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# Strong decays of newly observed heavy flavor hadrons*

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**Abstract** In this talk, we briefly review the experimental status of newly observed charmed hadrons during the past years. Then we introduce the theoretical progresses on these charmed hadrons, especially our studies on the strong decays of new charmed hadrons during the past one year.

**Key words** heavy flavor hadrons, strong decay, $^3P_0$ model

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## 1 Introduction

During the past years, a series of heavy flavor hadrons were observed, which provide us with a good chance to study heavy flavor physics. At present the properties of most heavy flavor hadrons are still not determined. Thus the effort from the experimental and theoretical study is very important to finally identify the properties of these new states. In this proceeding we review the experimental and theoretical status of new charmed hadrons and at the same time introduce our work about new charmed hadrons.

## 2 $\mathrm{D_{sJ}}(2860)$ and $\mathrm{D_{sJ}}(2715)/\mathrm{D_{sJ}}(2700)$

In the summer of 2006, the Babar collaboration observed a new $c\bar{s}$ state $\mathrm{D_{sJ}}(2860)$ with a mass 2856.6±1.5±5.0 MeV and width $\Gamma=(48\pm7\pm10)$ MeV. Babar observed it only in the $\mathrm{D^0K^+}$, $\mathrm{D^+K^0_S}$ channels and found no evidence of $\mathrm{D^{*0}K^+}$ and $\mathrm{D^{*+}K^0_S}$. Thus its $J^P=0^+,1^-,2^+,3^-,\cdots$[1]. At the same time, the Belle collaboration reported a broader $c\bar{s}$ state $\mathrm{D_{sJ}}(2715)$ with $J^P=1^-$ in the $\mathrm{B^+\to\bar{D}^0D^0K^+}$ decay[2]. Its mass is $2715\pm11^{+11}_{-14}$ MeV and its width $\Gamma=115\pm20^{+36}_{-32}$ MeV. Very recently the Belle collaboration reported a new measurement for this $c\bar{s}$ meson with a mass $m=2708\pm9^{+11}_{-10}$ MeV/$c^2$ and width $\Gamma=108\pm23^{+36}_{-31}$ MeV/$c^2$[3]. This $c\bar{s}$ state is renamed as $\mathrm{D_{sJ}}(2700)$ in Ref. [3]. In this talk, we still use the name $\mathrm{D_{sJ}}(2715)$.

According to the heavy quark effective field theory, heavy mesons form doublets. For example, we have one $s$-wave $c\bar{s}$ doublet $(0^-,1^-)=(\mathrm{D_s}(1965),\mathrm{D_s^*}(2115))$ and two $p$-wave doublets $(0^+,1^+)=(\mathrm{D^*_{sJ}}(2317),\mathrm{D_{sJ}}(2460))$ and $(1^+,2^+)=(\mathrm{D_{s1}}(2536),\mathrm{D_{s2}}(2573))$[4]. The two $d$-wave $c\bar{s}$ doublets $(1^-,2^-)$ and $(2^-,3^-)$ have not yet been observed. The possible quantum numbers of $\mathrm{D_{sJ}}(2860)$ include $0^+(2^3P_0)$, $1^-(1^3D_1)$, $1^-(2^3S_1)$, $2^+(2^3P_2)$, $2^+(1^3F_2)$ and $3^-(1^3D_3)$. The $2^3P_2$ $c\bar{s}$ state is expected to lie around $(2.95\sim3.0)$ GeV while the mass of the $1^3F_2$ state will be much higher than 2.86 GeV.

$\mathrm{D_{sJ}}(2860)$ was proposed as the first radial excitation of $\mathrm{D^*_{sJ}}(2317)$ in Refs. [5, 6], as a $J^P=3^-$ $c\bar{s}$ state in Ref. [7] and as $c\bar{s}$(2P) state in Ref. [8]. $\mathrm{D_{sJ}}(2715)$ sits exactly on the quark model prediction 2720 MeV for the $2^3S_1$ $c\bar{s}$ state[9]. The $1^-$ state lies around 2721 MeV if one requires the $(1^+,1^-)$ $c\bar{s}$ states form a chiral doublet[10]. In Ref. [11], the strong decay of $D$-wave $c\bar{s}$ mesons to light pseudoscalar mesons are studied in the framework of the light cone QCD sum rule (LCQSR).

