PHYSICAL REVIEW D VOLUME 43, NUMBER 1 1 JANUARY 1991

Cabibbo-enhanced weak decays of charmed baryons in the SU(4) semidynamical scheme

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(Received 14 May 1990)

Treating the weak decay $B \rightarrow B' + P$ as the process $S + B \rightarrow P + B'$, expressing the decay amplitudes in terms of the reduced matrix elements in all the s, t, and u channels, and restricting the intermediate states to be nonexotic, we study the weak decays of charmed baryons. Using the experimental data of strange baryons, we calculate the decay rates in the Glashow-Iliopoulos-Maiani (GIM) model. We find that the addition of a **15** representation to the weak GIM Hamiltonian gives good agreement with experiment.

I. INTRODUCTION

Weak decays have always been a rich source of information on basic interactions. The nonleptonic weak decays of hadrons, in particular, provide insight into the interplay of strong with weak interactions. Up to now the greater part of theoretical efforts to understand charm decays has gone to charmed mesons. Here, we study charmed baron decays, which belong to a relatively unexplored territory at the present time. A few candidates have been identified experimentally. For example, a few decay models of Λ_c^+, the lightest charmed baryon, have been measured. However, the available data seem to pose a problem for its theoretical explanation. The observed values of the decay rates are much smaller as compared to the estimated values.

The weak nonleptonic decays of charmed baryons have been studied earlier using the U(2,2) quark model,[1] nonrelativistic SU(6) wave functions,[2] and the MIT bag model.[3-5]

For the nonleptonic hyperon decays, one employs the conventional soft-meson technique,[6] where the equal-time commutator and the pole terms yield the s- and the p-wave amplitudes, respectively. It has been known for quite some time that although the current-algebra approach gives the correct relative sign for s- and p-wave amplitudes, it still fails to reproduce their relative magnitudes.[5-7] To improve the agreement between theory and experiment, additional mechanisms such as the meson-pole terms,[8] factorizable contribution,[9-11] and $\frac{1}{2}^-$ low-lying baryon pole contribution[12] have been attempted.

In an earlier work, most of the observed features of the nonleptonic decays of the ordinary baryons have been obtained using simple dynamical assumptions.[13] The effective Hamiltonian is treated as a spurion and the decay $B \rightarrow B' + P$ is related to the process $S + B \rightarrow B' + P$. The decay amplitudes are expressed in terms of the reduced matrix elements corresponding to each intermediate state in all the s, t, and u channels. The weak Hamiltonian $(8+27)$ with nonexotic intermediate states[14] and s-u-channel symmetry[15] gives a well satisfied Lee-Sugawara sum rule for the parity-violating (PV) as well as for the parity-conserving (PC) modes, without the assumption of octet dominance. In addition the relations $\Sigma_+^+ = 0$ for the PV mode and $\sqrt{2}\Sigma_+^+ - \Sigma_0^+ = \sqrt{3}\Lambda_-^0$ for the PC mode are obtained. The important features of this model are that it simultaneously explains the $\Delta I = \frac{1}{2}$ rule for baryons and allows $\Delta I = \frac{1}{2}$ rule violation in Ω^- decays. We note that the PV decays occur through the t channel, whereas the PC decays obtain dominant contributions from the s and u channels.[13] These features are in accordance with the results of duality arguments,[16] current algebra,[6] and the constituent rearrangement quark model.[17]

Encouraged by the success of our model in SU(3)-flavor symmetry generated by u, d, and s quarks, we extended our approach to the decays of charmed baryons[18,19] in SU(4) symmetry by including the charm flavor. We observed that the PV decay amplitudes vanish for **20**$''$ as well as for **84** parts of the Glashow-Iliopoulos-Maiani (GIM) Hamiltonian and for the PC mode **84** representation contributes only through the t channel. Since the data on charmed-baryon decays have started coming in and more and more data are likely to become available in the near future, we, in this paper, reanalyze our approach in SU(4) symmetry to study the two-body decays of the charmed baryons. We consider only the Cabibbo-enhanced mode with $\Delta C = \Delta S = -1$. Starting with the GIM model, we expand the weak decay amplitudes in terms of the eigenamplitudes for nonexotic intermediate states in all the three Mandelstam channels. We note that the PC decay amplitude for $\Lambda_c^+ \rightarrow \Lambda\pi^+$ arises dominantly through the s and u channels and for $\Lambda_c^+ \rightarrow p\bar{K}^0$ through the t channel. Using data on hyperon decays we determine the reduced matrix elements and calculate the amplitudes and decay widths for Λ_c^+ and find that the GIM Hamiltonian gives a large width. We then include the **15** representation which does not contribute to the charm decays but affects the values of the reduced matrix elements through its contribution to the hyperon sector.

The estimated values now are in better agreement with experiment. We finally include the **84** representation. The method and the results on the decay amplitudes are described in Secs. II and III, respectively. Summary and discussion are given in the last section.

II. THE METHOD

The effective weak Hamiltonian is treated as a symmetry-breaking spurion S and the decay $B \to B' + P$ is treated as the process $S + B \to P + B'$. The transition amplitudes are expressed in terms of reduced matrix elements (amplitudes) in s, t, and u channels corresponding to each intermediate state $|m\rangle$ which are defined as

$$\langle B' \| P \| m \rangle \langle m \| S \| B \rangle \quad \text{for } s \text{ channel } S + B \to m \to B' + P \; ,$$

$$\langle P \| \bar{S} \| m \rangle \langle m \| B' \| B \rangle \quad \text{for } t \text{ channel } B + \bar{B}' \to m \to \bar{S} + P \; ,$$

$$\langle B' \| \bar{S} \| m \rangle \langle m \| \bar{P} \| B \rangle \quad \text{for } u \text{ channel } B + \bar{P} \to m \to B' + \bar{S} \; .$$

The details of these elements for different $|m\rangle$ states are given in the Appendix. The baryonic intermediate states appear in the s and u channels while the mesons are exchanged in the t channel. We assume that the dominant contribution to the process comes through the single-particle nonexotic intermediate states. Thus only **4***, **20**, and **20′** SU(4) baryon multiplets occur as the intermediate states in the s and u channels while singlet and fifteenplet mesons are exchanged in the t channel. We assume that the weak Hamiltonian is symmetric in the s and u channels implying that the same reduced matrix elements appear in the s and u channels. That is,

$$\langle B' \| P \| m \rangle \langle m \| S \| B \rangle = \langle B' \| \bar{S} \| m \rangle \langle m \| \bar{P} \| B \rangle \; .$$

