Spectroscopy and Strong Decays of Charmed Baryons

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Spectroscopy and strong decays of the charmed baryons are reviewed. Possible spin-parity quantum numbers of several newly observed charmed baryon resonances are discussed. Strong decays of charmed baryons are analyzed in the framework of heavy hadron chiral perturbation theory in which heavy quark symmetry and chiral symmetry are synthesized.

1. Introduction

In the past years many new excited charmed baryon states have been discovered by BaBar, Belle and CLEO. In particular, $B$ factories have provided a very rich source of charmed baryons both from $B$ decays and from the continuum $e^+e^- \rightarrow cc$. A new era for the charmed baryon spectroscopy is opened by the rich mass spectrum and the relatively narrow widths of the excited states. Experimentally and theoretically, it is important to identify the quantum numbers of these new states and understand their properties. Since the pseudoscalar mesons involved in the strong decays of charmed baryons are soft, the charmed baryon system offers an excellent ground for testing the ideas and predictions of heavy quark symmetry of the heavy quarks and chiral symmetry of the light quarks.

2. Spectroscopy

Charmed baryon spectroscopy provides an ideal place for studying the dynamics of the light quarks in the environment of a heavy quark. The charmed baryon of interest contains a charmed quark and two light quarks, which we will often refer to as a diquark. Each light quark is a triplet of the flavor SU(3). Since light quarks, which we will often refer to as a diquark.

In the quark model, the orbital angular momentum of the light diquark can be decomposed into $L = L_\mu + L_\lambda$, where $L_\mu$ is the orbital angular momentum between the two light quarks and $L_\lambda$ the orbital angular momentum between the diquark and the charmed quark. The lowest-lying orbitally excited baryon states are the $p$-wave charmed baryons. Denoting the quantum numbers $L_\rho$ and $L_\lambda$ as the eigenvalues of $L^2_\mu$ and $L^2_\lambda$, respectively, the $p$-wave heavy baryon can be either in the $(L_\rho = 0, L_\lambda = 1)$ $\lambda$-state or the $(L_\rho = 1, L_\lambda = 0)$ $\rho$-state. It is obvious that the orbital $\lambda$-state ($\rho$-state) is symmetric (antisymmetric) under the interchange of two light quarks $q_1$ and $q_2$. The total angular momentum of the diquark is $J_\ell = S_\ell + L_\ell$ and the total angular momentum of the charmed baryon is $J = S_c + J_\ell$. In the heavy quark limit, the spin of the charmed quark $S_c$ and the total angular momentum of the two light quarks $J_\ell$ are separately conserved.

There are seven lowest-lying $p$-wave $\Lambda_c$ arising from combining the charmed quark spin $S_c$ with light constituents in $J^{P_c}_\ell = 1^−$ state: three $J^P = \frac{1}{2}^−$ states, three $J^P = \frac{3}{2}^−$ states and one $J^P = \frac{5}{2}^−$ state. They form three doublets $\Lambda_{c1}(\frac{1}{2}^−, \frac{3}{2}^−), \Lambda_{c2}(\frac{1}{2}^−, \frac{3}{2}^−), \Lambda_{c3}(\frac{3}{2}^−, \frac{5}{2}^−)$ and one singlet $\Lambda_{c0}(\frac{1}{2}^−)$ in the notation $\Lambda_{c}J_{\ell}(J^P)\ell$, where we have used a tilde to denote the multiplets antisymmetric in the orbital wave functions under the exchange of two light quarks. Quark models [1] indicate that the untilded states for $\Lambda$- and $\Sigma$-type charmed baryons with symmetric orbital wave functions lie about 150 MeV below the tilde ones. The two states in each doublet with $J = J_\ell \pm \frac{1}{2}$ are nearly degenerate; their masses split only by a chromomagnetic interaction.

The next orbitally excited states are the positive parity excitations with $L_\rho + L_\lambda = 2$. There are two multiplets for the first positive-parity excited $\Lambda_c$ with the symmetric orbital wave function, corresponding to $L_\lambda = 2, L_\rho = 0, L = 2$ and $L_\lambda = 0, L_\rho = 2, L = 2$; see Table III (for other charmed baryons, see [2] for details). For the case of $L_\lambda = L_\rho = 1$, the total orbital angular momentum $L_\ell$ of the diquark is 2, 1 or 0. Since the orbital states are antisymmetric under the interchange of two light quarks, we shall use a tilde to denote the $L_\lambda = L_\rho = 1$ states. The Fermi-Dirac statistics for baryons yields seven more multiplets for positive-parity excited $\Lambda_c$ states.