In Ref. [12], we investigated the strong decays of the excited $c\bar{s}$ states using the $^3P_0$ model[13]. The numerical results are listed in Table 1.

After comparing the theoretical decay widths and decay patterns with the available experimental data, we tend to conclude:

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Table 1. The decay widths of $D_{sJ}(2860)$ and $D_{sJ}(2715)$ as different $c\bar{s}$ candidates. The two-body decay width and total width are in units of MeV while the three-body decay width is in units of keV.

| | assignment | DK | $D_s\eta$ | $D^*K$ | $D_s^*\eta$ | $DK^*$ | $D_s^*\pi\pi$ | $D_{sJ}^*(2317)\pi\pi$ | total |
|---|---|---|---|---|---|---|---|---|---|
| $D_{sJ}(2860)$ | $0^+(2^3P_0)$ | 37 | 16 | — | — | — | 1600 | 2 | 54 |
| | $1^-(1^3D_1)$ | 84 | 24 | 14 | 2 | 7.8 | 313 | 13 | 132 |
| | $1^-(2^3S_1)$ | 0.012 | 0.104 | 24 | 1.6 | 64 | 923 | 30 | 90 |
| | $3^-(1^3D_3)$ | 22 | 1.2 | 13 | 0.3 | 0.71 | — | — | 37 |
| $D_{sJ}(2715)$ | $1^-(2^3S_1)$ | 3.2 | 0.05 | 27.2 | 0.54 | — | 477 | 1.63 | 32 |
| | $1^-(1^3D_1)$ | 49.4 | 13.2 | 8 | 2.4 | — | 49 | 0.5 | 73 |

Table 2. A summary of recently observed charmed baryons by the Babar and Belle collaborations.

| state | mass and width/MeV | decay channels | other information |
|---|---|---|---|
| $\Lambda_c(2880)^+$ | $2881.5\pm0.3,\ <8$ [20] | $\Lambda_c\pi^+\pi^-$ | $J^P$ favors $\frac{5}{2}^+$ [15], |
| | $2881.9\pm0.1\pm0.5,\ 5.8\pm1.5\pm1.1$ [14] | $D^0p$ | $\frac{\Gamma(\Sigma_c^\star(2520)\pi^\pm)}{\Gamma(\Sigma_c(2455)\pi^\pm)}=0.225\pm0.062\pm0.025$ [15] |
| | $2881.2\pm0.2^{+0.4}_{-0.3},\ 5.5^{+0.7}_{-0.5}\pm0.4$ [15] | $\Sigma_c^{\star0,++}(2520)\pi^{+,-}$ | |
| $\Lambda_c(2940)^+$ | $2939.\pm1.3\pm1.0,\ 17.5\pm5.2\pm5.9$ [14] | $D^0p$ | — |
| | $2937.9\pm1.0^{+1.8}_{-0.4},\ 10\pm4\pm5$ [15] | $\Sigma_c(2455)^{0,++}\pi^{+,-}$ | |
| $\Xi_c(2980)^+$ | $2967.1\pm1.9\pm1.0,\ 23.6\pm2.8\pm1.3$ [16] | $\Lambda_c^+K^-\pi^+$ | — |
| | $2978.5\pm2.1\pm2.0,\ 43.5\pm7.5\pm7.0$ [17] | $\Lambda_c^+K^-\pi^+$ | |
| $\Xi_c(2980)^0$ | $2977.1\pm8.8\pm3.5,\ 43.5$ [17] | $\Lambda_c^+K_S^0\pi^-$ | — |
| $\Xi_c(3077)^+$ | $3076.4\pm0.7\pm0.3,\ 6.2\pm1.6\pm0.5$ [16] | $\Lambda_c^+K^-\pi^+$ | — |
| | $3076.7\pm0.9\pm0.5,\ 6.2\pm1.2\pm0.8$ [17] | $\Lambda_c^+K^-\pi^+$ | |
| $\Xi_c(3077)^0$ | $3082.8\pm1.8\pm1.5,\ 5.2\pm3.1\pm1.8$ [17] | $\Lambda_c^+K_S^0\pi^-$ | — |
| $\Xi_c(3055)^+$ [19] | $3054.2\pm1.2\pm0.5,\ 17\pm6\pm11$ | $\Lambda_c^+K^-\pi^+$ | — |
| $\Xi_c(3122)^+$ [19] | $3122.9\pm1.3\pm0.3,\ 4.4\pm3.4\pm1.7$ | $\Lambda_c^+K^-\pi^+$ | — |
| $\Omega_c(2768)^0$ | $2768.3\pm3.0$ [18] | $\Omega_c^0\gamma$ | $J^P=\frac{3}{2}^+$ |