Weak Hamiltonian. The hadronic part of the weak $V-A$ left-handed quark current

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

transforms like the **15** representation of SU(4). The general current $\times$ current weak-interaction Hamiltonian

$$H_W = \frac{G}{2\sqrt{2}}(J^\mu J_\mu^\dagger + J^{\mu\dagger} J_\mu)$$

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

$$\mathbf{15} \otimes \mathbf{15} = \mathbf{1} \oplus \mathbf{15} \oplus \mathbf{15} \oplus \mathbf{20''} \oplus \mathbf{45} \oplus \mathbf{45^*} \oplus \mathbf{84} \; . \tag{2.1}$$

Because of the symmetric nature of the Hamiltonian, only 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 GIM Hamiltonian[20] that the bilinears in currents do not contain adjoint representation in the exact SU(4) limit.[21] Therefore, **15** does not contribute also. The GIM Hamiltonian thus transforms like

$$H_W^{\mathrm{GIM}} = \mathbf{20''} + \mathbf{84} \; . \tag{2.2}$$

However, the $\mathbf{15}_s$ representation may reappear through the SU(4) breaking,[22] gluon-exchange[10,23] generating penguin diagrams, Melosh transformations on the left-handed quark,[24] etc. We shall later include the admixture of **15** in the weak interaction. The most general weak Hamiltonian for $B \to B' + P$ decays is then given by

$$H_W = H_W^{20''} + H_W^{84} + H_W^{15} \; , \tag{2.3}$$

where

$$\begin{aligned} H_W^{20''} = {} & a_1 \bar{B}^{c}_{[a,b]} B^{[n,d]}_{m} P^{m}_{n} H^{[a,b]}_{[c,d]} + a_2 \bar{B}^{m}_{[a,b]} B^{[n,c]}_{m} P^{d}_{n} H^{[a,b]}_{[c,d]} + a_3 \bar{B}^{m}_{[a,b]} B^{[c,d]}_{n} P^{n}_{m} H^{[a,b]}_{[c,d]} \\ & + a_4 \bar{B}^{m}_{[n,b]} B^{[c,d]}_{a} P^{n}_{m} H^{[a,b]}_{[c,d]} + a_5 \bar{B}^{n}_{[m,a]} B^{[c,d]}_{n} P^{m}_{b} H^{[a,b]}_{[c,d]} + a_6 \bar{B}^{c}_{[m,n]} B^{[m,n]}_{a} P^{d}_{b} H^{[a,b]}_{[c,d]} + a_7 \bar{B}^{m}_{[n,a]} B^{[n,c]}_{m} P^{d}_{b} H^{[a,b]}_{[c,d]} \end{aligned} \tag{2.4}$$

and

$$\begin{aligned} H_W^{84} = {} & b_1 \bar{B}^{c}_{[e,f]} B^{[e,f]}_{a} P^{d}_{b} H^{(a,b)}_{(c,d)} + b_2 \bar{B}^{c}_{[f,a]} B^{[e,d]}_{b} P^{f}_{e} H^{(a,b)}_{(c,d)} + b_3 \bar{B}^{e}_{[a,f]} B^{[c,f]}_{e} P^{d}_{b} H^{(a,b)}_{(c,d)} \\ & + b_4 \bar{B}^{e}_{[a,f]} B^{[c,f]}_{b} P^{d}_{e} H^{(a,b)}_{(c,d)} + b_5 \bar{B}^{c}_{[a,f]} B^{[d,f]}_{e} P^{e}_{b} H^{(a,b)}_{(c,d)} + b_6 \bar{B}^{c}_{[e,f]} B^{[e,d]}_{a} P^{f}_{b} H^{(a,b)}_{(c,d)} + b_7 \bar{B}^{c}_{[e,a]} B^{[e,f]}_{b} P^{d}_{f} H^{(a,b)}_{(c,d)} \end{aligned} \tag{2.5}$$

and

$$\begin{aligned} H_W^{15} = {} & A_1 \bar{B}^{m}_{[n,c]} B^{[b,c]}_{a} P^{n}_{m} H^{a}_{b} + A_2 \bar{B}^{m}_{[c,d]} B^{[c,d]}_{a} P^{b}_{m} H^{a}_{b} + A_3 \bar{B}^{m}_{[d,a]} B^{[b,d]}_{c} P^{c}_{m} H^{a}_{b} + A_4 \bar{B}^{b}_{[m,c]} B^{[c,d]}_{a} P^{m}_{d} H^{a}_{b} \\ & + A_5 \bar{B}^{c}_{[m,d]} B^{[b,d]}_{c} P^{m}_{a} H^{a}_{b} + A_6 \bar{B}^{c}_{[m,a]} B^{[b,d]}_{c} P^{m}_{d} H^{a}_{b} + A_7 \bar{B}^{m}_{[c,d]} B^{[c,d]}_{m} P^{b}_{a} H^{a}_{b} + A_8 \bar{B}^{b}_{[c,d]} B^{[c,d]}_{m} P^{m}_{a} H^{a}_{b} \\ & + A_9 \bar{B}^{m}_{[a,d]} B^{[d,c]}_{m} P^{b}_{c} H^{a}_{b} + A_{10} \bar{B}^{b}_{[a,d]} B^{[d,n]}_{m} P^{m}_{n} H^{a}_{b} \; . \end{aligned} \tag{2.6}$$

CP invariance demands

$$a_1 = -a_4, \quad a_2 = -a_5, \quad a_3 = a_6 = a_7 = 0 \; , \tag{2.7a}$$

$$b_4 = -b_5, \quad b_6 = -b_7, \quad b_1 = b_2 = b_3 = 0 \; , \tag{2.7b}$$

$$\begin{aligned} & A_1 = A_{10}, \quad A_2 = -A_8 \; , \\ & A_5 = A_9, \quad A_3 = A_4 = A_6 = A_7 = 0 \end{aligned} \tag{2.7c}$$