The observed mass spectra and decay widths of charmed baryons are summarized in Table III. For the experimental status of charmed baryons, see [2]. In the following we discuss some of the new excited charmed baryon states:

2.1. $\Lambda_c$

It is known that $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ form a doublet $\Lambda_{c1}(\frac{1}{2}^−, \frac{3}{2}^−)$ [3]. The dominant decay mode is $\Sigma_\pi\pi$ in an $S$ wave for $\Lambda_{c1}(\frac{1}{2}^−)$ and $\Lambda_{c2}\pi\pi$ in a $P$ wave for $\Lambda_{c1}(\frac{3}{2}^−)$. (The two-body mode $\Sigma_\pi\pi$ is a $D$-wave in $\Lambda_{c}(\frac{5}{2}^−)$ decay.) This explains why the width
of $\Lambda_c(2625)^+$ is narrower than that of $\Lambda_c(2595)^+$.

$\Lambda_c(2765)^+$ is a broad state ($\Gamma \approx 50$ MeV) first seen in $\Lambda^+_c\pi^+\pi^-$ by CLEO [8]. It appears to resonate through $\Sigma_c$ and probably also $\Sigma_c^*$. However, whether it is a $\Lambda_c^+$ or a $\Sigma_c^+$ or whether the width might be due to overlapping states are not known. According to PDG [6], this state has a nickname, namely, $\Lambda_c(2765)^+$. The Skyme model [12] and the quark model [1] suggest a $J^P = \frac{1}{2}^+$, $\Lambda_c$ state with a mass 2742 and 2775 MeV, respectively. Therefore, $\Lambda_c(2765)^+$ could be a first positive-parity excitation of $\Lambda_c$. However, two recent studies based on the relativistic quark model advocate a different assignment: a radial excitation $2\pi^{++}$ by [8] and a negative-parity state with $J^P = \frac{3}{2}^-$ by [9].

The state $\Lambda_c(2880)^+$ first observed by CLEO [5] in $\Lambda^+_c\pi^+\pi^-$ was also seen by BaBar in the $D^0p$ spectrum [10]. It was originally conjectured that, based on its narrow width, $\Lambda_c(2880)^+$ might be a $\Lambda_c^0(\frac{3}{2}^-)$ state [5]. Recently, Belle has studied the experimental constraint on the $J^P$ quantum numbers of $\Lambda_c(2880)^+$ [11]. The angular analysis of $\Lambda_c(2880)^+ \to \Sigma_{cc}^0\pi^+$ indicates that $J = \frac{3}{2}$ is favored over $J = \frac{1}{2}$ or $\frac{3}{2}$. In the quark model, the candidates for the spin-$\frac{3}{2}$ state are $\Lambda_c(\frac{3}{2}^+)$, $\Lambda_c(\frac{5}{2}^+)$, $\Lambda_c(\frac{3}{2}^-)$, $\Lambda_c^*(\frac{3}{2}^+)$, $\Lambda_c^*(\frac{5}{2}^+)$ and $\Lambda_c^*(\frac{3}{2}^-)$ (see Table 1). And only one of them has odd parity.

Belle has also studied the resonant structure of $\Lambda_c(2880)^+ \to \Lambda^+_c\pi^+\pi^-$ and found the existence of the $\Sigma_c^*\pi$ intermediate states [11]. The ratio of $\Sigma_c^*\pi/\Sigma_c\pi$ is measured to be

$$R = \frac{\Gamma(\Lambda_c(2880)^+ \to \Sigma_c^*\pi^+)}{\Gamma(\Lambda_c(2880)^+ \to \Sigma_c\pi^+)} = (24.1 \pm 6.4_{-4.3}^{+1.1})\%.$$  

(1)

For $J^P = \frac{5}{2}^-$, $\Lambda_c(2880)^+$ decays to $\Sigma_c^*\pi$ and $\Sigma_c\pi$ in a $D$ wave and we obtain

$$\frac{\Gamma(\Lambda_c(2880)^+ \to \Sigma_c^*\pi) \Gamma(\Lambda_c(2880)^+ \to \Sigma_c\pi)}{\Gamma(\Lambda_c(2880)^+ \to \Sigma_c^*\pi) \Gamma(\Lambda_c(2880)^+ \to \Sigma_c\pi)} = \frac{7}{2} \frac{p_6^2(\Lambda_c(2880)^+ \to \Sigma_c^*\pi)}{p_6^2(\Lambda_c(2880)^+ \to \Sigma_c\pi)} = 1.45,$$

(2)

where the factor of $7/2$ follows from heavy quark symmetry. Hence, the assignment of $J^P = \frac{5}{2}^-$ for $\Lambda_c(2880)^+$ is disfavored. For $J^P = \frac{5}{2}^+$, $\Lambda_c$, $\Lambda_c^*$, $\Lambda_c^*$ and $\Lambda_c^*$ are allowed. However, two recent studies based on the relativistic quark model [11] predict $J = \frac{5}{2}$ for these states.

