Charm-conserving strangeness-changing two body hadronic decays of charmed baryons

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The charm-conserving strangeness-changing two body hadronic decays of charmed baryons are examined in the SU(4) symmetry scheme. In addition to the **20**″ Hamiltonian, we consider a **15** piece of the weak Hamiltonian which may arise due to SU(4) breaking or due to some nonconventional dynamics. The numerical estimates for decay widths of some of the modes are presented.

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I. INTRODUCTION

The hyperon nonleptonic weak decays have so far evaded our complete understanding [1]. It is expected that the hadronic decays of the charmed and heavier baryons will be simpler and their study would help in the understanding of the nonleptonic decay processes, in general. Recently, the study of hadronic two body decays of the charmed baryons has gained some attention [2]. It is primarily due to the fact that some data on these decays have already started coming and more experimental information on these decays is expected in the near future. The scarce data [3] which are available at present are already beginning to discriminate between the models.

In this paper, we study the heavy flavor-conserving weak decays of charmed baryons such as $\Xi_c \to \Lambda_c \pi$ and $\Omega_c \to \Xi_c \pi$. These decays are singly Cabibbo suppressed. But, since the enhancement of the strangeness-changing Hamiltonian is more than the one for the charm-changing decays the suppression of the charm-nonchanging strangeness-changing decays of the charmed baryons may not be as much as given by the Cabibbo factor and so these decays may be observed in the near future as more data come from the ARGUS and CLEO Collaborations as well as from CERN and Fermilab experiments. Further, these decays could be of theoretical interest, as they are described by the same Hamiltonian which is responsible for the hyperon decays and may throw some light on the dynamics of the hyperon decays. Cheng *et al.* [4] have studied these decays in the heavy quark approximation with the help of chiral perturbation theory. They have assumed that the c quark does not participate in the weak interaction and acts as a spectator. We feel that their approximation is far from realistic. We study these decays in the framework of SU(4) symmetry, a limit opposite to the one considered by Cheng *et al.* In the SU(4) limit c quarks and u quarks play a role on the same footing. The reality will be somewhere in between. We also study some of the charm-changing decays in the same framework with the hope of learning about their departure from SU(4) symmetry considerations. The amplitudes we obtain are of the same order of magnitude as in Ref. [4], though some numbers are different.

II. WEAK HAMILTONIAN

The hadronic part of the weak left-handed quark current

$$J_\mu = \bar{u}\gamma_\mu(1-\gamma_5)(d\cos\theta + s\sin\theta) + \bar{c}\gamma_\mu(1-\gamma_5)(s\cos\theta - d\sin\theta) \quad (1)$$

transforms like the **15** representation of SU(4). The general weak current × weak current Hamiltonian

$$H_W = \frac{G}{2\sqrt{2}}(J^\mu J_\mu^\dagger + \text{H.c.}) \quad (2)$$

may thus belong to the SU(4) representation present in the direct product

$$\mathbf{15}\times\mathbf{15} = 1 + \mathbf{15}_A + \mathbf{15}_S + \mathbf{20}'' + \mathbf{45} + \mathbf{45}^* + \mathbf{84}. \quad (3)$$

Because of the symmetric nature of the Hamiltonian, only the representations **1**, $\mathbf{15}_S$, **20**″, and **84** contribute. The singlet cannot contribute to the strangeness- or charm-changing decays. It is also a specific property of the Glashow-Iliopoulos-Maiani (GIM) Hamiltonian that bilinears in current do not contain adjoint representation in the exact SU(4) limit. Therefore, **15** does not contribute also. The GIM Hamiltonian thus transforms as

$$H_W^{\text{GIM}} = H_W^{\mathbf{20}''} + H_W^{\mathbf{84}}. \quad (4)$$

A. Hyperon decays

The experimental data on hyperon decays imply that the nonleptonic Hamiltonian is dominated by the octet of SU(3) whereas the current × current picture assigns equal strength to the **8** and **27** representations of SU(3). Further, within the framework of the conventional theory

