the baryon decay process

$$B_c \to B + P \tag{3}$$

is expressed as

$$-\langle BP|H_w|B_c\rangle = \bar{u}_B(A + B\gamma_5)u_{B_c}\phi_M , \tag{4}$$

where A and B are the (parity-violating) s-wave and (parity-conserving) p-wave amplitudes, respectively. The three-hadron matrix element may be reduced to the baryon-baryon transition matrix element of H_w by applying the standard current-algebra techniques along with the PCAC (partial conservation of axial-vector current) hypothesis[9] as

$$= \frac{1}{f_P}\langle B|[Q_i^5, H_w]|B_c\rangle + P(q) + R(q) . \tag{5}$$

Here Q_i^5 is the axial-vector generator associated with the meson P_i and f_P is the pseudoscalar-meson decay constant ($f_\pi = 93$ MeV, $f_K = 1.28 f_\pi$). Besides the commutator term, the matrix element contains contributions from the possible pole diagrams denoted by $P(q)$ and the quark decay diagrams denoted by $R(q)$. The latter term takes the form of factorizable product of two current matrix elements when inserting vacuum intermediate states, and vanishes in the soft-meson limit. As $\langle B'|H_w^{\rm PV}|B\rangle=0$, the parity-conserving amplitude receives contributions from the pole terms and factorization terms[9] as

$$B=B^{\rm pole}+B^{\rm fac}$$
$$=\frac{g_{lki}a_{jl}}{m_j-m_l}\frac{m_j+m_k}{m_l+m_k}\quad (s\text{-channel term})$$
$$+\frac{g_{jl'i}a_{l'k}}{m_k-m_{l'}}\frac{m_j+m_k}{m_j+m_{l'}}\quad (u\text{-channel term})$$
$$+f_B\left[\frac{G_F\cos^2\theta_C}{\sqrt{2}}\right]\langle B|J_\mu^A|B_c\rangle\langle M|J_\mu|0\rangle\ , \quad (6)$$

where J_μ^A is the axial-vector part of the weak current that contributes to the parity-conserving amplitude. a_{jl} are the baryon matrix elements of the parity-conserving Hamiltonian and g_{lki} are the strong baryon-pion coupling constants. l and l' are the indices for the intermediate baryon states in the s and u channels, respectively.

Correspondingly, the parity-violating amplitude A is added by contributions from the equal-time commutator and factorization terms:[9]

$$A=A^{\rm ETC}+A^{\rm fac}$$
$$=\frac{1}{f_P}\langle B|[Q_i^5,H_w]|B_c\rangle$$
$$+f_B\left[\frac{G_F\cos^2\theta_C}{\sqrt{2}}\right]\langle B|J_\mu^V|B_c\rangle\langle M|J_\mu|0\rangle\ . \quad (7)$$

J_μ^V is the vector part of the weak current.

IV. CALCULATIONS

We first calculate the factorization term, which is just the statement that

$$\langle BP|H_w|B_c\rangle=(C_1/C_2)\left[\frac{G_F\cos^2\theta_c}{\sqrt{2}}\right]\times\langle B|J_\mu|B_c\rangle\langle M|J_\mu|0\rangle\ . \quad (8)$$

With the first-order parametrization

$$\langle B|\bar q_f\gamma_u(1+\gamma_5)q_i|B_c\rangle=\bar u_B[i\gamma_u(f_1+\gamma_5 g_1)]u_{B_c} \quad (9)$$

it reduces to the form

$$\langle BP|H_w|B_c\rangle=\bar u_B[(m_{B_c}-m_B)f_1-(m_B+m_{B_c})g_1\gamma_5]u_{B_c} \quad (10)$$

where the first term corresponds to the parity-violating amplitude $A^{\rm fac}$ and the second term represents the parity-conserving amplitude $B^{\rm fac}$. For numerical values of form factors, we use the fit to semileptonic decays: $\Lambda_c^+\to\Lambda e^+\nu$ and $\Xi_c'^0\to\Xi^- e^+\nu$, given recently by Avila-Aoki *et al.* and Perez Marcial *et al.*[10] in the bag model and for dipole form factors. Further, the form factors for $\Lambda_c^+\to p$ are related to that of $\Lambda_c^+\to\Lambda$ by an SU(3) factor of $\sqrt{3/2}$. For masses of the baryons, we use the values of the Particle Data Group, 1990.[12] The calculated values for all the five decays are listed in Table I.