At first glance, it appears that this is in good agreement with experiment. However, the $\Sigma_c^*\pi$ channel is available via a $P$-wave and is enhanced by a factor of $1/p_6^*$ relative to the $F$-wave one. Unfortunately, we cannot apply heavy quark symmetry to calculate the contribution of the $[\Sigma_c^*\pi)^+\pi^+\pi^-$ to the ratio $R$ as the reduced matrix elements are different for $P$-wave and $F$-wave modes. In this case, one has to rely on a phenomenological model to compute the ratio $R$. At any event, the $\Sigma_c^*\pi$ mode produced in $\Lambda_c(2880)$ is a priori not necessarily suppressed relative to $[\Sigma_c\pi)^+\pi^+\pi^-$. Therefore, if $\Lambda_c(2880)^+$ is one of the states $\Lambda_c^0$, $\Lambda_c^*$, $\Lambda_c^*$ and $\Lambda_c^*$, the prediction $R = 0.23$ is not robust as it can be easily upset by the contribution from the $P$-wave $\Sigma_c^*\pi$.

As for $\Lambda_c^0(\frac{3}{2}^+)$, it decays to $\Sigma^*\pi$, $\Sigma_c\pi$ and $\Lambda_c\pi$ all in $F$ waves. Since $J = 3$, $L = 2$, it turns out that

$$\frac{\Gamma(\Lambda_c^0(\frac{3}{2}^+)^{1/2} \to [\Sigma^*\pi)^+\pi^+\pi^-)}{\Gamma(\Lambda_c^0(\frac{3}{2}^+)^{1/2} \to [\Sigma^*\pi)^+\pi^+\pi^-)} = \frac{5}{4} \frac{p_6^2(\Lambda_c(2880)^+ \to \Sigma_c^*\pi)}{p_6^2(\Lambda_c(2880)^+ \to \Sigma_c\pi)} = 0.36.$$  

(3)

Although this deviates from the experimental measurement [11] by 1σ, it is a robust prediction. This has motivated Chun-Khiang Chua and me to conjecture that the first positive-parity excited charmed baryon $\Lambda_c(2880)^+$ could be an admixture of $\Lambda_c^0(\frac{3}{2}^+)$, $\Lambda_c^0(\frac{5}{2}^+)$ and $\Lambda_c^0(\frac{3}{2}^-)$ [2].

It is worth mentioning that very recently the Peking group [12] has studied the strong decays of charmed baryons based on the so-called $^3P_0$ recombination model. For the $\Lambda_c(2880)$, Peking group found that (i) the possibility of $\Lambda_c(2880)$ being a radial excitation is ruled out as its decay into $D^0p$ is prohibited in the $^3P_0$ model if $\Lambda_c(2880)$ is a first radial excitation of $\Lambda_c$, and (ii) the only possible assignment is $\Lambda_c^0(\frac{3}{2}^+)$.
Table II: Mass spectra and decay widths (in units of MeV) of charmed baryons taken from [2]. Except for the parity of the lightest $\Lambda_c^+$ and the spin-parity of $\Lambda_c(2880)^+$, none of the other $J^P$ quantum numbers given in the table has been measured. One has to rely on the quark model to determine the spin-parity assignments.