for the PV mode and

$$a_1=a_4,\quad a_2=a_5\ , \tag{2.8a}$$

$$b_4=b_5,\quad b_6=b_7\ , \tag{2.8b}$$

$$A_1=-A_{10},\quad A_2=A_8,\quad A_5=-A_9 \tag{2.8c}$$

for the PC mode. The dominance of nonexotic intermediate states yields

$$a_4=a_5=a_6=a_7=0\ , \tag{2.9a}$$

$$b_3=b_5=0,\quad b_2=b_6,\quad 2b_1=-b_7\ , \tag{2.9b}$$

$$2A_7=2A_8=A_9=A_{10},\quad A_5=A_6 \tag{2.9c}$$

for the s channel,

$$a_1=a_2=a_3=a_4=a_5=0\ , \tag{2.10a}$$

$$b_2=b_4=b_5=b_6=b_7=0\ , \tag{2.10b}$$

$$A_1=A_3=A_4=A_6=A_{10}=0 \tag{2.10c}$$

for the t channel, and

$$a_1=a_2=a_6=a_7=0\ , \tag{2.11a}$$

$$b_3=b_4=0,\quad 2b_1=-b_6,\quad b_2=b_7\ , \tag{2.11b}$$

$$A_9=-A_6,\quad 2A_7=2A_2=-A_5=-A_1 \tag{2.11c}$$

for the u channel. The s-u-channel symmetry gives the conditions

$$a_1=a_4,\quad a_2=a_3\ , \tag{2.12a}$$

$$b_2=-b_4=-b_5=b_6=b_7\ , \tag{2.12b}$$

$$A_1=-A_{10},\quad A_2=A_8,\quad A_5=-A_9,\quad A_3=A_4\ . \tag{2.12c}$$

III. DECAY AMPLITUDES

The matrix elements for baryon decay processes can be written as[6]

$$M=-\langle B'P|H_w|B\rangle=\bar{u}_{B'}(A+B\gamma_5)u_B\phi_p\ ,$$

where A and B are parity-violating and parity-conserving amplitudes, respectively. For the Cabibbo-enhanced $\Delta C=\Delta S=-1$ mode, the charm-changing effective weak Hamiltonian[21] is

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

The ground-state s-wave $\frac{1}{2}^+$ baryons belong to the $\mathbf{20'}$ representation of SU(4) with the following isospin and SU(3) content:

$$\mathbf{20'}=\mathbf{8}_0\begin{bmatrix}N\\ \Lambda\\ \Sigma\\ \Xi\end{bmatrix}+\mathbf{3}_1^*\begin{bmatrix}\Lambda\\ \Xi_c'\end{bmatrix}+\mathbf{6}_1\begin{bmatrix}\Sigma_c\\ \Xi_c\\ \Omega_c\end{bmatrix}+\mathbf{3}_2\begin{bmatrix}\Xi_{cc}\\ \Omega_{cc}\end{bmatrix}\ ,$$

where the subscript denotes the charm quantum number. According to the observed masses of $\frac{1}{2}^+$ baryons,[25] and the mass pattern expected in the De Rújula–Georgi–Glashow (DGG) model,[26] $\mathbf{3}_1$ and $\mathbf{3}_2$ and Ω^- (css) states of $\mathbf{6}_1$ are stable against the strong and electromagnetic interactions and so must decay weakly.

A. GIM model

We first work in the GIM model of the weak interaction with a $(\mathbf{20''}+\mathbf{84})$ Hamiltonian. The decay amplitudes are obtained by choosing H_{13}^{24} components in (2.4) and (2.5).

1. Parity-violating mode

It is clear from the constraints (2.7) and (2.9)–(2.11) that the CP invariance and the absence of the exotic intermediate states forbid $\mathbf{20''}$ and $\mathbf{84}$ components of the Hamiltonian to contribute to the decays in all the s, t, and u channels. Thus the parity-violating decays of the charmed baryons are forbidden in the SU(4)-symmetry limit. The same result has earlier been obtained in the duality framework[27] and in the constituent rearrangement quark model.[17] It is also consistent with the observation that the factorizable contribution to s-wave amplitudes vanishes in the SU(4)-symmetric limit.[4,5] Thus parity-violating decays seem to arise purely from the SU(4) breaking.[28] The measurement of decay asymmetries would clarify the situation. We may remark here that if we apply our scheme for the GIM Hamiltonian $\mathbf{6^*}+\mathbf{15}$ at the SU(3) level, the decays $\Lambda_c^+\to p\bar{K}^0$ and $\Lambda_c^+\to\Lambda\pi^+$ are allowed in the PV mode. The dominance of nonexotic intermediate states, however, forbids[29]

$$\Lambda_c^+\to\Sigma\pi/\Sigma\eta/\Xi^0K^+ \quad\text{and}\quad \Xi_c^{0'}\to\Xi^0\eta\ .$$

2. Parity-conserving mode

For a $20''$-dominant weak Hamiltonian, our approach expresses all the PC decays of the uncharmed and charmed baryons in terms of just three parameters. With the conditions obtained for CP invariance (2.7a) and the dominance of nonexotic intermediate states (2.9a), (2.10a), and (2.11a), we find that the terms involving a_3 for the s and u channels and the terms carrying the coefficients a_6 and a_7 for the t channel in (2.4) survive. The following decay amplitude sum rules are then obtained. (See Tables I and II.)

$B(3^*)\to B(8)+P(8)$:

$$0=\langle\Xi^0\pi^0|\Xi_c'^0\rangle\ , \tag{3.1}$$

$$\begin{aligned}\langle\Sigma^+\pi^0|\Lambda_c^+\rangle&=\sqrt{3}\langle\Sigma^+\eta|\Lambda_c^+\rangle\\ &=-\langle\Sigma^0\pi^+|\Lambda_c^+\rangle=\frac{1}{\sqrt{2}}\langle\Xi^0K^+|\Lambda_c^+\rangle\\ &=\frac{1}{\sqrt{2}}\langle\Sigma^+K^-|\Xi_c'^0\rangle=\sqrt{2}\langle\Xi^0\eta|\Xi_c'^0\rangle\ ,\end{aligned} \tag{3.2}$$

$$\langle p\bar{K}^0|\Lambda_c^+\rangle=\langle\Sigma^+\bar{K}^0|\Xi_c'^+\rangle\ , \tag{3.3}$$

$$\langle\Xi^0\pi^+|\Xi_c'^+\rangle=\langle\Xi^-\pi^+|\Xi_c'^0\rangle\ , \tag{3.4}$$

$$\langle\Xi^0\pi^+|\Xi_c'^+\rangle=-\langle p\bar{K}^0|\Lambda_c^+\rangle\ , \tag{3.5}$$

$$\sqrt{3}\langle\Lambda\pi^+|\Lambda_c^+\rangle=\langle\Sigma^+\pi^0|\Lambda_c^+\rangle-\sqrt{2}\langle\Xi^0\pi^+|\Xi_c'^+\rangle\ , \tag{3.6}$$

$$\sqrt{6}\langle\Lambda\bar{K}^0|\Xi_c'^0\rangle=\sqrt{2}\langle\Sigma^+\pi^0|\Lambda_c^+\rangle-\langle p\bar{K}^0|\Lambda_c^+\rangle\ , \tag{3.7}$$

$$-\sqrt{2}\langle\Sigma^0\bar{K}^0|\Xi_c'^0\rangle=\sqrt{2}\langle\Sigma^+\pi^0|\Lambda_c^+\rangle+\langle p\bar{K}^0|\Lambda_c^+\rangle\ . \tag{3.8}$$

TABLE I. Decay amplitudes for hyperon decays.