The pole-term contribution is given by the standard formula (6). The various terms of baryon intermediate states contributing to the five processes listed above are $\{(\Sigma^+,\Sigma_c^0);\Sigma^+;(\Sigma^+,\Sigma_c^0);\ (\Sigma^+,\Xi_c^0,\Xi_c'^0);\Xi^0\}$. The matrix elements a_{jl} for these processes are related as

$$a_{\Lambda_c^+\Sigma^+}=a_{\Sigma_c^0\Lambda}=a_{\Xi_c'^0\Xi^0}$$
$$=-\frac{1}{\sqrt{3}}a_{\Sigma_c^0\Sigma^0}=\frac{1}{\sqrt{3}}a_{\Sigma_c^+\Sigma^+}\ . \quad (11)$$

The matrix element $a_{\Lambda_c^+\Sigma^+}$ is related by SU(4) symmetry to the matrix element $a_{\Sigma^+p}=\langle p|H_w^{\rm PC}|\Sigma^+\rangle$, which has been estimated in a number of ways, e.g., by model calculations,[11] by fitting s-wave hyperon decays, and by fitting p-wave hyperon decays. For calculation purposes, we

TABLE I. Numerical estimates for the various terms contributing to the s- and p-wave amplitudes for differing decay processes.

Amplitude (10^6)	Factorization term	Commutator or pole term	Total
$A(\Lambda_c^+\to\Lambda\pi^+)$	−0.59	0.0	−0.59
$A(\Lambda_c^+\to p\bar K^0)$	0.49	1.24	1.73
$A(\Lambda_c^+\to\Sigma^0\pi^+)$	0.0	2.25	2.25
$A(\Lambda_c^+\to\Xi^0 K^+)$	0.0	0.0	0.0
$A(\Xi_0'^0\to\Xi\pi^+)$	0.746	−1.59	−0.84
$B(\Lambda_c^+\to\Lambda\pi^+)$	1.88	0.96	2.84
$B(\Lambda_c^+\to p\bar K^0)$	−1.8	−1.24	−3.04
$B(\Lambda_c^+\to\Sigma^0\pi^+)$	0	0.26	0.26
$B(\Lambda_c^+\to\Xi^0 K^+)$	0	−1.74	−1.74
$B(\Xi_c'^0\to\Xi^-\pi^+)$	−2.64	−1.09	−3.73

TABLE II. Values of decay rate Γ in units of 10^{11} sec^{-1} and asymmetry parameter α. (a) Values for symmetric couplings. (b) Values for broken couplings. (c) Experimental numbers.

Decay mode	Decay rate Γ (a)	(b)	(c)	Asymmetry parameter α (a)	(b)	(c)
$\Lambda_c^+ \to \Lambda\pi^+$	1.49	1.0	0.28	-0.90	-0.97	$-1.0^{+0.4}_{-0.0}$
$\Lambda_c^+ \to p\bar{K}^0$	4.48	3.96	0.84	-0.93	-0.84	(Ref. 15)
$\Lambda_c^+ \to \Sigma^0\pi^+$	5.84	5.86		0.07	-0.143	
$\Lambda_c^+ \to \Xi^0 K^+$	0.157	0.83		0	0	
$\Xi_c'^0 \to \Xi^-\pi^+$	2.65	2.31		-0.96	-0.98	

take the value

$$\langle p|H_w^{PC}|\Sigma^+\rangle = 1.2\times10^{-7}\ \text{GeV} \tag{12}$$

obtained from p-wave hyperon decay and which is in fair agreement with the model estimate. Other matrix elements are evaluated through relation (11). The strong meson-baryon coupling constants are evaluated using SU(4) symmetry. We also compare our results with those for broken-SU(4) symmetry.[13] The symmetry is broken using the generalized Goldberger-Treiman relation.

Finally, we calculate the contribution of the commutator term given by (7). The $V-A$ structure of H_w leads to $[Q_i^5, H_w^{PV}] = [Q_i, H_w^{PC}]$, so that

$$A^{\text{ETC}} = \frac{1}{f_P}\langle B|[Q_i, H_w^{PC}]|B_c\rangle\ . \tag{13}$$

Further, by SU(3) rotation the matrix element (13) for all the above decays is related to $\langle\Sigma^+|H_w^{PC}|\Lambda_c^+\rangle$ and $\langle\Xi^0|H_w^{PC}|\Xi_c'^0\rangle$. The numerical values of these are the same as used for the pole-term calculations.

Table I contains estimates for the factorization terms, pole contributions, and the commutator terms contributing to the A and B amplitudes of various decays. The computed values of the decay rate and asymmetry parameter, both for symmetric and broken couplings, are listed in Table II along with the available experimental numbers.

