Quark-diagram analysis of charmed-baryon decays

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The Cabibbo-allowed two-body nonleptonic decays of charmed baryons to a SU(3)-octet (or -decuplet) baryon and a pseudoscalar meson are examined on the basis of the quark-diagram scheme. Some relations among the decay amplitudes or rates of various decay modes are derived. The decays of Ξ_c^+ to a decuplet baryon are forbidden.

I. INTRODUCTION

The nonleptonic decays of charmed baryons are of current interest. Some decay modes have been experimentally observed [1] and more data will become available soon. Just after the discovery of the charm quark there were a lot of theoretical investigations [2] based on flavor-SU(4) symmetry, and sum rules among the decay amplitudes were derived. However, since SU(4) symmetry is badly broken, these sum rules may not hold. Recently, the decays of charmed baryons were examined by two groups [3] on the basis of flavor-SU(3) symmetry. It is believed that SU(3) symmetry is considerably good to work with. On the other hand, Igarashi and Shin-Mura [4] applied a constituent rearrangement scheme to the nonleptonic hyperon decays based on SU(4). Chau and Chen [5] analyzed pseudoscalar-pseudoscalar and pseudoscalar-vector two-body decays of charmed mesons in the quark-diagram scheme, which provided a useful model-independent analysis. Furthermore, this scheme was applied to the baryonic decays of bottom mesons [6]. It is expected that the quark-diagram analysis gives good results for the charmed-baryon decays also.

Charmed baryons with a single charm quark are classified into an antitriplet and sextet in the SU(3) representation. Antitriplet baryons (Λ_c^+, Ξ_c^+, and Ξ_c^0) are stable under strong and electromagnetic interactions. They can decay weakly to an ($\frac{1}{2}^+$ or $\frac{3}{2}^+$) baryon and a (pseudoscalar or vector) meson. In this paper we will investigate Cabibbo-allowed ($\Delta C=-1$, $\Delta S=-1$) two-body nonleptonic decays of antitriplet charmed baryons based on the quark-diagram scheme.

In Sec. II we examine the decay amplitudes of charmed baryons to an octet baryon and a pseudoscalar meson. The decay amplitudes to a decuplet baryon and a pseudoscalar meson are studied in Sec. III. They are represented in terms of only two parameters, and some relations between the decay rates, which are able to be compared with experimental data, are derived. Section IV contains our conclusions.

II. $B_c \to B(\frac{1}{2}^+)+P(0^-)$ decays

In this section we examine the Cabibbo-allowed decays of antitriplet charmed baryons (B_c) to a $\frac{1}{2}^+$ ground-state octet baryon (B) and a pseudoscalar meson (P). The transition matrix element for the decay $B_c \to B+P$ takes the form

$$M=i\bar{u}_B(A+B\gamma_5)u_{B_c}\varphi_P \; . \tag{2.1}$$

where A and B denote the parity-violating and the parity-conserving amplitudes, respectively. Charmed-baryon decays arise from the interaction

$$\mathcal{L}_w=\frac{g}{2\sqrt{2}}W_\mu^+[V_{cs}(\bar{c}s)_L+V_{ud}(\bar{u}d)_L]+\text{H.c.} \; , \tag{2.2}$$

where $(\bar{q}q)_L$ is the usual shorthand notation for the left-chiral color-singlet combination of quark fields and V_{ab} are the corresponding Kobayashi-Maskawa matrix elements. There are six types of quark diagrams which occur in baryon decays. Three of them are quark-decay-type diagrams [Fig. 1(a)–(c)], and the other three are W-

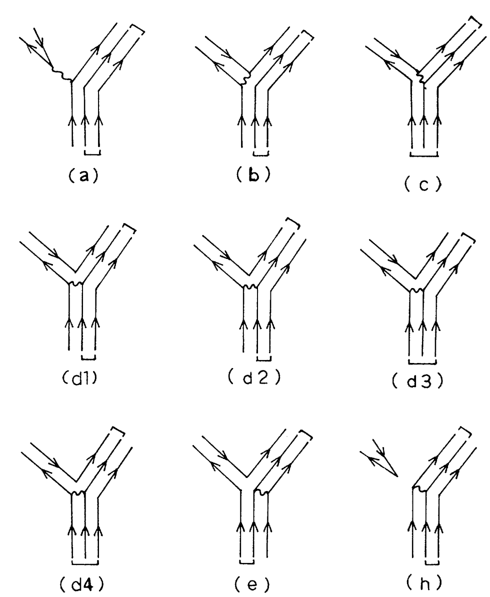

FIG. 1. Quark diagrams of charmed-baryon decays to an octet baryon. The brackets denote antisymmetric pairs of constituents.

exchange-type diagrams [Fig. 1(d)–1(h)].