Table 3. The decay widths of $\Lambda_c^+(2880)$ with different $D$-wave assignments. All results are in units of MeV.

| assignment | $\Sigma_c^{0,+,++}\pi^{+,0,-}$ | $\Sigma_c^{\star0,+,++}\pi^{+,0,-}$ | $\frac{\Gamma(\Sigma_c^\star\pi^\pm)}{\Gamma(\Sigma_c\pi^\pm)}$ | $D^0p$ | remark |
|---|---|---|---|---|---|
| $\Lambda_{c2}\left(\frac{3}{2}^+\right)$ | 7.8 | 0.9 | 0.11 | 0.0 | × |
| $\Lambda_{c2}\left(\frac{5}{2}^+\right)$ | 0.06 | 5.34 | 89 | 0.0 | × |
| $\hat{\Lambda}_{c2}\left(\frac{3}{2}^+\right)$ | 78.3 | 59.1 | 0.75 | 0.0 | × |
| $\hat{\Lambda}_{c2}\left(\frac{5}{2}^+\right)$ | 78.3 | 59.1 | 0.75 | 0.0 | × |
| $\check{\Lambda}_{c1}^0\left(\frac{1}{2}^+\right)$ | 0.9 | 2.3 | 2.6 | 2.3 | × |
| $\check{\Lambda}_{c1}^0\left(\frac{3}{2}^+\right)$ | 0.22 | 6.0 | 27 | 2.3 | × |
| $\check{\Lambda}_{c0}^1\left(\frac{1}{2}^+\right)$ | 132 | 144 | 1.1 | 0.0 | × |
| $\check{\Lambda}_{c1}^1\left(\frac{1}{2}^+\right)$ | 66.3 | 18.0 | 0.27 | 150 | × |
| $\check{\Lambda}_{c1}^1\left(\frac{3}{2}^+\right)$ | 16.5 | 45.0 | 2.7 | 150 | × |
| $\check{\Lambda}_{c2}^1\left(\frac{3}{2}^+\right)$ | 82.8 | 9.0 | 0.10 | 0.0 | × |
| $\check{\Lambda}_{c2}^1\left(\frac{5}{2}^+\right)$ | 0.0 | 54.1 | — | 0.0 | × |
| $\check{\Lambda}_{c1}^2\left(\frac{1}{2}^+\right)$ | 25.7 | 8.1 | 0.32 | 64 | × |
| $\check{\Lambda}_{c1}^2\left(\frac{3}{2}^+\right)$ | 6.5 | 20.4 | 3.1 | 64 | × |
| $\check{\Lambda}_{c2}^2\left(\frac{3}{2}^+\right)$ | 57.9 | 14.2 | 0.24 | 0.0 | × |
| $\check{\Lambda}_{c2}^2\left(\frac{5}{2}^+\right)$ | 9.4 | 47.1 | 5.0 | 0.0 | × |
| $\check{\Lambda}_{c3}^2\left(\frac{5}{2}^+\right)$ | 10.8 | 5.5 | 0.51 | 12 | |
| $\check{\Lambda}_{c3}^2\left(\frac{7}{2}^+\right)$ | 6.1 | 7.4 | 1.2 | 12 | × |