| State          | $J^P$ | $S_c$ | $L_c$ | $J_c^P$ | Mass            | Width     | Principal decay modes       |
|----------------|-------|-------|-------|---------|-----------------|-----------|-----------------------------|
| $\Lambda_c^+$ | $\frac{1}{2}^+$ | 0     | 0     | 0       | 2286.46 ± 0.14  | weak      |                             |
| $\Lambda_c(2595)^+$ | $\frac{3}{2}^+$ | 0     | 1     | 1       | 2452.9 ± 0.4    | $<4.6$    | $\Lambda_c\pi$             |
| $\Lambda_c(2625)^+$ | $\frac{3}{2}^+$ | 0     | 1     | 1       | 2453.76 ± 0.18  | 2.2 ± 0.4 | $\Lambda_c\pi$             |
| $\Lambda_c(2750)^+$ | $\frac{3}{2}^+$ | 1     | 0     | 1       | 2518.4 ± 0.6    | 14.9 ± 1.9 | $\Lambda_c\pi$             |
| $\Lambda_c(2820)^+$ | $\frac{3}{2}^+$ | 1     | 0     | 1       | 2517.5 ± 2.3    | $<17$     | $\Lambda_c\pi$             |
| $\Sigma_c(2455)^+$ | $\frac{1}{2}^+$ | 1     | 0     | 1       | 2467.9 ± 0.4    | weak      |                             |
| $\Sigma_c(2455)^0$ | $\frac{1}{2}^-$ | 0     | 0     | 0       | 2471.0 ± 0.4    | weak      |                             |
| $\Xi_c(2790)^+$ | $\frac{1}{2}^+$ | 1     | 0     | 1       | 2575.7 ± 3.1    | $\Xi_{c\gamma}$ |                             |
| $\Xi_c(2790)^0$ | $\frac{1}{2}^-$ | 1     | 0     | 1       | 2578.0 ± 2.9    | $\Xi_{c\gamma}$ |                             |
| $\Xi_c(2820)^+$ | $\frac{3}{2}^+$ | 1     | 0     | 1       | 2646.6 ± 1.4    | $<3.1$    | $\Xi_{c\pi}$               |
| $\Xi_c(2820)^0$ | $\frac{3}{2}^-$ | 1     | 0     | 1       | 2646.1 ± 1.2    | $<5.5$    | $\Xi_{c\pi}$               |
| $\Xi_c(2795)^+$ | $\frac{1}{2}^+$ | 0     | 1     | 1       | 2789.2 ± 3.2    | $<15$     | $\Xi_{c\pi}$               |
| $\Xi_c(2795)^0$ | $\frac{1}{2}^-$ | 0     | 1     | 1       | 2791.9 ± 3.3    | $<12$     | $\Xi_{c\pi}$               |
| $\Xi_c(2815)^+$ | $\frac{3}{2}^+$ | 0     | 1     | 1       | 2816.5 ± 1.2    | $<3.5$    | $\Xi_{c\pi}, \Xi_{c\pi}, \Xi_{c\pi}$ |
| $\Xi_c(2815)^0$ | $\frac{3}{2}^-$ | 0     | 1     | 1       | 2818.2 ± 2.1    | $<6.5$    | $\Xi_{c\pi}, \Xi_{c\pi}, \Xi_{c\pi}$ |
| $\Xi_c(2980)^+$ | $\frac{1}{2}^+$ | 0     | 0     | 0       | 2971.1 ± 1.7    | 25.2 ± 3.0 | see Table 7 of [2]         |
| $\Xi_c(2980)^0$ | $\frac{1}{2}^-$ | 0     | 0     | 0       | 2977.1 ± 9.5    | 43.5      | see Table 7 of [2]         |
| $\Xi_c(3055)^+$ | $\frac{1}{2}^+$ | 0     | 0     | 0       | 3054.2 ± 1.3    | 17 ± 13   | $\Lambda_c^0 K^0, \Lambda_c^0 K^+ K^- +$ |
| $\Xi_c(3080)^+$ | $\frac{1}{2}^+$ | 0     | 0     | 0       | 3076.5 ± 1.6    | 6.2 ± 1.1 | see Table 7 of [2]         |
| $\Xi_c(3080)^0$ | $\frac{1}{2}^-$ | 0     | 0     | 0       | 3082.8 ± 2.3    | 5.2 ± 3.6 | see Table 7 of [2]         |
| $\Omega_c(2770)^+$ | $\frac{1}{2}^+$ | 1     | 0     | 1       | 2697.5 ± 2.6    | weak      |                             |

Since according to the $^3P_0$ model [12]

$$\frac{\Gamma(\Lambda_{c2}(5/2^+)^+ \to \Sigma_c^*\pi)}{\Gamma(\Lambda_{c2}(5/2^+)^+ \to \Sigma_c\pi)} = 0.06,$$

$$\frac{\Gamma(\hat{\Lambda}_{c2}(5/2^+)^+ \to \Sigma_c^*\pi)}{\Gamma(\hat{\Lambda}_{c2}(5/2^+)^+ \to \Sigma_c\pi)} = 78.3.$$

(5)

Both symmetric states $\Lambda_{c2}$ and $\hat{\Lambda}_{c2}$ are thus ruled out as the predicted ratio $R$ is either too small or too big compared to experiment. However, the assignment of $\Lambda_{c3}(\frac{5}{2}^+)$ for $\Lambda_c(2880)$ has an issue with the spectrum:

The quark model indicates a $\Lambda_{c2}(\frac{5}{2}^+)$ state around 2910 MeV which is close to the mass of $\Lambda_c(2880)$, while the mass of $\Lambda_{c3}(\frac{5}{2}^+)$ is higher [11].