	$H^{20''}$ u and s channels $\frac{G}{\sqrt{2}}\sin\theta\cos\theta$	$H^{20''}$ t channel $\frac{G}{\sqrt{2}}\sin\theta\cos\theta$	H^{84} s and u channels $\frac{G}{\sqrt{2}}\sin\theta\cos\theta$	H^{84} t channel $\frac{G}{\sqrt{2}}\sin\theta\cos\theta$	H^{15} u and s channels $\frac{G}{\sqrt{2}}\sin\theta\cos\theta$	H^{15} t channel $\frac{G}{\sqrt{2}}\sin\theta\cos\theta$	Experimental values
Λ^0_-	$\frac{4}{\sqrt{6}}a_3$	$\frac{-4}{\sqrt{6}}a_6+\frac{1}{\sqrt{6}}a_7$	0	$-\frac{4}{\sqrt{6}}b_1+\frac{1}{\sqrt{6}}b_3$	$-\sqrt{6}A_2-\frac{1}{\sqrt{6}}A_3$	$\frac{-4}{\sqrt{6}}A_2+\frac{1}{\sqrt{6}}A_5$	9.98
Λ^0_0	$\frac{-2}{\sqrt{3}}a_3$	$\frac{2}{\sqrt{3}}a_6-\frac{1}{2\sqrt{3}}a_7$	0	$\frac{-2}{\sqrt{3}}b_1+\frac{1}{2\sqrt{3}}b_3$	$\sqrt{3}A_2+\frac{1}{2\sqrt{3}}A_3$	$\frac{2}{\sqrt{3}}A_2-\frac{1}{2\sqrt{3}}A_5$	−7.14
Σ^+_+	$4a_3$	0	0	0	$-2A_2-A_3$	0	19.07
Σ^-_-	0	a_7	0	b_3	$-4A_2$	A_5	−0.65
Σ^+_0	$2\sqrt{2}a_3$	$\frac{-1}{\sqrt{2}}a_7$	0	$\frac{1}{\sqrt{2}}b_3$	$\frac{2}{\sqrt{2}}A_2-\frac{1}{\sqrt{2}}A_3$	$\frac{-1}{\sqrt{2}}A_5$	12.04
Ξ^-_-	0	$\frac{-2}{\sqrt{6}}a_6+\frac{2}{\sqrt{6}}a_7$	0	$\frac{-2}{\sqrt{6}}b_1+\frac{2}{\sqrt{6}}b_3$	$-\sqrt{6}A_2+\frac{1}{\sqrt{6}}A_4$	$\frac{-2}{\sqrt{6}}A_2+\frac{2}{\sqrt{6}}A_5$	−6.93
Ξ^0_0	0	$\frac{-1}{\sqrt{3}}a_6+\frac{1}{\sqrt{3}}a_7$	0	$\frac{1}{\sqrt{3}}b_1-\frac{1}{\sqrt{3}}b_3$	$-\sqrt{3}A_2+\frac{1}{2\sqrt{3}}A_4$	$\frac{-1}{\sqrt{3}}A_2+\frac{1}{\sqrt{3}}A_5$	−6.43

$B(3)\to B(8)+P(3^*)$:

$$0=\langle\Sigma^+D^+|\Xi^{++}_{cc}\rangle=\langle\Xi^0D^+|\Omega^+_{cc}\rangle\ , \tag{3.9}$$

$$\langle\Xi^0D_s^+|\Xi^{++}_{cc}\rangle=-\sqrt{2}\langle\Sigma^0D^+|\Xi^+_{cc}\rangle\ , \tag{3.10}$$

$$\langle\Sigma^+D^0|\Xi^+_{cc}\rangle=\sqrt{6}\langle\Lambda D^+|\Xi^+_{cc}\rangle=-\sqrt{2}\langle\Sigma^0D^+|\Xi^+_{cc}\rangle\ . \tag{3.11}$$

$B(3)\to B(3^*)+P(8)$:

$$0=\langle\Xi_c'^+\pi^0|\Xi^+_{cc}\rangle=\langle\Xi_c'^+\eta|\Xi^+_{cc}\rangle\ , \tag{3.12}$$

$$\langle\Xi_c'^+\bar{K}^0|\Omega^+_{cc}\rangle=-\langle\Lambda_c^+\bar{K}^0|\Xi^+_{cc}\rangle\ , \tag{3.13}$$

$$\langle\Xi_c'^0\pi^+|\Xi^+_{cc}\rangle=\langle\Xi_c'^+\pi^+|\Xi^{++}_{cc}\rangle\ , \tag{3.14}$$

$$\langle\Xi_c'^+\pi^+|\Xi^{++}_{cc}\rangle=-\langle\Lambda_c^+\bar{K}^0|\Xi^+_{cc}\rangle\ . \tag{3.15}$$

$B(3)\to B(6)+P(8)$:

$$0=\langle\Omega_c^0K^+|\Xi^+_{cc}\rangle=\langle\Xi_c^+\pi^0|\Xi^+_{cc}\rangle$$
$$=\langle\Xi_c^+\eta|\Xi^+_{cc}\rangle=\langle\Sigma_c^{++}K^-|\Xi^+_{cc}\rangle\ , \tag{3.16}$$

$$\langle\Omega_c^0\pi^+|\Omega^+_{cc}\rangle=\sqrt{2}\langle\Xi_c^0\pi^+|\Xi_c^{++}\rangle$$
$$=\sqrt{2}\langle\Xi_c^+\pi^+|\Xi^{++}_{cc}\rangle\ , \tag{3.17}$$

$$\sqrt{2}\langle\Xi_c^+\bar{K}\,|\Omega^+_{cc}\rangle=\sqrt{2}\langle\Sigma_c^+\bar{K}^0|\Xi^+_{cc}\rangle$$
$$=-\langle\Sigma_c^{++}\bar{K}^0|\Xi^{++}_{cc}\rangle\ , \tag{3.18}$$

$$\sqrt{2}\langle\Xi_c^+\pi^+|\Xi^{++}_{cc}\rangle=\langle\Sigma_c^{++}\bar{K}^0|\Xi^{++}_{cc}\rangle\ , \tag{3.19}$$

$$\langle\Lambda D^+|\Xi^+_{cc}\rangle=\sqrt{2}\langle\Sigma^+\pi^0|\Lambda_c^+\rangle\ , \tag{3.20}$$

$$-2\langle\Lambda_c^+\bar{K}^0|\Xi^+_{cc}\rangle+\langle p\bar{K}^0|\Lambda_c^+\rangle=\frac{3}{\sqrt{6}}\langle\Xi^0\bar{K}^0|\Omega_c^0\rangle\ , \tag{3.21}$$

$$-2\sqrt{2}\langle\Xi_c^+\pi^+|\Xi^{++}_{cc}\rangle=\sqrt{6}\langle p\bar{K}^0|\Lambda_c^+\rangle+\langle\Xi^0\bar{K}^0|\Omega_c^0\rangle\ . \tag{3.22}$$