1) $D_{sJ}(2715)$ is probably the $1^-(1^3D_1)$ $c\bar{s}$ state although the $1^-(2^3S_1)$ assignment is not completely excluded;

2) $D_{sJ}(2860)$ seems unlikely to be the $1^-(2^3S_1)$ and $1^-(1^3D_1)$ candidate;

3) $D_{sJ}(2860)$ as either a $0^+(2^3P_0)$ or $3^-(1^3D_3)$ $c\bar{s}$ state is consistent with the experimental data;

4) experimental search of $D_{sJ}(2860)$ in the channels $D_s\eta$, $DK^*$, $D^*K$ and $D_s^*\eta$ will be crucial to distinguish the above two possibilities.

## 3 Charmed baryons

The Babar and Belle collaborations observed several excited charmed baryons: $\Lambda_c(2880, 2940)^+$, $\Xi_c(2980, 3077)^{+,0}$ and $\Omega_c(2768)^0$ last year[14—18]. In the recent 2007 Europhysics Conference on High Energy Physics, the Babar Collaboration reported preliminary results about the observations of two new excited charmed baryons $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$ in the mass distribution of $\Lambda_c^+K^-\pi^+$[19]. Besides these new observations, Babar also confirmed the observation of $\Xi_c(2980)^+$ and $\Xi_c(3077)^+$[16, 17]. We collect the experimental information of these recently observed hadrons in Table 2. Their quantum numbers have not been determined except for $\Lambda_c(2880)^+$.

In the past decades, there has been some research work on heavy baryons[21—23]. However these new observation inspired several investigations of these states in literature[24—27]. In Ref. [25], the authors studied the $\Lambda_c(2940)^+$ and its possible decay modes assuming $\Lambda_c(2940)^+$ to be a $D^{*0}p$ molecular state[25]. Cheng et al. calculated the strong decays of newly observed charmed mesons in the framework of heavy hadron chiral perturbation theory (HHChPT)[26]. In order to understand their structures using the present experimental information, in Refs. [28, 29], the strong decay pattern of the excited charmed baryons are studied systematically in the framework of the $^3P_0$ strong decay model. We have also calculated the strong decay widths of the newly observed $\Lambda_c(2880, 2940)^+$, $\Xi_c(2980, 3077)^{+,0}$ and $\Xi_c(3055, 3123)^+$ assuming they are candidates of $D$-wave charmed baryons. After comparing the theoretical results with the available experimental data, their favorable quantum numbers and assignments are obtained in the quark model. The numerical results are shown in Tables 3—8.

Table 4. The decay widths of $\Lambda_c^+(2940)$ with different $D$-wave assignments. Here all results are in units of MeV.