V. WEAK DECAY AMPLITUDES AND DISCUSSION

We find the contributions to A and B amplitudes for the $\Lambda_c^+ \to \Lambda_\pi^+$ and $\Lambda_c^+ \to p\bar{K}^0$ modes as

$$A_{\Lambda\pi^+}^{\text{ETC}} = 0,\quad A_{p\bar{K}^0}^{\text{ETC}} = \frac{-1}{f_K} a_{\Lambda_c^+\Sigma^+}\ ,$$

$$B_{\Lambda\pi^+}^{P} = \frac{g_{\Sigma\Lambda\pi} a_{\Lambda_c^+\Sigma^+}}{m_{\Lambda_c} - m_\Sigma}\frac{m_{\Lambda_c}+m_\Lambda}{m_\Lambda + m_\Sigma} + \frac{g_{\Lambda_c\Sigma_c\pi} a_{\Sigma_c^0\Lambda}}{m_\Lambda - m_{\Sigma_c}}\frac{m_{\Lambda_c}+m_\Lambda}{m_{\Lambda_c}+m_{\Sigma_c}}\ ,$$

$$B_{p\bar{K}^0}^{P} = -\frac{g_{\Sigma NK} a_{\Lambda_c^+\Sigma^+}}{m_{\Lambda_c} - m_\Sigma}\frac{m_{\Lambda_c}+m_n}{m_\Sigma + m_n}\ , \tag{14}$$

$$\begin{bmatrix} A^{\text{fac}} \\ B^{\text{fac}} \end{bmatrix}_{\Lambda\pi^+} = C_1 f_\pi \left[\frac{G_F\cos^2\theta_C}{\sqrt{2}}\right] \times \bar{u}_\Lambda[(0.538\ \text{GeV}) - (1.7\ \text{GeV})\gamma_5]u_{\Lambda_c}\ ,$$

$$\begin{bmatrix} A^{\text{fac}} \\ B^{\text{fac}} \end{bmatrix}_{p\bar{K}^0} = C_2 f_K \left[\frac{G_F\cos^2\theta_c}{\sqrt{2}}\right] \times \bar{u}_p[(0.76\ \text{GeV}) - (1.97\ \text{GeV})\gamma_5]u_{\Lambda_c}\ .$$

Here we have used $C_1 = 1.1$ and $C_2 = 0.5$. Also the pole term is calculated for both the symmetric and broken coupling-constant values. The numerical values are tabulated in Table I. Comparison of the decay rate values for symmetric and broken couplings is made in Table II. We find that the pole term contributes significantly to the parity-conserving amplitude. As such there is no reason, *a priori*, to neglect it. Further it is observed from Table II that the contributions of the pole term for symmetry-broken couplings lead to better consistency with experimental data. As it turns out, our prediction for $\Lambda_c^+ \to \Lambda\pi^+$ compares with a recent estimate made by Pakvasa *et al.* excluding the pole term and is a factor of 3 larger than the experimental value.[14] On the other hand, our rate $\Gamma(\Lambda_c^+ \to p\bar{K}^0)$ is a factor of 1.33 larger than theirs. However, our ratio $\Gamma(\Lambda_c^+\to\Lambda\pi^+)/\Gamma(\Lambda_c^+\to p\bar{K}^0) \simeq 0.25$ is consistent with the experimental data, which give <0.26.[12] Our value for the asymmetry parameter α, for $\Lambda_c^+\to\Lambda\pi^+$, is comparable to that of Pakvasa *et al.* and also the experiment.[15]

We find the $\Lambda_c^+ \to \Xi^0 K^+$ mode particularly interesting as the total amplitude receives a contribution only from the pole term:

$$B_{\Xi^0 K^+}^{P} = \sqrt{2}\frac{g_{\Xi\Sigma K} a_{\Lambda_c^+\Sigma^+}}{m_{\Lambda_c} - m_\Sigma}\frac{m_{\Lambda_c}+m_\Xi}{m_\Xi + m_\Sigma} + \frac{g_{\Lambda_c\Xi_c K} a_{\Xi_c^0\Xi}}{m_\Xi - m_{\Xi_c}}\frac{m_{\Lambda_c}+m_\Xi}{m_{\Lambda_c}+m_{\Xi_c}} + \frac{g_{\Lambda_c\Xi_c' K} a_{\Xi_c'^0\Xi^0}}{m_\Xi - m_{\Xi_c}}\frac{m_{\Lambda_c}+m_\Xi}{m_{\Lambda_c}+m_{\Xi_c^0}}\ . \tag{15}$$

The rate calculated from (15) for broken couplings $=0.83\times10^{-11}$ sec^{-1}. Generalizing the above observations to this mode, the decay rate here also may be overestimated by a factor of about 3, but the crucial point is that the experimental observations on this are a pertinent test for the pole model.