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it has not been possible to fit the s-wave and p-wave hyperon decay amplitudes simultaneously in any consistent manner, even if the octet dominance is assumed. The enhancement of the octet piece due to the renormalization caused by the strong interaction has been proved [5,6], but the numerical estimate of the enhancement factor is below the required value. The solution to the problem seems to require the addition of a new nonconventional SU(3)-octet piece of the weak Hamiltonian for nonleptonic decays. Several attempts to generate a new piece through Higgs-scalar meson exchange [7], the introduction of right-handed currents [8], and specific spontaneous symmetry breakdown [9] have been made in the past. In these attempts it has been assumed that the new nonconventional octet dominates the nonleptonic Hamiltonian for the parity-violating part. It has also been suggested [10] that there may be a $\Delta I = \frac{1}{2}$ parity-violating quark tadpole piece of the Hamiltonian due to an $s \rightarrow$d self-energy (W-loop) transition, which cannot be transformed away.

We believe that the effective Hamiltonian for the nonleptonic decays must contain both the current-current theory octet and a nonconventional octet. At the SU(4) level, since the **15** representation of SU(4) is not contained in the current-current Hamiltonian [11], the enhanced octet must be a part of the **20″** representation of SU(4). A nonconventional octet piece is phenomenologically equivalent to a tadpole model [12] and hence belongs to the **15** representation of SU(4). This octet cannot contribute to the parity-conserving process because the tadpole term in the Hamitonian can be transformed away [12]. Hence the only term contributing to the parity-conserving baryon decays is the enhanced conventional octet belonging to the **20″** of SU(4). This octet gives a reasonable fit to the observed PC amplitudes. The parity-violating decays, however, can obtain contributions, in general, from both the conventional and nonconventional octets belonging to the **20″** and **15** representations of SU(4), respectively.

B. Charmed baryon decays

In the very first work on the nonleptonic weak interactions in SU(4) [13], it was observed that the **20″** dominance works up to about 40%. The SU(4) breaking thus plays an important role at least in the parity-violating mode. The $\mathbf{15}_S$ representation may reappear through the SU(4) breaking [14] or as argued above through other considerations. We shall include the admixture of **15** in the weak interaction. The most general weak Hamiltonian for $B_i \rightarrow B_f + P$ decays is then given by

$$H_W^{\mathrm{GIM}} = H_W^{\mathbf{20}''} + H_W^{\mathbf{84}} + H_W^{\mathbf{15}}, \tag{5}$$

where

$$\begin{aligned} H_W^{\mathbf{20}''} = {} & a_1 \bar{B}^c_{[a,b]} B^{[n,d]}_m P^m_n H^{[a,b]}_{[c,d]} + a_2 \bar{B}^m_{[a,b]} B^{[n,c]}_m P^d_n H^{[a,b]}_{[c,d]} + a_3 \bar{B}^m_{[a,b]} B^{[c,d]}_n P^n_m H^{[a,b]}_{[c,d]} \\ & + a_4 \bar{B}^m_{[n,b]} B^{[c,d]}_a P^n_m H^{[a,b]}_{[c,d]} + a_5 \bar{B}^n_{[m,a]} B^{[c,d]}_n P^m_b H^{[a,b]}_{[c,d]} + a_6 \bar{B}^c_{[m,n]} B^{[m,n]}_a P^d_b H^{[a,b]}_{[c,d]} + a_7 \bar{B}^m_{[n,a]} B^{[n,c]}_m P^d_b H^{[a,b]}_{[c,d]}, \end{aligned} \tag{5a}$$