| assignment | $\Sigma_c^{0,+,++}\pi^{+,0,-}$ | $\Sigma_c^{*0,+,++}\pi^{+,0,-}$ | $\frac{\Gamma(\Sigma_c^*\pi^\pm)}{\Gamma(\Sigma_c\pi^\pm)}$ | $D^0p$ | remark |
|---|---|---|---|---|---|
| $\Lambda_{c2}\left(\frac{3}{2}^+\right)$ | 11.7 | 9.1 | 0.77 | 0.0 | × |
| $\Lambda_{c2}\left(\frac{5}{2}^+\right)$ | 0.2 | 9.1 | 46 | 0.0 | × |
| $\hat{\Lambda}_{c2}\left(\frac{3}{2}^+\right)$ | 170 | 150 | 0.88 | 0.0 | × |
| $\hat{\Lambda}_{c2}\left(\frac{5}{2}^+\right)$ | 170 | 150 | 0.88 | 0.0 | × |
| $\check{\Lambda}_{c1}^0\left(\frac{1}{2}^+\right)$ | 2.2 | 0.5 | 0.23 | 11 | |
| $\check{\Lambda}_{c1}^0\left(\frac{3}{2}^+\right)$ | 0.6 | 1.4 | 2.3 | 11 | |
| $\check{\Lambda}_{c0}^1\left(\frac{1}{2}^+\right)$ | 212 | 259 | 1.2 | 0.0 | × |
| $\check{\Lambda}_{c1}^1\left(\frac{1}{2}^+\right)$ | 106 | 32.4 | 0.31 | 340 | × |
| $\check{\Lambda}_{c1}^1\left(\frac{3}{2}^+\right)$ | 26.5 | 81.0 | 3.1 | 340 | × |
| $\check{\Lambda}_{c2}^1\left(\frac{3}{2}^+\right)$ | 142 | 16.2 | 0.11 | 0.0 | × |
| $\check{\Lambda}_{c2}^1\left(\frac{5}{2}^+\right)$ | 0.0 | 97.0 | — | 0.0 | × |
| $\check{\Lambda}_{c1}^2\left(\frac{1}{2}^+\right)$ | 34.5 | 12.6 | 0.37 | 95 | × |
| $\check{\Lambda}_{c1}^2\left(\frac{3}{2}^+\right)$ | 8.6 | 31.7 | 3.7 | 95 | × |
| $\check{\Lambda}_{c2}^2\left(\frac{3}{2}^+\right)$ | 77.7 | 27.7 | 0.36 | 0.0 | × |
| $\check{\Lambda}_{c2}^2\left(\frac{5}{2}^+\right)$ | 19.5 | 75.6 | 3.9 | 0.0 | × |
| $\check{\Lambda}_{c3}^2\left(\frac{5}{2}^+\right)$ | 22.2 | 12.9 | 0.58 | 49 | × |
| $\check{\Lambda}_{c3}^2\left(\frac{7}{2}^+\right)$ | 12.4 | 17.5 | 1.4 | 49 | × |

Table 5. The decay widths of $\Xi_c^+(2980)$ with different $D$-wave assignments. Here all results are in units of MeV.