In addition we obtain the following equations relating the charmed-baryon decays with the strange-baryon ones:

$$\langle\Sigma^+\pi^0|\Lambda_c^+\rangle=\frac{1}{2\sqrt{3}}\Sigma^+_+\cot\theta\ , \tag{3.23}$$

$$\langle p\bar{K}^0|\Lambda_c^+\rangle=(\Lambda^0_--\frac{1}{\sqrt{6}}\Sigma^+_+)\cot\theta\ , \tag{3.24}$$

$$\langle\Xi^0\bar{K}^0|\Omega_c^0\rangle=(\sqrt{2}\Sigma_0^+-\Sigma^+_+)\cot\theta\ , \tag{3.25}$$

$$\langle\Sigma^+D^0|\Xi^+_{cc}\rangle=\Sigma^+_+\cot\theta\ , \tag{3.26}$$

$$\langle\Lambda_c^+\bar{K}^0|\Xi^+_{cc}\rangle=\left[\frac{1}{2}\Lambda^0_-+\frac{1}{\sqrt{6}}\Sigma^+_+-\frac{\sqrt{3}}{2}\Sigma_0^+\right]\cot\theta\ , \tag{3.27}$$

$$2\langle\Xi_c^+\pi^+|\Xi^{++}_{cc}\rangle=(\sqrt{2}\Sigma^+_+-\Sigma_0^+-\sqrt{3}\Lambda^0_-)\cot\theta\ . \tag{3.28}$$

Determining the parameters (in units of $10^5 m_\pi^{-1/2}\sec^{-1/2}$) from the hyperon decays Λ^0_-, Σ^+_+, and Σ^+_+ (Table I), we obtain

TABLE II. Decay amplitudes for charmed baryon decays.

	$H^{20''}$ s and u channels $\cos\theta^2$	$H^{20''}$ t channel $\cos\theta^2$	H^{84} t channel $\cos\theta^2$
$B(3^*)\to B(8)+B(9)$			
$\Lambda_c^+\to P+\bar{K}^0$	0	$\frac{-4}{\sqrt{6}}a_6+\frac{1}{\sqrt{6}}a_7$	$\frac{4}{\sqrt{6}}b_1-\frac{1}{\sqrt{6}}b_3$
$\Lambda_c^+\to\Sigma^++\pi^0$	$\frac{4}{2\sqrt{3}}a_3$	0	0
$\Lambda_0^+\to\Sigma^++\eta^0$	$\frac{2}{\sqrt{6}}a_3$	0	0
$\Lambda_c^+\to\Sigma^++\eta$	$\frac{2}{3}a_3$	0	0
$\Lambda_c^+\to\Lambda+\pi^+$	$\frac{2}{3}a_3$	$\frac{-4}{3}a_6+\frac{1}{3}a_7$	$\frac{-4}{3}b_1+\frac{1}{3}b_3$
$\Lambda_c^+\to\Sigma^0+\pi^+$	$\frac{-2}{\sqrt{3}}a_3$	0	0
$\Lambda_c^+\to\Xi^0+K^+$	$\frac{4}{\sqrt{6}}a_3$	0	0
$\Xi_c'^+\to\Sigma^++\bar{K}^0$	0	$\frac{-4}{\sqrt{6}}a_6+\frac{1}{\sqrt{6}}a_7$	$\frac{4}{\sqrt{6}}b_1-\frac{1}{\sqrt{6}}b_3$
$\Xi_c'^+\to\Xi^0+\pi^+$	0	$\frac{4}{\sqrt{6}}a_6-\frac{1}{\sqrt{6}}a_7$	$\frac{4}{\sqrt{6}}b_1-\frac{1}{\sqrt{6}}b_3$
$\Xi_c'^0\to\Sigma^++K^-$	$\frac{4}{\sqrt{6}}a_3$	0	0
$\Xi_c'^0\to\Lambda+\bar{K}^0$	$\frac{2}{3}a_3$	$\frac{4}{6}a_6-\frac{1}{6}a_7$	$\frac{-4}{6}b_1+\frac{1}{6}b_3$
$\Xi_c'^0\to\Sigma^0+\bar{K}^0$	$\frac{-2}{\sqrt{3}}a_3$	$\frac{4}{2\sqrt{3}}a_6-\frac{1}{2\sqrt{3}}a_7$	$\frac{-2}{\sqrt{3}}b_1+\frac{1}{2\sqrt{3}}b_3$
$\Xi_c'^0\to\Xi_0+\pi^0$	0	0	0
$\Xi_c'^0\to\Xi^0+\eta$	$\frac{2}{\sqrt{6}}a_3$	0	0
$\Xi_c'^0\to\Xi^-+\pi^+$	0	$\frac{4}{\sqrt{6}}a_6-\frac{1}{\sqrt{6}}a_7$	$\frac{4}{\sqrt{6}}b_1-\frac{1}{\sqrt{6}}b_3$
$B(6)\to B(8)+P(9)$			
$\Omega_c^0\to\Xi^0+\bar{K}^0$	0	$-a_7$	b_3
$B(3)\to B(8)+B(3^*)$			
$\Omega_{cc}^+\to\Xi^0+D^+$	0	0	0
$\Xi_{cc}^+\to\Xi^0+D_s^+$	$4a_3$	0	0
$\Xi_{cc}^+\to\Sigma^0+D^+$	$\frac{-4}{\sqrt{2}}a_3$	0	0
$\Xi_{cc}^+\to\Sigma^++D^0$	$4a_3$	0	0
$\Xi_{cc}^{++}\to\Lambda+D^+$	$\frac{4}{\sqrt{6}}a_3$	0	0
$\Xi_{cc}^{++}\to\Sigma^++D^+$	0	0	0
$B(3)\to B(3^*)+B(9)$			
$\Omega_{cc}^+\to\Xi_c'^++\bar{K}^0$	0	$\frac{2}{\sqrt{6}}a_6-\frac{2}{\sqrt{6}}a_7$	$\frac{-2}{\sqrt{6}}b_1+\frac{2}{\sqrt{6}}b_3$
$\Xi_{cc}^+\to\Xi_c'^0+\pi^+$	0	$\frac{2}{\sqrt{6}}a_6-\frac{2}{\sqrt{6}}a_7$	$\frac{2}{\sqrt{6}}b_1-\frac{2}{\sqrt{6}}b_3$
$\Xi_{cc}^+\to\Xi_c'^++\pi^0$	0	0	0
$\Xi_{cc}^+\to\Xi_c'^++\eta$	0	0	0
$\Xi_{cc}^+\to\Lambda_c^++\bar{K}^0$	0	$\frac{-2}{\sqrt{6}}a_6+\frac{2}{\sqrt{6}}a_7$	$\frac{2}{\sqrt{6}}b_1-\frac{2}{\sqrt{6}}b_3$
$\Xi_{cc}^{++}\to\Xi_c'^++\pi^+$	0	$\frac{2}{\sqrt{6}}a_6-\frac{2}{\sqrt{6}}a_7$	$\frac{2}{\sqrt{6}}b_1-\frac{2}{\sqrt{6}}b_3$