$$\begin{aligned} H_W^{\mathbf{84}} = {} & b_1 \bar{B}^c_{[e,f]} B^{[e,f]}_a P^d_b H^{(a,b)}_{(c,d)} + b_2 \bar{B}^c_{[f,a]} B^{[e,d]}_b P^f_e H^{(a,b)}_{(c,d)} + b_3 \bar{B}^e_{(a,f)} B^{(c,f)}_e P^d_b H^{(a,b)}_{(c,d)} \\ & + b_4 \bar{B}^e_{[a,f]} B^{[c,f]}_b P^d_e H^{(a,b)}_{(c,d)} + b_5 \bar{B}^c_{[a,f]} B^{[d,f]}_e P^e_b H^{(a,b)}_{(c,d)} + b_6 \bar{B}^c_{[e,f]} B^{[e,d]}_a P^f_b H^{(a,b)}_{(c,d)} + b_7 \bar{B}^c_{[e,a]} B^{[e,f]}_b P^d_f H^{(a,b)}_{(c,d)}, \end{aligned} \tag{5b}$$

$$\begin{aligned} H_W^{\mathbf{15}} = {} & A_1 \bar{B}^m_{[n,c]} B^{[b,c]}_a P^n_m H^a_b + A_2 \bar{B}^m_{[c,d]} B^{[c,d]}_a P^b_m H^a_b + A_3 \bar{B}^m_{[d,a]} B^{[b,d]}_c P^c_m H^a_b \\ & + A_4 \bar{B}^b_{[m,c]} B^{[c,d]}_a P^m_d H^a_b + A_5 \bar{B}^c_{[m,d]} B^{[b,d]}_c P^m_a H^a_b + A_6 \bar{B}^c_{[m,a]} B^{[b,d]}_c P^m_d H^a_b + A_7 \bar{B}^m_{[c,d]} B^{[c,d]}_m P^b_a H^a_b \\ & + A_8 \bar{B}^b_{[c,d]} B^{[c,d]}_m P^m_a H^a_b + A_9 \bar{B}^m_{[a,d]} B^{[d,c]}_m P^b_c H^a_b + A_{10} \bar{B}^b_{[a,d]} B^{[d,n]}_m P^m_n H^a_b, \end{aligned} \tag{5c}$$

where $B^{[a,b]}_c, P^a_b$, and $H^{[a,b]}_{[c,d]}, H^{(a,c)}_{(c,d)}, H^a_b$ denote **20′** baryon, **15** meson, and **20″**, **84**, **15** weak spurions, respectively. CP dominance demands

$$a_1 = -a_4, a_2 = -a_5; a_3 = a_6 = a_7 = 0, \tag{6a}$$

$$b_4 = -b_5, b_6 = -b_7; b_1 = b_2 = b_3 = 0, \tag{6b}$$

$$A_1 = A_{10}, A_2 = -A_8, A_5 = A_9, A_3 = A_4 = A_6 = A_7 = 0, \tag{6c}$$

for the PV mode and

$$a_1 = a_4, a_2 = a_5, \tag{7a}$$

$$b_4 = b_5, b_6 = b_7, \tag{7b}$$

$$A_1 = -A_{10}, A_2 = A_8; a_5 = -A_9, \tag{7c}$$

for the PC mode. We ignore the **84** piece of the weak Hamiltonian because for the $\Delta S = 1$ decays it is not enhanced. For $\Delta C = 1$ decays also it is usually ignored though it may contribute in those processes. But we do not consider them here in detail.

III. DECAY AMPLITUDES AND DECAY RATES

The matrix element for the baryon decay process is written as

$$M = -\langle B_f P | H_W | B \rangle = \bar{u}_{B_f}(A + \gamma_5) u_{B_i} \phi_P, \tag{8}$$

where A and B are parity-violating and parity-conserving amplitudes respectively. For the Cabibbo allowed ($\Delta C = \Delta S = 1$) mode the effective weak Hamiltonian is

$$H^{\rm eff} = \frac{G}{2\sqrt{2}} \cos^2\theta_C [\bar{u}\gamma_\mu(1-\gamma_5)d][\bar{s}\gamma^\mu(1-\gamma_5)c], \quad (9)$$