| assignment | $\Xi_c^0\pi^+$ | $\Xi_c'^0\pi^+$ | $\Xi_c^{*0}\pi^+$ | $\Sigma_c^{++}K^-$ | $\Lambda_c^+\bar{K}^0$ | remark |
|---|---|---|---|---|---|---|
| $\Xi_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 1.1 | 0.11 | 0.37 | 0.0 | × |
| $\Xi_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | $0.12\times10^{-2}$ | 0.67 | $0.11\times10^{-3}$ | 0.0 | × |
| $\Xi'_{c1}\left(\frac{1}{2}^+\right)$ | 4.4 | 0.72 | 0.18 | 0.25 | 5.3 | |
| $\Xi'_{c1}\left(\frac{3}{2}^+\right)$ | 4.4 | 0.18 | 0.46 | 0.062 | 5.3 | |
| $\Xi'_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 0.16 | 0.17 | 0.56 | 0.0 | × |
| $\Xi'_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | $0.47\times10^{-2}$ | 1.0 | $0.71\times10^{-4}$ | 0.0 | × |
| $\Xi'_{c3}\left(\frac{5}{2}^+\right)$ | 0.054 | $0.53\times10^{-2}$ | $0.14\times10^{-2}$ | $0.82\times10^{-4}$ | 0.053 | × |
| $\Xi'_{c3}\left(\frac{7}{2}^+\right)$ | 0.054 | $0.30\times10^{-2}$ | $0.19\times10^{-2}$ | $0.46\times10^{-4}$ | 0.053 | × |
| $\hat{\Xi}_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 9.5 | 6.1 | 0.61 | 0.0 | |
| $\hat{\Xi}_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 9.5 | 6.1 | 0.61 | 0.0 | |
| $\hat{\Xi}'_{c1}\left(\frac{1}{2}^+\right)$ | 74 | 6.3 | 1.0 | 0.40 | 78 | × |
| $\hat{\Xi}'_{c1}\left(\frac{3}{2}^+\right)$ | 74 | 1.6 | 2.5 | 0.10 | 78 | × |
| $\hat{\Xi}'_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 14 | 4.5 | 0.91 | 0.0 | |
| $\hat{\Xi}'_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 6.3 | 7.1 | 0.40 | 0.0 | |
| $\hat{\Xi}'_{c3}\left(\frac{5}{2}^+\right)$ | 48 | 7.2 | 2.9 | 0.46 | 50 | × |
| $\hat{\Xi}'_{c3}\left(\frac{7}{2}^+\right)$ | 48 | 4.1 | 3.9 | 0.26 | 50 | × |
| $\check{\Xi}'^0_{c0}\left(\frac{1}{2}^+\right)$ | 0.0 | 0.30 | 1.4 | 1.3 | 0.0 | × |
| $\check{\Xi}^0_{c1}\left(\frac{1}{2}^+\right)$ | 1.0 | 0.40 | 0.46 | 1.7 | 0.46 | × |
| $\check{\Xi}^0_{c1}\left(\frac{3}{2}^+\right)$ | 1.0 | 0.10 | 1.2 | 0.43 | 0.46 | × |
| $\check{\Xi}'^1_{c1}\left(\frac{1}{2}^+\right)$ | 0.0 | 18 | 4.4 | 5.5 | 0.0 | |
| $\check{\Xi}'^1_{c1}\left(\frac{3}{2}^+\right)$ | 0.0 | 4.5 | 11 | 1.4 | 0.0 | |
| $\check{\Xi}^1_{c0}\left(\frac{1}{2}^+\right)$ | 0.0 | 18 | 18 | 5.5 | 0.0 | |
| $\check{\Xi}^1_{c1}\left(\frac{1}{2}^+\right)$ | 62 | 9.1 | 2.2 | 2.8 | 72 | × |
| $\check{\Xi}^1_{c1}\left(\frac{3}{2}^+\right)$ | 62 | 2.3 | 5.5 | 0.69 | 72 | × |
| $\check{\Xi}^1_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 11 | 1.1 | 0.34 | 0.0 | × |
| $\check{\Xi}^1_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 0.0 | 6.6 | 0.0 | 0.0 | × |
| $\check{\Xi}'^2_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 5.6 | 1.8 | 2.4 | 0.0 | |
| $\check{\Xi}'^2_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 1.7 | 4.32 | 0.24 | 0.0 | |
| $\check{\Xi}^2_{c1}\left(\frac{1}{2}^+\right)$ | 19 | 3.7 | 1.1 | 1.6 | 23 | |
| $\check{\Xi}^2_{c1}\left(\frac{3}{2}^+\right)$ | 19 | 0.93 | 2.6 | 0.40 | 23 | |
| $\check{\Xi}^2_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 8.4 | 1.7 | 0.36 | 0.0 | |
| $\check{\Xi}^2_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 1.2 | 6.0 | 0.16 | 0.0 | |
| $\check{\Xi}^2_{c3}\left(\frac{5}{2}^+\right)$ | 8.1 | 1.3 | 60 | 0.19 | 8.7 | × |
| $\check{\Xi}^2_{c3}\left(\frac{7}{2}^+\right)$ | 8.1 | 0.75 | 0.81 | 0.10 | 8.7 | |

Table 6. The decay widths of $\Xi_c^+(3077)$ with different $D$-wave assignments. Here all results are in units of MeV.