TABLE II. (*Continued*).

	$H^{20''}$		H^{84}
	s and u channels $\cos\theta^2$	t channel $\cos\theta^2$	t channel $\cos\theta^2$
$B(3)\to B(6)+P(9)$			
$\Omega_{cc}^+\to\Omega_c^0+\pi^+$	0	$2a_6$	$2b_1$
$\Omega_{cc}^+\to\Xi_c^+ +\bar{K}^0$	0	$-\sqrt{2}a_6$	$\sqrt{2}b_1$
$\Xi_{cc}^+\to\Omega_c^0+K^+$	0	0	0
$\Xi_{cc}^+\to\Xi_c^0+\pi^+$	0	$\sqrt{2}a_6$	$\sqrt{2}b_1$
$\Xi_{cc}^+\to\Xi_c^+ +\pi^0$	0	0	0
$\Xi_{cc}^+\to\Xi_c^+ +\eta_8$	0	0	0
$\Xi_{cc}^+\to\Sigma_c^+ +\bar{K}^0$	0	$-\sqrt{2}a_6$	$\sqrt{2}b_1$
$\Xi_{cc}^+\to\Sigma_c^{++}+K^-$	0	0	0
$\Xi_{cc}^{++}\to\Xi_c^0+\pi^+$	0	$\sqrt{2}a_6$	$\sqrt{2}b_1$
$\Xi_{cc}^{++}\to\Sigma_c^{++}+\bar{K}^0$	0	$2a_6$	$-2b_1$

$$a_3=22.13\ ,$$

$$a_6=-6.94\ ,$$

$$a_7=-3.01\ .$$

We then compute the decay widths of the charmed baryons from

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

where

$$C_1=\frac{1}{8\pi}K\frac{(m+m')^2-m_\pi^2}{m^2}\ ,$$

$$C_2=\frac{(m-m')^2-m_\pi^2}{(m+m')^2+m_\pi^2}\ ,$$

and

$$K=\frac{1}{2m}\sqrt{[m^2-(m'-m_\pi)^2][m^2-(m'+m_\pi)^2]}\ .$$

We find that the computed value (Table III, fifth column) for the decay $\Lambda_C^+\to p\bar{K}^0$ is in good agreement with experimental value[25,30] ($0.43+0.13\times10^{-10}$ MeV), and that of $\Lambda_c^+\to\Lambda\pi^+$ is larger than the observed value ($0.11+0.04\times10^{-10}$ MeV).

Since $20''$ dominance does not give good results, we include the **84** part of the weak nonleptonic Hamiltonian. For the **84** representation, *CP* invariance (2.7b), the nonexotic intermediate states (2.9b), (2.11b), and s-u-channel symmetry (2.12b) forbid decays to occur through the s and u channels. However, t-channel contributions through terms involving coefficients b_1 and b_3 in (2.5) are allowed. In the presence of **84**, the relations (3.1)–(3.4), (3.6)–(3.14), (3.16), (3.17), (3.18), (3.20),and (3.21) remain satisfied. Others [(3.5), (3.15), (3.19), and (3.22)] get modified to

$$2\langle\Xi^0\pi^+|\Xi_c'^+\rangle+2\langle p\bar{K}^0|\Lambda_c^+\rangle=\langle\Xi_c'^+\pi^+|\Xi_{cc}^{++}\rangle+\langle\Lambda_c^+\bar{K}^0|\Xi_{cc}^+\rangle-\frac{\sqrt{6}}{2}\langle\Sigma_c^{++}\bar{K}^0|\Xi_{cc}^{++}\rangle+\sqrt{3}\langle\Xi_c^+\pi^+|\Xi_c^{++}\rangle\ , \tag{3.29}$$

$$2\langle\Xi^0\pi^+|\Xi_c'^+\rangle-2\langle p\bar{K}^0|\Lambda_c^+\rangle=\langle\Xi_c'^+\pi^+|\Xi_{cc}^{++}\rangle-\langle\Lambda_c^+\bar{K}^0|\Xi_{cc}^+\rangle+\sqrt{3}\langle\Xi_c^+\pi^+|\Xi_{cc}^{++}\rangle+\frac{\sqrt{6}}{2}\langle\Sigma_c^{++}\bar{K}^0|\Xi_{cc}^{++}\rangle\ . \tag{3.30}$$

The charmed decays are given in terms of the uncharmed ones through

$$2\langle\Sigma_c^{++}\bar{K}^0|\Xi_{cc}^{++}\rangle+2\sqrt{2}\langle\Xi_c^+\pi^+|\Xi_{cc}^{++}\rangle=[(3\Sigma_+^+-\sqrt{2}\Sigma_0^+ +\Sigma_-^-)-\sqrt{6}\Lambda_-^0+\sqrt{12}\Lambda_0^0]\cot\theta\ , \tag{3.31}$$

$$\sqrt{6}(\langle\Xi^0\pi^+|\Xi_c'^+\rangle-\langle p\bar{K}^0|\Lambda_c^+\rangle-2\langle\Xi_c'^+\pi^+|\Xi_{cc}^{++}\rangle+2\langle\Lambda_c^+\bar{K}^0|\Xi_{cc}^+\rangle)=3(\Sigma_+^+ +\Sigma_-^- -\sqrt{2}\Sigma_0^+)\cot\theta\ , \tag{3.32}$$

$$2\sqrt{2}\langle\Xi_c^+\pi^+|\Xi_{cc}^{++}\rangle-4\langle\Sigma_c^{++}\bar{K}^0|\Xi_{cc}^{++}\rangle=(\Delta\Sigma-\sqrt{6}\Delta\Lambda)\cot\theta\ , \tag{3.33}$$