It is interesting to notice that, based on the diquark idea, the quantum numbers $J^P = \frac{5}{2}^+$ have been correctly predicted in [13] for the $\Lambda_c(2880)$ before the Belle experiment.

The highest $\Lambda_c(2940)^+$ was first discovered by BaBar in the $D^0\pi$ decay mode [10] and confirmed by
Belle in the decays $\Sigma^0 \pi^+ \pi^- \pi^0$ which subsequently decay into $\Lambda_c^+ \pi^- \pi^-$ [11]. Since the mass of $\Lambda_c(2940)^+$ is barely below the threshold of $D^{*0} p$, this observation has motivated the authors of [14] to suggest an exotic molecular state of $D^{*0}p$ with a binding energy of order 6 MeV and $J^P = \frac{5}{2}^+$ for $\Lambda_c(2940)^+$. The quark potential model predicts a $\frac{5}{2}^-$ $\Lambda_c$ state at 2900 MeV and a $\frac{3}{2}^+$ $\Lambda_c$ state at 2910 MeV [1]. A similar result of 2906 MeV for $\frac{3}{2}^+ \Lambda_c$ is also obtained in the relativistic quark model [15]. Given the uncertainty of order 50 MeV for the quark model calculation, this suggests that the possible allowed $J^P$ numbers of the highest $\Lambda_c(2940)^+$ are $\frac{5}{2}^-$ and $\frac{3}{2}^+$. Hence, the potential candidates are $\bar{\Lambda}_c(\frac{5}{2}^-$), $\Lambda_c(\frac{3}{2}^+)\), $\bar{\Lambda}_c(\frac{3}{2}^+)\), $\bar{\Lambda}_c(\bar{\Lambda}_c(\frac{3}{2}^-))$, $\Lambda^0(\frac{1}{2}^+)$ and $\Lambda^0(\frac{3}{2}^+)$. Since the predicted ratios differ significantly for different $J^P$ quantum numbers, the measurements of the ratio of $\Sigma_c^0 \pi/\Sigma_c^+ \pi$ will enable us to discriminate the $J^P$ assignments for $\Lambda_c(2940)^+$ [2]. Note that it has been argued in [8] that $\Lambda_c(2940)^+$ is the first radial excitation of $\Sigma_c$ (not $\Lambda_c$!) with $J^P = 3/2^+$. 

2.2. $\Sigma_c$

The highest isotriplet charmed baryons $\Sigma_c(2800)^+, \Sigma_c^0, \Sigma_c(2790)$ decaying to $\Lambda_c^+ \pi$ were first measured by Belle [14]. They are most likely to be the $J^P = \frac{3}{2}^+$ $\Sigma_c$ states because the $\Sigma_c^0$($\frac{1}{2}^-$) baryon decays principally into the $\Lambda_c \pi$ system in a $D$-wave, while $\Sigma_c^0$($\frac{3}{2}^-$) decays mainly to the two pion system $\Lambda_c \pi$ in a $P$-wave. The state $\Sigma_c^0$($\frac{3}{2}^-$) can decay into $\Lambda_c^+ \pi$ in an $S$-wave, but it is very broad with width of order 406 MeV. Therefore, $\Sigma_c(2800)^+, \Sigma_c^0, \Sigma_c(2790)$ are likely to be $\Sigma_c^0$($\frac{3}{2}^-$) with a possible small mixing with $\Sigma_c^0$($\frac{1}{2}^-$). 

2.3. $\Xi_c$

The states $\Xi_c(2790)$ and $\Xi_c(2815)$ form a doublet $\Xi_c(\frac{1}{2}^-, \frac{3}{2}^-)$. Since the diquark transition $1^- \rightarrow 0^+ + \pi$ is prohibited, $\Xi_c(\frac{1}{2}^-$) cannot decay to $\Xi_c \pi$. The dominant decay mode is $[\Xi_c^0 \pi]^S$ for $\Xi_c(\frac{1}{2}^-)$ and $[\Xi_c^+ \pi]^S$ for $\Xi_c(\frac{3}{2}^-)$ where $\Xi_c^0$ stands for $\Xi_c(2645)$. 