Two noncharm quarks in an antitriplet charmed baryon are antisymmetric. The tensor representation of antitriplet baryons is $B_{[ab]}$. We take one pair of quarks in an octet baryon to be antisymmetric. Therefore octet baryons are represented in terms of $B_{a[bc]}$. The relation between $B_{a[bc]}$ and the usual $q\bar{q}$ octet representation B_a^d is

$$B_a^d = \tfrac{1}{2}\varepsilon^{dbc}B_{a[bc]} \; . \tag{2.3}$$

These $B_{a[bc]}$'s satisfy the Jacobi identity

$$B_{a[bc]} + B_{b[ca]} + B_{c[ab]} = 0 \; , \tag{2.4}$$

which corresponds to the traceless condition of B_a^d. Because of this equation two of them are independent.

The Körner-Pati-Woo [7] theorem requires that the quark pair produced by weak interaction is antisymmetric in one baryon. This is a result of the fact that the $(V-A)\times(V-A)$ structure of weak interactions is invariant under Fierz transformations and that the quarks in baryons are color antisymmetric. Therefore the produced quark pair in Figs. 1(c), 1(e), and 1(h) is flavor antisymmetric.

We need to distinguish which pair of quarks in the diagrams is antisymmetric. Considering Eq. (2.4) and the relation

$$\bar{B}^{x[ab]}B_{[ab]} = 2\bar{B}^{a[xb]}B_{[ab]} \quad (\text{for } x = 1,2,3) \; , \tag{2.5}$$

there are nine independent decay diagrams, which are depicted in Fig. 1. The decay amplitudes are written as

$$\begin{aligned}\mathcal{A} = {} & a\bar{B}^{3[ab]}B_{[ab]}M_2^1 + b\bar{B}^{1[ab]}B_{[ab]}M_2^3 + c\bar{B}^{b[13]}B_{[ab]}M_2^a + d_1\bar{B}^{a[1b]}B_{[2b]}M_a^3 + d_2\bar{B}^{b[1a]}B_{[2b]}M_a^3 \\ & + d_3\bar{B}^{a[3b]}B_{[2b]}M_a^1 + d_4\bar{B}^{b[3a]}B_{[2b]}M_a^1 + e\bar{B}^{a[13]}B_{[2b]}M_a^b + h\bar{B}^{b[13]}B_{[2b]}M_a^a \; ,\end{aligned} \tag{2.6}$$

where M_a^b denotes nonet pseudoscalar mesons. A summation over repeated indices is implied. They run from 1 to 3, where we identify $u=1$, $d=2$, and $s=3$. In this equation the first term corresponds to the Fig. 1(a), and so on. The decay amplitudes of various decay modes are given in Table I. They mean both the parity-violating and the parity-conserving amplitudes. In this table η_8 and η_1 represent the octet and singlet members of $S=I=0$ pseudoscalar mesons, respectively. The hairpin diagram (h) is likely to be suppressed due to the Okubo-Zweik-Iizuka rule [8]. As the masses of the decaying charmed baryons lie in the resonance region, it is thought that the final-state interactions may give considerably large effects. The amplitudes with final-state interactions are given in the last column of Table I. Here δ_I^{BP} denotes the isospin I phase shift of BP scattering, and they are complex in general.

Our amplitudes have slight differences from those of Ref. [3]. When we neglect final-state interactions, we can extract the SU(2) or SU(3) relations which are already

TABLE I. $B_c \to BP$ decay amplitudes.