$$\sqrt{6}\langle\Xi^0\pi^+|\Xi_c'^+\rangle+\langle p\bar{K}^0|\Lambda_c^+\rangle-2\langle\Xi_c'^+\pi^+|\Xi_{cc}^{++}\rangle-2\langle\Lambda_c^+\bar{K}^0|\Xi_{cc}^{++}\rangle=3\Delta\Sigma\cot\theta_C\ , \tag{3.34}$$

where

$$\Delta\Sigma=\sqrt{2}\Sigma_0^+-\Sigma_+^+ +\Sigma_-^-$$

and

$$\Delta\Lambda=\Lambda_-^0+\sqrt{2}\Lambda_0^0\ .$$

As in the $20''$ case, using experimental results of hyperon decays (Table I), we obtain the parameters

$$a_3=22.13\ ,$$

$$a_6=-5.58\ ,$$

TABLE III. Charm-baryon decay widths (1×10^{-10} MeV).

				GIM model		15 admixture	
	c_1	c_2	K	$H^{20''}$	$H^{20''+84}$	$H^{20''+15}$	$H^{20''+15+84}$
$B(3^*)\to B(8)+P(8)$							
$\Lambda_c^+\to p+\bar{K}^0$	67.39	0.147	871.9	0.45	0.50	0.43*	0.43*
$\Lambda_c^+\to\Sigma^++\pi^0$	75.86	0.098	825.9	2.14	2.14	0.08	0.11
$\Lambda_c^+\to\Sigma^++\eta$ [a]	63.85	0.073	711.8	0.45	0.45	0.02	0.02
$\Lambda_c^+\to\Lambda+\pi^+$	75.95	0.116	863.4	2.06	2.07	0.12	0.08
$\Lambda_c^+\to\Sigma^0+\pi^+$	75.80	0.097	823.8	2.12	2.12	0.08	0.11
$\Lambda_c^+\to\Xi^0+K^+$	63.14	0.052	651.5	1.92	1.92	0.07	0.10
$\Xi_c'^+\to\Sigma^++\bar{K}^0$	73.89	0.100	857.9	0.33	0.37	0.33	0.33
$\Xi_c'^+\to\Xi^0+\pi^+$	81.57	0.091	872.0	0.33	0.33	0.33	0.30
$\Xi_c'^0\to\Sigma^++K^-$	73.89	0.100	857.9	4.16	4.31	0.15	0.21
$\Xi_c'^0\to\Lambda+\bar{K}^0$	74.12	0.120	899.4	0.44	0.42	0.19	0.21
$\Xi_c'^0\to\Sigma^0+\bar{K}^0$	73.84	0.100	857.9	3.49	3.58	0.02	0.01
$\Xi_c'^0\to\Xi^0+\pi^0$	81.62	0.090	872.4	0	0	0	0
$\Xi_c'^0\to\Xi^0+\eta$ [a]	70.01	0.069	763.6	0.70	0.70	0.03	0.03
$\Xi_c'^0\to\Xi^-+\pi^+$	81.52	0.089	868.5	0.33	0.33	0.33	0.30
$B(6)\to B(8)+P(8)$							
$\Omega_c^0\to\Xi^0+\bar{K}^0$	84.16	0.107	980.6	0.04	0.36	#	#
$B(3)\to B(8)+P(3^*)$							
$\Omega_{cc}^+\to\Xi^0+D^+$	70.12	0.106	1130.0	0	0	0	0
$\Xi_{cc}^+\to\Xi^0+D_s^+$	53.74	0.067	871.4	12.40	12.41	0.45	0.60
$\Xi_{cc}^+\to\Sigma^0+D^+$	62.21	0.107	1049.3	11.46	11.46	0.42	0.57
$\Xi_{cc}^+\to\Sigma^++D^0$	62.21	0.107	1049.3	23.32	23.34	0.85	1.14
$\Xi_{cc}^+\to\Lambda+D^+$	62.69	0.124	1097.0	4.37	4.49	0.16	0.22
$\Xi_{cc}^{++}\to\Sigma^++D^+$	62.21	0.107	1049.3	0	0	0	0
$B(3)\to B(3^*)+P(8)$							
$\Omega_{cc}^+\to\Xi_c'^++\bar{K}^0$	116.76	0.046	1115.0	0.02	0.30	#	#
$\Xi_{cc}^+\to\Xi_c'^0+\pi^+$	114.85	0.042	1049.0	0.02	0	#	#
$\Xi_{cc}^+\to\Xi_c'^++\pi^0$	114.85	0.042	1049.0	0	0	0	0
$\Xi_{cc}^+\to\Xi_c'^++\eta$ [a]	103.04	0.034	948.2	0	0	#	#
$\Xi_{cc}^+\to\Lambda_c^++\bar{K}^0$	112.13	0.051	1091.6	0.02	0.31	#	#
$\Xi_{cc}^{++}\to\Xi_c'^++\pi^+$	114.80	0.042	1048.6	0.02	0.02	#	#
$(B3)\to B(6)+P(8)$							
$\Omega_{cc}^+\to\Omega_c^0+\pi^+$	114.37	0.031	996.6	0.30	0.30	#	#
$\Omega_{cc}^+\to\Xi_c^++\bar{K}^0$	111.05	0.035	1015.6	0.16	0.06	#	#
$\Xi_{cc}^+\to\Omega_c^0+K^+$	91.63	0.019	769.2	0	0	0	0
$\Xi_{cc}^+\to\Xi_c^0+\pi^+$	108.94	0.031	950.6	0.14	0.14	#	#
$\Xi_{cc}^+\to\Xi_c^++\pi^0$	109.00	0.031	951.1	0	0	0	0
$\Xi_{cc}^+\to\Xi_c^++\eta$ [a]	94.92	0.020	834.2	0	0	0	0
$\Xi_{cc}^+\to\Sigma_c^++\bar{K}^0$	105.57	0.037	971.6	0.16	0.06	#	#
$\Xi_{cc}^+\to\Sigma_c^{++}+K^-$	105.74	0.037	973.1	0	0	0	0
$\Xi_{cc}^{++}\to\Xi_c^++\pi^+$	108.94	0.031	950.6	0.14	0.14	#	#
$\Xi_{cc}^{++}\to\Sigma_c^{++}+\bar{K}^0$	105.57	0.036	971.6	0.32	0.12	#	#

*Input.

#Undetermined.