Similarly, for the decays $\Lambda_c \rightarrow \Sigma^0\pi^+, \Xi_c'^0 \rightarrow \Xi^-\pi^+$, the individual contributions are

$$A^{\text{ETC}}_{\Sigma^0\pi^+} = \frac{\sqrt{2}}{f_\pi} a_{\Lambda_c^+\Sigma^+} , \quad A^{\text{ETC}}_{\Xi^-\pi^+} = \frac{1}{f_\pi} a_{\Xi_c'^0\Xi^0} ,$$

$$B^P_{\Sigma^0\pi^+} = -\frac{g_{\Sigma\Sigma\pi} a_{\Lambda_c^+\Sigma^+}}{m_{\Lambda_c} - m_\Sigma} \frac{m_{\Lambda_c} + m_\Sigma}{2m_\Sigma} + \frac{g_{\Lambda_c\Sigma_c\pi} a_{\Sigma_c^0\Sigma}}{m_\Sigma - m_{\Sigma_c}} \frac{m_{\Lambda_c} + m_\Sigma}{m_{\Lambda_c} + m_{\Sigma_c}} ,$$

$$B^P_{\Xi^-\pi^+} = \sqrt{2} \frac{g_{\Xi\Xi\pi} a_{\Xi_c'^0\Xi^0}}{m_{\Xi_c'} - m_\Xi} \frac{m_{\Xi_c'} + m_\Xi}{2m_\Xi} , \qquad (16)$$

$$\begin{bmatrix} A^{\text{fac}} \\ B^{\text{fac}} \end{bmatrix}_{\Sigma^0\pi^+} = 0 ,$$

$$\begin{bmatrix} A^{\text{fac}} \\ B^{\text{fac}} \end{bmatrix}_{\Xi^-\pi^+} = C_1 f_\pi \left[\frac{G_F \cos^2\theta_C}{\sqrt{2}} \right] \times \bar{u}_\Xi [(67 \text{ GeV}) - (2.38 \text{ GeV})\gamma_5] u_{\Xi_c'^0} .$$

In this case also the effect of the addition of a pole term is to reduce the branching ratio $\Gamma(\Lambda_c^+ \rightarrow \Sigma^0\pi^+)/\Gamma(\Lambda_c^+ \rightarrow p\bar{K}^0)$ from 1.65 to 1.47, thereby leading to better consistency with data. However, in the absence of any data for the $\Xi_c'^0 \rightarrow \Xi^-\pi^+$ mode, we cannot make any definite conclusion. Consequently, we look forward to the time when sufficient data become available to bear testimony to these observations and calculations.

In the published version of their paper, which appeared after the submission of the present paper, Pakvasa *et al.* have discussed the pole-term contribution to the $\Lambda_c^+ \rightarrow \Lambda\pi^+$ and $\Lambda_c^+ \rightarrow p\bar{K}^0$ decays. They have used the form

$$B^{\text{pole}} = \frac{g_{lki} a_{jl}}{m_j - m_l} \ (s \text{ channel}) + \frac{8 g_{jl'i} a_{l'k}}{m_k - m_{l'}} \ (u \text{ channel}) ,$$

which differs from our expression in the neglect of terms of the order of $\Delta m_B / 2m_B$, for example $(m_{\Lambda_c} - m_\Sigma)/(m_\Lambda + m_\Sigma)$ for $\Lambda_c^+ \rightarrow \Lambda\pi^+$. Their estimation of the pole term gives 10–20% contribution to the total PC amplitude and so may be neglected. However, since SU(4) symmetry is badly broken, it is apt to include the symmetry-breaking effects for the charm sector. The pole term[16] is then given by Eq. (6) of the text. The numerical estimation shows that the fractional contribution from pole terms is now enhanced to about 40% and so their neglect is not justified.

Before concluding this section, we would like to mention that, in general, the calculated values for charmed-baryon decay rates are larger than the corresponding experimental values. It is realized in our estimations that the calculations are very sensitive to the choice of the values of C_1 and C_2 and hence C_- and C_+. Various authors have varied the values[17] from 1.6–5.0 and 0.45–0.78 for C_- and C_+, respectively. A clear consensus on these might provide further insight to our understanding of the QCD effects in hadronic decays.

VI. CONCLUSIONS

We have applied current-algebra techniques to charmed-baryon decays with the aim of testing the relevance of the pole model to heavier baryons. It is seen that the pole term contributes significantly to the parity-conserving amplitude. The meager available data also accentuate its contributions, but we must await sufficient data to discern its relevance. The decay $\Lambda_c^+ \rightarrow \Xi^0 K^+$ may provide conclusive evidence of its pertinence. The future experimental data will, therefore, be able to test these predictions. Also, a more detailed study on QCD effects in hadronic decays is desired to enable their better understanding.

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