Decay modes	Amplitudes with SU(3) symmetry	Amplitudes with final-state interactions
$\Lambda_c^+ \to \Lambda\pi^+$	$\frac{1}{3}(-4a-c-d_3+d_4+e)$	$\frac{1}{3}(-4a-c-d_3+d_4+e)\exp(i\delta_1^{\Lambda\pi})$
$p\bar{K}^0$	$(2/\sqrt{6})(2b-d_2)$	$(2/\sqrt{6})(2b-d_2)\exp(i\delta_1^{N\bar{K}})$
$\Sigma^+\pi^0$	$(1/\sqrt{3})(-c-d_3-d_4+e)$	$(1/\sqrt{3})(-c-d_3-d_4+e)\exp(i\delta_1^{\Sigma\pi})$
$\Sigma^+\eta_8$	$\frac{1}{3}(c-2d_2-d_3-d_4+e)$	$\frac{1}{3}(c-2d_2-d_3-d_4+e)\exp(i\delta_1^{\Sigma\eta_8})$
$\Sigma^+\eta_1$	$(2/3\sqrt{2})(c+d_2-d_3-d_4+e+3h)$	$(2/3\sqrt{2})(c+d_2-d_3-d_4+e+3h)\exp(i\delta_1^{\Sigma\eta_1})$
$\Sigma^0\pi^+$	$(1/\sqrt{3})(c+d_3+d_4-e)$	$(1/\sqrt{3})(c+d_3+d_4-e)\exp(i\delta_1^{\Sigma\pi})$
Ξ^0K^+	$(2/\sqrt{6})(-d_3+e)$	$(2/\sqrt{6})(-d_3+e)\exp(i\delta_1^{\Xi K})$
$\Xi_c^+ \to \Xi^0\pi^+$	$(2/\sqrt{6})(2a+c)$	$(2/\sqrt{6})(2a+c)\exp(i\delta_{3/2}^{\Xi\pi})$
$\Sigma^+\bar{K}^0$	$(2/\sqrt{6})(2b-c)$	$(2/\sqrt{6})(2b-c)\exp(i\delta_{3/2}^{\Sigma\bar{K}})$
$\Xi_c^0 \to \Xi^-\pi^+$	$(2/\sqrt{6})(-2a+d_4)$	$-(2/3\sqrt{6})[(2a+c)\exp(i\delta_{3/2}^{\Xi\pi})$ $+(4a-c-3d_4)\exp(i\delta_{1/2}^{\Xi\pi})]$
$\Lambda\bar{K}^0$	$\frac{1}{3}(-2b-c+d_1+2d_2+e)$	$\frac{1}{3}(-2b-c+d_1+2d_2+e)\exp(i\delta_{1/2}^{\Lambda\bar{K}})$
$\Sigma^0\bar{K}^0$	$(1/\sqrt{3})(-2b+c-d_1-e)$	$(1/3\sqrt{3})[(-4b+2c)\exp(i\delta_{3/2}^{\Sigma\bar{K}})$ $+(-2b+c-3d_1-3e)\exp(i\delta_{1/2}^{\Sigma\bar{K}})]$
$\Xi^0\pi^0$	$(1/\sqrt{3})(-c-d_4)$	$(1/3\sqrt{3})[(-4a-2c)\exp(i\delta_{3/2}^{\Xi\pi})$ $-(-4a+c+3d_4)\exp(i\delta_{1/2}^{\Xi\pi})]$
$\Xi^0\eta_8$	$\frac{1}{3}(c-2d_1-2d_2-d_4-2e)$	$\frac{1}{3}(c-2d_1-2d_2-d_4-2e)\exp(i\delta_{1/2}^{\Xi\eta_8})$
$\Xi^0\eta_1$	$(2/3\sqrt{2})(c+d_1+d_2-d_4+e+3h)$	$(2/3\sqrt{2})(c+d_1+d_2-d_4+e+3h)\exp(i\delta_{1/2}^{\Xi\eta_1})$
Σ^+K^-	$(2/\sqrt{6})(d_1+e)$	$(2/3\sqrt{6})[(-2b+c)\exp(i\delta_{3/2}^{\Sigma\bar{K}})$ $-(-2b+c-3d_1-3e)\exp(i\delta_{1/2}^{\Sigma\bar{K}})]$

given in Refs. [2] and [3]. In addition, we obtain the sum rule

$$\sqrt{3}A(\Xi_c^0\to\Lambda\bar{K}^0)+A(\Xi_c^0\to\Sigma^0\bar{K}^0)+\sqrt{2}A(\Lambda_c^+\to p\bar{K}^0)=0\ . \tag{2.7}$$

This relation holds for both the parity-violating and parity-conserving amplitudes. When we take final-state interactions into consideration, this equation does not hold. Therefore it is inadequate to use this relation to test our scheme.