The new charmed strange baryons $\Xi_c(2980)^+$ and $\Xi_c(3080)^+$ that decay into $\Lambda_c^+ K^{-} \pi^+$ were first observed by Belle [17] and confirmed by BaBar [18]. For the charmed states $\Xi_c(2980)$ and $\Xi_c(3080)$, they could be the first positive-parity excitations of $\Xi_c$ in viewing of their large masses. Since the mass difference between the antitriplets $\Lambda_c$ and $\Xi_c$ for $J^P = \frac{1}{2}^+, \frac{3}{2}^-$ is of order 180~200 MeV, it is conceivable that $\Xi_c(2980)$ and $\Xi_c(3080)$ are the counterparts of $\Lambda_c(2765)$ and $\Lambda_c(2880)$, respectively, in the strange charmed baryon sector. As noted in passing, the state $\Lambda_c(2765)^+$ could be an even-parity orbital excitation or a radial excitation and $\Lambda_c(2880)$ has the quantum numbers $J^P = \frac{5}{2}^+$, it is thus tempting to assign $J^P = \frac{1}{2}^+$ for $\Xi_c(2980)$ and $\frac{3}{2}^-$ for $\Xi_c(3080)$. The possible strong decays of the first positive-parity excitations of the $\Xi_c$ states are summarized in Table VII of [2]. Since the two-body modes $\Xi_c \pi$, $\Lambda_c K$, $\Xi_c^0 \pi$ and $\Sigma_c K$ are in $P$ ($F$) waves and the three-body modes $\Xi_c \pi \pi$ and $\Lambda_c K \pi$ in are in $S$ ($D$) waves in the decays of $\frac{1}{2}^+$, this explains why $\Xi_c(2980)$ is broader than $\Xi_c(3080)$. Since both $\Xi_c(2980)$ and $\Xi_c(3080)$ are above the $D \Lambda$ threshold, it is important to search for them in the $D \Lambda$ spectrum as well. Two new $\Xi_c$ resonances $\Xi_c(3055)$ and $\Xi_c(3123)$ were recently reported by BaBar [19] with masses and widths shown in Table II.

2.4. $\Omega_c$

At last, the $J^P = \frac{3}{2}^+$ $\Omega_c(2770)$ charmed baryon was recently observed by BaBar in the decay $\Omega_c(2770)^0 \rightarrow \Omega_c^0 \gamma$ [20]. With this new observation, the $\frac{3}{2}^+$ sextet is finally completed. However, it will be very difficult to measure the electromagnetic decay rate because the width of $\Omega_c^0$, which is predicted to be of order 0.9 keV [21], is too narrow to be experimentally resolvable.

The possible spin-parity quantum numbers of the newly discovered charmed baryon resonances that have been suggested in the literature are summarized in Table III. Some of the predictions are already ruled out by experiment. For example, $\Lambda_c(2880)$ has $J^P = \frac{3}{2}^+$ as seen by Belle. Certainly, more experimental studies are needed in order to pin down the quantum numbers.

3. Strong decays

Due to the rich mass spectrum and the relatively narrow widths of the excited states, the charmed baryon system offers an excellent ground for testing the ideas and predictions of heavy quark symmetry and light flavor SU(3) symmetry. The pseudoscalar mesons involved in the strong decays of charmed baryons such as $\Xi_c \rightarrow \Lambda_c \pi$ are soft. Therefore, heavy quark symmetry of the heavy quark and chiral symmetry of the light quarks will have interesting implications for the low-energy dynamics of heavy baryons interacting with the Goldstone bosons. The strong decays of charmed baryons are most conveniently described by the heavy hadron chiral Lagrangians in which heavy quark symmetry and chiral symmetry are incorporated [22, 23]. The Lagrangian...
Table III Possible spin-parity quantum numbers for the newly discovered charmed baryon resonances that have been proposed in the literature. First radial excited states are denoted by $2P^j$.

|                | $\Lambda_c(2765)$ | $\Lambda_c(2880)$ | $\Lambda_c(2940)$ | $\Sigma_c(2800)$ | $\Xi_c(2980)$ | $\Xi_c(3080)$ |
|----------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Ebert et al. [8] | $\frac{2}{3}^+$, $\frac{3}{2}^+$ (\Sigma_c) | $\frac{2}{3}^+$, $\frac{3}{2}^-$ (\Sigma_c) | $\frac{3}{2}^+$, $\frac{1}{2}^-$ (\Sigma_c) | $\frac{3}{2}^+$, $\frac{1}{2}^-$ (\Sigma_c) | $\frac{1}{2}^+$, $\frac{3}{2}^+$ (\Xi_c) | $\frac{1}{2}^+$, $\frac{3}{2}^+$ (\Xi_c) |
| Garci1azo et al. [15] | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ |
| Gerasyuta et al. [9] | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ |
| Capstick et al. [1] | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ |
| Cheng et al. [2] | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ |
| Wilczek et al. [13] | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ |
| He et al. [14] | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ |

Involves two coupling constants $g_1$ and $g_2$ for P-wave transitions between s-wave and s-wave baryons [22], six couplings $h_3 - h_7$ for the S-wave transitions between s-wave and p-wave baryons, and eight couplings $h_8 - h_{15}$ for the D-wave transitions between s-wave and p-wave baryons [24].