| assignment | $\Xi_c^0\pi^+$ | $\Xi_c'^0\pi^+$ | $\Xi_c^{*0}\pi^+$ | $\Sigma_c^{++}K^-$ | $\Sigma_c^{++}K^-$ | $\Lambda_c^+\bar{K}^0$ | $D^+\Lambda$ | remark |
|---|---|---|---|---|---|---|---|---|
| $\Xi_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 2.1 | 0.30 | 0.73 | 0.054 | 0.0 | 0.0 | |
| $\Xi_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 0.037 | 1.7 | $0.42\times10^{-2}$ | 0.32 | 0.0 | 0.0 | |
| $\Xi'_{c1}\left(\frac{1}{2}^+\right)$ | 7.0 | 1.4 | 0.46 | 0.49 | 0.089 | 4.4 | 3.2 | |
| $\Xi'_{c1}\left(\frac{3}{2}^+\right)$ | 7.0 | 0.36 | 1.1 | 0.12 | 0.22 | 4.4 | 3.2 | |
| $\Xi'_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 3.2 | 0.43 | 1.1 | 0.081 | 0.0 | 0.0 | |
| $\Xi'_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | $0.025\times10^{-2}$ | 2.5 | $0.28\times10^{-2}$ | 0.48 | 0.0 | 0.0 | × |
| $\Xi'_{c3}\left(\frac{5}{2}^+\right)$ | 0.19 | 0.029 | 0.012 | $0.32\times10^{-2}$ | $0.32\times10^{-3}$ | 0.12 | 0.026 | × |
| $\Xi'_{c3}\left(\frac{7}{2}^+\right)$ | 0.19 | $0.016\times10^{-3}$ | 0.016 | $0.18\times10^{-2}$ | $0.44\times10^{-3}$ | 0.12 | 0.026 | × |
| $\hat{\Xi}_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 34 | 29 | 6.0 | 2.0 | 0.0 | 0.0 | × |
| $\hat{\Xi}_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 34 | 29 | 6.0 | 2.0 | 0.0 | 0.0 | × |
| $\hat{\Xi}'_{c1}\left(\frac{1}{2}^+\right)$ | 201 | 23 | 4.8 | 4.0 | 0.33 | 130 | 38 | × |
| $\hat{\Xi}'_{c1}\left(\frac{3}{2}^+\right)$ | 201 | 5.7 | 12 | 1.0 | 0.83 | 130 | 38 | × |
| $\hat{\Xi}'_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 51 | 22 | 8.9 | 1.5 | 0.0 | 0.0 | × |
| $\hat{\Xi}'_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 23 | 34 | 4.0 | 2.3 | 0.0 | 0.0 | × |
| $\hat{\Xi}'_{c3}\left(\frac{5}{2}^+\right)$ | 129 | 26 | 14 | 4.5 | 0.94 | 84 | 25 | × |
| $\hat{\Xi}'_{c3}\left(\frac{7}{2}^+\right)$ | 129 | 15 | 19 | 2.6 | 0.13 | 84 | 25 | × |
| $\check{\Xi}'^0_{c0}\left(\frac{1}{2}^+\right)$ | 0.0 | 0.69 | 0.13 | 0.29 | 1.2 | 0.0 | 0.0 | |
| $\check{\Xi}^0_{c1}\left(\frac{1}{2}^+\right)$ | 15 | 0.92 | 0.044 | 0.39 | 0.38 | 11 | $0.64\times10^{-3}$ | × |
| $\check{\Xi}^0_{c1}\left(\frac{3}{2}^+\right)$ | 15 | 0.23 | 0.11 | 0.096 | 0.96 | 11 | $0.64\times10^{-3}$ | × |
| $\check{\Xi}'^1_{c1}\left(\frac{1}{2}^+\right)$ | 0.0 | 39 | 12 | 12 | 0.21 | 0.0 | 0.0 | × |
| $\check{\Xi}'^1_{c1}\left(\frac{3}{2}^+\right)$ | 0.0 | 9.9 | 30 | 3.0 | 5.2 | 0.0 | 0.0 | × |
| $\check{\Xi}^1_{c0}\left(\frac{1}{2}^+\right)$ | 0.0 | 39 | 47 | 12 | 8.3 | 0.0 | 0.0 | × |
| $\check{\Xi}^1_{c1}\left(\frac{1}{2}^+\right)$ | 110 | 20 | 5.9 | 6.1 | 1.0 | 69 | 42 | × |
| $\check{\Xi}^1_{c1}\left(\frac{3}{2}^+\right)$ | 110 | 5.0 | 15 | 1.5 | 2.6 | 69 | 42 | × |
| $\check{\Xi}^1_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 25 | 3.0 | 7.6 | 0.52 | 0.0 | 0.0 | × |
| $\check{\Xi}^1_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 0.0 | 18 | 0.0 | 3.1 | 0.0 | 0.0 | × |
| $\check{\Xi}'^2_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 9.2 | 6.0 | 3.9 | 0.75 | 0.0 | 0.0 | |
| $\check{\Xi}'^2_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 5.8 | 10 | 1.1 | 2.1 | 0.0 | 0.0 | |
| $\check{\Xi}^2_{c1}\left(\frac{1}{2}^+\right)$ | 22 | 6.1 | 2.3 | 2.6 | 0.54 | 14 | 15 | × |
| $\check{\Xi}^2_{c1}\left(\frac{3}{2}^+\right)$ | 22 | 1.5 | 5.6 | 0.64 | 1.3 | 14 | 15 | × |
| $\check{\Xi}^2_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 14 | 5.2 | 5.8 | 0.77 | 0.0 | 0.0 | × |
| $\check{\Xi}^2_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 3.9 | 14 | 0.74 | 3.0 | 0.0 | 0.0 | × |
| $\check{\Xi}^2_{c3}\left(\frac{5}{2}^+\right)$ | 21 | 4.4 | 2.5 | 0.85 | 0.23 | 14 | 4.3 | × |
| $\check{\Xi}^2_{c3}\left(\frac{7}{2}^+\right)$ | 21 | 2.5 | 3.4 | 0.48 | 0.31 | 14 | 4.3 | × |