III. $B_c\to D(\frac{3}{2}^+)+P(0^-)$ decays

In this section we investigate the Cabibbo-allowed decays of antitriplet charmed baryons (B_c) to a $\frac{3}{2}^+$ decuplet baryon (D) and a pseudoscalar meson (P). The transition matrix element for these decays can be written as

$$M=ip_\mu\bar{u}_{D\mu}(p')(C\gamma_5+D)u_{B_c}(p)\varphi_P\ , \tag{3.1}$$

where $u_{D\mu}$ is the Rarita-Schwinger spinor representing the $\frac{3}{2}^+$ baryon, p_μ is the four-momentum of the charmed baryon, and C and D denote the parity-violating and the parity-conserving amplitudes, respectively.

The constituent quarks in a decuplet baryon are totally symmetric, and they are represented in terms of $D_{(abc)}$. In these decays most diagrams are forbidden due to the symmetry property of decuplet baryons, and there are only two independent diagrams shown in Fig. 2. These decays can arise only from the W-exchange diagrams. The decay $\Lambda_c^+\to\Delta^{++}K^-$ has been observed experimentally and its branching ratio $[(5.7\pm2.8)\times10^{-3}]$ is not very small [1, 9]. It shows that W-exchange diagrams give a very significant contribution to baryon decays [10].

The amplitudes for the two diagrams are written as

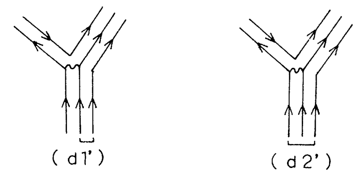

FIG. 2. Quark diagrams of charmed-baryon decays to a decuplet baryon.

$$\mathcal{A}=d_1'\bar{D}^{(1ab)}B_{[2a]}M_b^3+d_2'\bar{D}^{(3ab)}B_{[2a]}M_b^1\ . \tag{3.2}$$

Each term corresponds to the d1′ and d2′ diagram, respectively. The amplitudes for various modes without and with final-state interactions are given in Table II. In addition to the already known SU(2) or SU(3) relations we can find the following relations between decay rates:

$$\Gamma(\Xi_c^+\to\Sigma^{*+}\bar{K}^0)=\Gamma(\Xi_c^+\to\Xi^{*0}\pi^+)=0\ , \tag{3.3}$$

$$\Gamma(\Xi_c^0\to\Sigma^{*+}K^-)=2\Gamma(\Xi_c^0\to\Sigma^{*0}\bar{K}^0)\ , \tag{3.4}$$

$$\Gamma(\Xi_c^0\to\Xi^{*-}\pi^+)=2\Gamma(\Xi_c^0\to\Xi^{*0}\pi^0)\ . \tag{3.5}$$

These relations hold without depending on the final-state interaction phases. These relations, especially Eq. (3.3), give good tests of our scheme. Experimentally these decay rates have not been measured yet. Adding to these equations, if inelasticity and the difference of phase-space volumes can be neglected, the following relations are derived:

$$\Gamma(\Lambda_c^+\to\Delta^+\bar{K}^0)=\Gamma(\Xi_c^0\to\Sigma^{*+}K^-)\ , \tag{3.6}$$

$$\Gamma(\Lambda_c^+\to\Xi^{*0}K^+)=\Gamma(\Xi_c^0\to\Xi^{*-}\pi^+)=2\Gamma(\Lambda_c^+\to\Sigma^{*0}\pi^+)\ , \tag{3.7}$$

TABLE II. $B_c\to DP$ decay amplitudes.