3.1. Strong decays of s-wave charmed baryons

In principle, the coupling $g_1$ can be determined from the decay $\Sigma_c^+ \rightarrow \Sigma_c^0 \pi^+$. Unfortunately, this strong decay is kinematically prohibited since the mass difference between $\Sigma_c^+$ and $\Sigma_c$ is only of order 65 MeV. Consequently, the coupling $g_1$ cannot be extracted directly from the strong decays of heavy baryons. As for the coupling $g_2$, one can use the measured rates of $\Sigma_c^+ \rightarrow \Lambda_c^0 \pi^+$, $\Sigma_c^+ \rightarrow \Lambda_c^+ \pi^+$, and $\Sigma_c^0 \rightarrow \Lambda_c^+ \pi^-$ as inputs to obtain

$$|g_2| = 0.605^{+0.039}_{-0.041}, \quad 0.57 \pm 0.04, \quad 0.60 \pm 0.04,$$

respectively, where we have neglected the tiny contributions from electromagnetic decays. Hence, the averaged $g_2$ is

$$|g_2| = 0.591 \pm 0.023.$$

Using this value of $g_2$, the predicted total width of $\Xi_c^+ \pi^+$ is found to be in the vicinity of the current limit $\Gamma(\Xi_c^+ \pi^+) < 3.1$ MeV [23].

It is clear from Table IV that the strong decay width of $\Sigma_c$ is smaller than that of $\Sigma_c^+$ by a factor of $\sim 7$, although they will become the same in the limit of heavy quark symmetry. This is ascribed to the fact that the c.m. momentum of the pion is around 90 MeV in the decay $\Sigma_c \rightarrow \Lambda_c \pi$ while it is two times bigger in $\Sigma_c^+ \rightarrow \Lambda_c^+ \pi$. Since $\Sigma_c$ states are significantly narrower than their spin-$\frac{1}{2}$ counterparts, this explains why the measurement of their widths came out much later.

Table IV Decay widths (in units of MeV) of s-wave charmed baryons.

| Decay                  | Expt.    | HHChPT |
|------------------------|----------|--------|
| $\Sigma_c^0 \rightarrow \Lambda_c^0 \pi^+$ | $2.23 \pm 0.30$ | input |
| $\Sigma_c^+ \rightarrow \Lambda_c^0 \pi^+$ | $< 4.6$ | $2.5 \pm 0.2$ |
| $\Sigma_c^+ \rightarrow \Lambda_c^+ \pi^-$ | $2.2 \pm 0.4$ | input |
| $\Sigma_c(2520)^0 \rightarrow \Lambda_c^+ \pi^+$ | $14.9 \pm 1.9$ | input |
| $\Sigma_c(2520)^+ \rightarrow \Lambda_c^0 \pi^0$ | $< 17$ | $16.6 \pm 1.3$ |
| $\Sigma_c(2520)^0 \rightarrow \Lambda_c^0 \pi^-$ | $16.1 \pm 2.1$ | input |
| $\Xi_c(2645)^0 \rightarrow \Xi_c^0 \pi^+ \pi^0$ | $< 3.1$ | $2.7 \pm 0.2$ |
| $\Xi_c(2645)^+ \rightarrow \Xi_c^0 \pi^+ \pi^-$ | $< 5.5$ | $2.8 \pm 0.2$ |