[a] η-η' mixing is ignored.

$$a_7 = 3.24 \ ,$$

$$b_1 = -1.40 \ ,$$

$$b_3 = -6.26 \ ,$$

calculate the charmed decay widths, and list the values in the sixth column of Table III. The agreement is not much improved. Particularly, the decay rate for $\Lambda_c^+ \to \Lambda\pi^+$ remains large.

B. 15 admixture

Next we take the contribution from **20″** and **15**. Since the **15** part of the Hamiltonian does not contribute to the charmed decays, the decay amplitude relations (3.1)–(3.22) remain valid. But because this piece of the Hamiltonian does contribute to the strange-particle decays, the relations among charmed and uncharmed ones, (3.23) and (3.26), get modified to

$$\frac{4}{\sqrt{2}} \langle \Sigma^+\pi^0 | \Lambda_C^+ \rangle = \frac{2}{\sqrt{6}} \langle \Sigma^+ D^0 | \Xi_{cc}^+ \rangle = (\sqrt{3}\Sigma_0^+ - \Lambda_-^0 + 2\Xi_-^-)\cot\theta \ . \qquad (3.35)$$

The value of the parameter a_3 is reduced to

$$a_3 = -4.23 \ .$$

In order to determine other parameters, we use $\Lambda_c^+ \to p\bar{K}^0$ as input and get

$$-4a_6 + a_7 = 24.20 \ ,$$

which increases the t-channel contribution. The calculated values of the decays are given in the seventh column of Table III. We note that the $\Lambda_c^+ \to \Lambda\pi^+$ decay width is reduced and is in better agreement with the experiment than the GIM model value.

Finally we take the contribution from all three pieces of the Hamiltonian (2.3). The amplitude relations which hold are (3.31) and (3.32). The equation (3.35) gets modified to

$$\frac{8}{\sqrt{2}} \langle \Sigma^+\pi^0 | \Lambda_c^+ \rangle = \frac{4}{\sqrt{6}} \langle \Sigma^+ D^0 | \Xi_{cc}^+ \rangle = \left[\frac{\sqrt{3}}{\sqrt{2}} (\sqrt{2}\Sigma_0^+ - \Sigma_-^- + \Sigma_+^+) - \Lambda_-^0 + \sqrt{2}\Lambda_0^0 + 2(\Xi_-^- + \sqrt{2}\Xi_0^0) \right] \cot\theta_C \ .$$

The parameters now become

$$a_3 = -5.05 \ ,$$

$$-4a_4 + a_7 = 23.68 \ ,$$

$$b_1 = -1.40 \ ,$$

$$b_3 = -6.26 \ .$$

The calculated values are given in the eighth column of Table III.

IV. SUMMARY AND DISCUSSION

By treating the weak decay $B \to B' + P$ as the process $S + B \to B' + P$, expressing the decay amplitudes in terms of the reduced matrix elements in all the s, t, and u channels, and restricting the intermediate states to be nonexotic, we have studied the two-body decays of the charmed baryons. We first assume the weak Hamiltonian to be **20″** dominant in the GIM scheme. We find that the calculated values of branching ratio for $\Lambda_C^+ \to \Lambda\pi^+$ do not match well with experimental data. The inclusion of the **84** piece of the Hamiltonian does not improve the situation. Then we introduce a **15** admixture to the **20″** piece of the GIM Hamiltonian. The **15** piece of the weak Hamiltonian does not contribute to the Cabibbo-enhanced $\Delta C = \Delta S = -1$ mode of the charmed baryons, yet since it contributes to the hyperon decays, the values of the parameters get modified. The values thus calculated are in better agreement with experiment than those calculated with **20″** dominance as well as with the **20″+84** Hamiltonian. Finally we compute the decay rates with all the three pieces **15**, **20″**, and **84** of the weak Hamiltonian. The agreement with experiment is further improved.

ACKNOWLEDGMENTS

R.C.V. would like to thank Professor A. N. Kamal for the hospitality at the University of Alberta. This work was partially supported by a grant from the Natural Sciences and Engineering Research Council of Canada.

APPENDIX

Following are the reduced matrix elements for the $B(\frac{1}{2})^+ \to B(\frac{1}{2})^+ + P(0)^{-1}$ decays.

$H_W^{20''}$:

s channel: $\langle 20' \| 15 \| m \rangle \langle m \| 20'' \| 20' \rangle$,

$m = \mathbf{4^*, 20'_1, 20'_2, 36^*, 60^*, 140''}$.

t channel: $\langle 15 \| 20'' \| m \rangle \langle m \| 20^* \| 20' \rangle$,

$m = \mathbf{15_1, 15_2, 20'', 45, 45^*, 175''}$.

u channel: $\langle 20' \| 20'' \| m \rangle \langle m \| 15 \| 20' \rangle$,

$m = \mathbf{4^*, 20'_1, 20'_2, 36^*, 60^*, 140''}$.

H_W^{84}:

s channel: $\langle 20' \| 15 \| m \rangle \langle m \| 84 \| 20' \rangle$,

$m = \mathbf{20, 20'_1, 20'_2, 36^*, 60^*, 140''}$.

t channel: $\langle 15 \| 84 \| m \rangle \langle m \| 20^* \| 20' \rangle$,

$m = \mathbf{15_1, 15_2, 45, 45^*, 84, 175}$.

u channel: $\langle 20' \| 84 \| m \rangle \langle m \| 15 \| 20' \rangle$,

$m = \mathbf{20, 20'_1, 20'_2, 36^*, 60^*, 140''}$.

H_W^{15}:

$$s \text{ channel: } \langle 20' \| 15 \| m \rangle \langle m \| 15 \| 20' \rangle ,$$

$$m = \mathbf{4^*}, \mathbf{20}, \mathbf{20'_{11}}, \mathbf{20'_{12}}, \mathbf{20'_{21}}, \mathbf{20'_{22}}, \mathbf{36^*}, \mathbf{60^*}, \mathbf{140''} .$$

$$t \text{ channel: } \langle 15 \| 15 \| m \rangle \langle m \| 20^* \| 20' \rangle ,$$

$$m = \mathbf{1}, \mathbf{15_{11}}, \mathbf{15_{12}}, \mathbf{15_{21}}, \mathbf{15_{22}}, \mathbf{20''}, \mathbf{45}, \mathbf{45^*}, \mathbf{84} .$$

$$u \text{ channel: } \langle 20' \| 15 \| m \rangle \langle m \| 15 \| 20' \rangle ,$$

$$m = \mathbf{4^*}, \mathbf{20}, \mathbf{20'_{11}}, \mathbf{20'_{12}}, \mathbf{20'_{21}}, \mathbf{20'_{22}}, \mathbf{36^*}, \mathbf{60^*}, \mathbf{140''} .$$

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