Decay modes	Decay amplitudes with SU(3) symmetry	Decay amplitudes with final-state interactions
$\Lambda_c\to\Delta^{++}K^-$	$-(2/\sqrt{6})d_1'$	$-(2/\sqrt{6})d_1'\exp(i\delta_1^{\Delta\bar{K}})$
$\Delta^+\bar{K}^0$	$-(2/3\sqrt{2})d_1'$	$-(2/3\sqrt{2})d_1'\exp(i\delta_1^{\Delta\bar{K}})$
$\Sigma^{*+}\eta_8$	$(1/3\sqrt{3})(2d_1'-d_2')$	$(1/3\sqrt{3})(2d_1'-d_2')\exp(i\delta_1^{\Sigma^*\eta_8})$
$\Sigma^{*+}\eta_1$	$-(2/3\sqrt{6})(d_1'+d_2')$	$-(2/3\sqrt{6})(d_1'+d_2')\exp(i\delta_1^{\Sigma^*\eta_1})$
$\Sigma^{*+}\pi^0$	$-\frac{1}{3}d_2'$	$-\frac{1}{3}d_2'\exp(i\delta_1^{\Sigma^*\pi})$
$\Sigma^{*0}\pi^+$	$-\frac{1}{3}d_2'$	$-\frac{1}{3}d_2'\exp(i\delta_1^{\Sigma^*\pi})$
$\Xi^{*0}K^+$	$-(2/3\sqrt{2})d_2'$	$-(2/3\sqrt{2})d_2'\exp(i\delta_1^{\Xi^*K})$
$\Xi_c^+\to\Sigma^{*+}\bar{K}^0$	0	0
$\Xi^{*0}\pi^+$	0	0
$\Xi_c^0\to\Sigma^{*+}K^-$	$-(2/3\sqrt{2})d_1'$	$-(2/3\sqrt{2})d_1'\exp(i\delta_{1/2}^{\Sigma^*\bar{K}})$
$\Sigma^{*0}\bar{K}^0$	$-\frac{1}{3}d_1'$	$-\frac{1}{3}d_1'\exp(i\delta_{1/2}^{\Sigma^*\bar{K}})$
$\Xi^{*0}\eta_8$	$(1/3\sqrt{3})(2d_1'-d_2')$	$(1/3\sqrt{3})(2d_1'-d_2')\exp(i\delta_{1/2}^{\Xi^*\eta_8})$
$\Xi^{*0}\eta_1$	$-(2/3\sqrt{6})(d_1'+d_2')$	$-(2/3\sqrt{6})(d_1'+d_2')\exp(i\delta_{1/2}^{\Xi^*\eta_1})$
$\Xi^{*0}\pi^0$	$-\frac{1}{3}d_2'$	$-\frac{1}{3}d_2'\exp(i\delta_{1/2}^{\Xi^*\pi})$
$\Xi^{*-}\pi^+$	$-(2/3\sqrt{2})d_2'$	$-(2/3\sqrt{2})d_2'\exp(i\delta_{1/2}^{\Xi^*\pi})$
Ω^-K^+	$-(2/\sqrt{6})d_2'$	$-(2/\sqrt{6})d_2'\exp(i\delta_{1/2}^{\Omega K})$

$$\Gamma(\Lambda_c^+ \to \Sigma^{*+}\eta_8) = \Gamma(\Xi_c^0 \to \Xi^{*0}\eta_8) , \quad (3.8)$$

$$\Gamma(\Lambda_c^+ \to \Sigma^{*+}\eta_1) = \Gamma(\Xi_c^0 \to \Xi^{*0}\eta_1) . \quad (3.9)$$

These are approximate relations.

IV. CONCLUSION

We have studied the Cabibbo-allowed decays of charmed baryons to a baryon and a pseudoscalar meson in the quark-diagram scheme, and derived some relations among decay amplitudes or rates for different decay modes. Especially the relations for the decay rates to decuplet baryons are very simple and do not depend on the final-state-interaction phase shifts. As they occur only via W exchange, the decay rates give the measure of W-exchange contribution in a baryon decay, in which helicity suppression does not work, contrary to meson decays. Our interesting conclusion is that the decays $\Xi_c^+ \to \Sigma^{*+}\bar{K}^0$ and $\Xi_c^+ \to \Xi^{*0}\pi^+$ are forbidden.

Charmed baryons can decay also to vector mesons. In fact the decays $\Lambda_c^+ \to p\bar{K}^{*0}$, $\Delta\bar{K}^*$ were observed [9, 11]. Replacing pseudoscalar mesons of our amplitudes by corresponding vector mesons, we can obtain the two-body decay amplitudes to a baryon and a vector meson. The only difference between the two is singlet-octet mixing angle.

At the present time few decay modes have been experimentally observed. However, other decay modes will be observed in the near future. Then we will be able to compare our results with experimental data.

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