3.2. Strong decays of p-wave charmed baryons

Some of the S-wave and D-wave couplings of p-wave baryons to s-wave baryons can be determined. In principle, the coupling $h_2$ is readily extracted from $\Lambda_c(2595)^+ \rightarrow \Sigma_c^0 \pi^+$ with $\Lambda_c(2595)$ being identified as $\Lambda_c(1^+)$ [24]. However, since $\Lambda_c(2595)^+ \rightarrow \Sigma_c \pi$ is kinematically barely allowed, the finite width effects of the intermediate resonant states could become important. Before proceeding to a more precise determination of $h_2$, we make several remarks on the partial widths of $\Lambda_c(2595)^+$ decays. (i) PDG [2] has assumed the isospin relation, namely, $\Gamma(\Lambda_c^+ \pi^+ \pi^-) = 2 \Gamma(\Lambda_c^0 \pi^0 \pi^0)$ to extract the branching ratios for $\Sigma_c \pi$ modes. However, the decay $\Lambda_c(2595) \rightarrow \Lambda_c \pi \pi$ occurs very close to the threshold as $m_{\Lambda_c(2595)} - m_{\Lambda_c} = 308.9 \pm 0.6$ MeV. Hence, the phase space is very sensitive to the small isospin-violating mass differences between members of pions and charmed Sigma baryon multiplets. Since the neutral pion is slightly lighter than the charged one, it turns out that both $\Lambda_c^+ \pi^+ \pi^-$ and $\Lambda_c^0 \pi^0 \pi^0$ have very similar rates. (ii) Taking $B(\Lambda_c(2595)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-) \approx 0.5$ and using the measured ratios of $\Lambda_c(2595)^+ \rightarrow \Sigma_c^0 \pi^+$ and $\Sigma_c^0 \pi^+$ rela-
Table V. Same as Table IV except for p-wave charmed baryons.

| Decay | Expt. | HHCPT |
|-------|-------|-------|
| $\Lambda_c(2595)^+ \rightarrow (\Lambda_c^0 \pi^+\pi^-)$ | $2.63^{+0.56}_{-0.59}$ | input |
| $\Lambda_c(2595)^+ \rightarrow \Sigma_c^0 \pi^-$ | $0.65^{+0.44}_{-0.31}$ | $0.72^{+0.43}_{-0.30}$ |
| $\Lambda_c(2595)^+ \rightarrow \Sigma_c^0 \pi^+$ | $0.67^{+0.41}_{-0.31}$ | $0.77^{+0.46}_{-0.32}$ |
| $\Lambda_c(2595)^+ \rightarrow \Sigma_c^0 \pi^-$ | $1.55^{+0.93}_{-0.65}$ |
| $\Lambda_c(2625)^+ \rightarrow \Sigma_c^0 \pi^-$ | $< 0.10$ | $< 0.029$ |
| $\Lambda_c(2625)^+ \rightarrow \Sigma_c^0 \pi^+$ | $< 0.09$ | $< 0.029$ |
| $\Lambda_c(2625)^+ \rightarrow \Sigma_c^0 \pi^-$ | $< 0.041$ |
| $\Lambda_c(2625)^+ \rightarrow \Lambda_c^0 \pi^-$ | $< 1.9$ | $< 0.21$ |
| $\Sigma_c(2800)^+ \rightarrow \Lambda_c \pi, \Sigma_c^{(*)} \pi$ | $75^{+22}_{-17}$ | input |
| $\Sigma_c(2800)^0 \rightarrow \Lambda_c \pi, \Sigma_c^{(*)} \pi$ | $62^{+60}_{-40}$ | input |
| $\Xi_c(2790)^+ \rightarrow \Xi_c^{0, +} \pi^+$ | $< 15$ | $8.0^{+4.7}_{-3.5}$ |
| $\Xi_c(2790)^0 \rightarrow \Xi_c^{0, +} \pi^+$ | $< 12$ | $8.5^{+5.0}_{-3.5}$ |
| $\Xi_c(2815)^+ \rightarrow \Xi_c^{0, +} \pi^+$ | $< 3.5$ | $3.4^{+2.0}_{-1.4}$ |
| $\Xi_c(2815)^0 \rightarrow \Xi_c^{0, +} \pi^+$ | $< 6.5$ | $3.6^{+2.1}_{-1.5}$ |

Assuming the coupling $h_2$ obtained from (10) and the experimental observation that the $\Xi_c \pi$ mode in $\Xi_c(2815)$ decays is consistent with being entirely via $\Xi_c^0 \pi$ [27], the predicted $\Xi_c(2790)$ and $\Xi_c(2815)$ widths are shown in Table V. The predictions are consistent with the current experimental limits.

Some information on the coupling $h_3$ can be inferred from the strong decays of $\Sigma_c(2800)$. Assuming the widths of the states $\Sigma_c(2800)^{0, +, 0}$ are dominated by the two-body $D$-wave modes $\Lambda_c \pi, \Sigma_c \pi$ and $\Sigma_c^* \pi$, and applying the quark model relation $|h_3| = |h_{10}|$ [24], we then have

$$|h_3| \leq (0.86^{+0.08}_{-0.10}) \times 10^{-3} \text{ MeV}^{-1},$$

which improves the previous limit [10] by a factor of 4.

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