whereas for the $\Delta C = 0, \Delta S = 1$ mode which we are considering, it is

$$H^{eff} = \frac{G}{2\sqrt{2}} \cos\theta_C \sin\theta_C [\bar{u}\gamma_\mu(1-\gamma_5)d][\bar{s}\gamma^\mu(1-\gamma_5)u] - \frac{G}{2\sqrt{2}} \cos\theta_C \sin\theta_C [\bar{c}\gamma_\mu(1-\gamma_5)d] \times [\bar{s}\gamma^\mu(1-\gamma_5)c]. \quad (10)$$

Therefore, only $H^{13}_{12} = -H^{34}_{24}$ is nonzero in $\Delta C = 0, \Delta S = 1$ processes. The decay width is computed from

$$\Gamma = C_1[|A|^2 + C_2|B|^2], \quad (11)$$

where

$$C_1 = \frac{|\mathbf{q}|}{8\pi} \frac{(m_i + m_f)^2 - m_P^2}{m_i^2}, \quad (11a)$$

$$C_2 = \frac{(m_i - m_f)^2 - m_P^2}{(m_i + m_f)^2 + m_P^2}, \quad (11b)$$

$$|\mathbf{q}| = \frac{1}{2m_i} \sqrt{[m_i^2 - (m_f - m_P)^2][m_i^2 - (m_f + m_P)^2]}. \quad (11c)$$

m_i and m_f are the masses of the initial and final baryons and m_P is the mass of the emitted meson. For the decays under consideration C_2 is very small due to p-wave suppression (for example, for the decay $\Xi^0_c \to \Lambda^+_c \pi^-$, it is 0.000 75), so that the contribution to the width from the parity-conserving mode may be ignored. We, therefore, need to consider only the parity-violating decays.

IV. RESULTS AND CONCLUSION

The expressions for the decay amplitudes in terms of the parameters are given in Tables I, II, and III. In addition we get $\sqrt{2}(\Xi^+_c \to \Lambda^+_c \pi^0) = (\Xi^0_c \to \Lambda^+_c \pi^-)$ and $(\Omega^0_c \to \Xi^+_c \pi^-) = -\sqrt{2}(\Omega^0_c \to \Xi^0_c \pi^0)$. The values of the parameters $(2a_1 - A_1)$, $(2a_2 - A_9)$, and A_2 are calculated from the experimental values of the hyperon decay amplitudes which we have taken from Ref. [15] and have listed in the last column of Table I. The values for the parameters turn out to be 4.6, −0.81, and −0.14, respectively, giving a fit to about 5% whereas $\mathbf{20''}$ dominance works up to 40% [13]. They are then used to estimate the decay amplitudes for the charm-conserving strangeness-changing decays of charmed baryons. The computed values are given in the last column of Table II. We are able to give here only a very rough estimate of the decay amplitude for the charm-changing decays in the fourth column of Table III. This is because the contribution to the charm-changing decays comes only from the $\mathbf{20''}$ part of the weak Hamiltonian and we are not able to disentangle its contribution from that of the **15** piece in the hyperon decays. We estimate these amplitudes by assuming that the hyperon decays are dominantly described by the $\mathbf{20''}$ Hamiltonian, which as already recognized [13] very early is a bad approximation. Also we feel that these values are overestimated because the enhancement of the $\mathbf{20''}$ piece of the weak Hamiltonian due to the strong interaction renormalization for the charm-changing decays would be less than that for the strangeness-changing decays. Further, in the charm-changing decays, the factorizable contributions are important. The factorizable contributions are explicitly symmetry breaking and so cannot be calculated from symmetry considerations. We do not discuss the charm-changing decays here. They have been already extensively analyzed recently, particularly by Cheng and Tseng, Korner and Kramer, and Xu and Kamal in Ref. [2]. Further analysis will be called for when data become more precise, as there are several competing terms and only data will be able to decide on their importance. The factorizable contributions for the hyperon decays and for the $\Delta C = 0, \Delta S = 1$ charmed

TABLE I. PV decay amplitudes for hyperons. Each entry displays the appropriate coefficient. Experimental values are in units of 10^{-7}.

Decay	$-(2a_1 + A_1)$	$(2a_2 - A_9)$	A_2	Expt. value
$\Lambda \to p\pi^-$	0	$\frac{1}{\sqrt{6}}$	$-\frac{4}{\sqrt{6}}$	3.25 ±0.03
$\Sigma^+ \to n\pi^+$	1	0	0	0.14 ±0.03
$\Sigma^- \to n\pi^-$	1	1	0	4.27 ±0.01
$\Sigma^+ \to p\pi^0$	0	$-\frac{1}{\sqrt{2}}$	0	−3.29 ±0.11
$\Xi^- \to \Lambda\pi^-$	0	$\frac{2}{\sqrt{6}}$	$-\frac{2}{\sqrt{6}}$	4.49 ±0.02

TABLE II. $\Delta C = 0, \Delta S = 1$ PV decay amplitudes for charmed baryons. Each entry displays the appropriate coefficient. Computed values are in units of 10^{-7}.

Decay	$(2a_1 - A_1)$	$(2a_2 - A_9)$	A_2	Comp. value
$\Xi^0_c \to \Lambda^+_c \pi^-$	$-\frac{1}{6}$	$-\frac{5}{6}$	$\frac{1}{3}$	−4.1
$\Xi^{0\prime}_c \to \Lambda^+_c \pi^-$	$-\frac{1}{\sqrt{12}}$	$\frac{1}{\sqrt{12}}$	$-\frac{1}{\sqrt{3}}$	1.8
$\Omega^0_c \to \Xi^+_c \pi^-$	$-\frac{1}{\sqrt{6}}$	$-\frac{1}{\sqrt{6}}$	$-\frac{2}{\sqrt{6}}$	−2.5
$\Omega^0_c \to \Xi^{+\prime}_c \pi^-$	$\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$	$\sqrt{2}$	−4.4

TABLE III. $\Delta C = \Delta S = 1$ PV decay amplitudes for charmed baryons. Each entry displays the appropriate coefficient and is to be multiplied by $\cot\theta_C$. Computed values are in units of 10^{-7}.

Decay	a_1	a_2	Comp. value
$\Lambda^+_c \to p\bar{K}^0$	0	$\sqrt{\frac{2}{3}}$	10
$\Lambda^+_c \to \Lambda\pi^+$	0	0	0
$\Lambda^+_c \to \Sigma^+\pi^0$	0	$\frac{2}{\sqrt{3}}$	15
$\Lambda^+_c \to \Xi^0 K^+$	1	0	0.5

baryon decays are, however, expected to be negligible as they are proportional to the mass difference of the initial and final baryons. This contribution to the amplitude for $\Gamma(\Xi_c^+ \to \Lambda_c^+\pi^0)$ has actually been estimated in Ref. [4] to be 3.4×10^{-8}. So we feel that our considerations for strangeness-changing decays are reasonable. Our estimates for these decay widths are

$$\Gamma(\Xi_c^+ \to \Lambda_c^+\pi^0) = 1.5 \times 10^{-15}\ \text{GeV}, \tag{12a}$$

$$\Gamma(\Xi_c^0 \to \Lambda_c^+\pi^-) = 2.7 \times 10^{-15}\ \text{GeV}, \tag{12b}$$

$$\Gamma(\Omega_c \to \Xi_c^+\pi^-) = 1.5 \times 10^{-15}\ \text{GeV}. \tag{12c}$$

The phase space for the decay $\Omega_c \to \Xi_c'^+\pi^-$ is too small for it to have any significant width. The order of magnitude of these numbers is the same as in Ref. [4], though some numbers are different.

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