Table 7. The decay widths of $\Xi_c^+(3055)$ with different $D$-wave assignments. Here we list the results with the typical values $\alpha_\rho = 0.6$ GeV and $\alpha_\lambda = 0.6$ GeV.

| assignment | $\Xi_c^0\pi^+$ | $\Xi_c'^0\pi^+$ | $\Xi_c^{*0}\pi^+$ | $\Sigma_c^{++}K^-$ | $\Sigma_c^{*++}K^-$ | $\Lambda_c^+\bar{K}^0$ | $D^+\Lambda$ | remark |
|---|---|---|---|---|---|---|---|---|
| $\Xi_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 1.9 | 0.25 | 2.2 | 0.12 | 0.0 | 0.0 | |
| $\Xi_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 0.028 | 1.4 | $0.83\times10^{-2}$ | 0.69 | 0.0 | 0.0 | |
| $\Xi'_{c1}\left(\frac{1}{2}^+\right)$ | 6.4 | 1.3 | 0.38 | 1.5 | 0.19 | 8.0 | 2.4 | |
| $\Xi'_{c1}\left(\frac{3}{2}^+\right)$ | 6.4 | 0.32 | 0.96 | 0.37 | 0.48 | 8.0 | 2.4 | |
| $\Xi'_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 2.9 | 0.36 | 3.3 | 0.17 | 0.0 | 0.0 | |
| $\Xi'_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 0.019 | 2.1 | $0.55\times10^{-2}$ | 1.0 | 0.0 | 0.0 | |
| $\Xi'_{c3}\left(\frac{5}{2}^+\right)$ | 0.15 | 0.022 | $0.78\times10^{-2}$ | $0.63\times10^{-2}$ | $0.30\times10^{-3}$ | 0.18 | 0.0067 | × |
| $\Xi'_{c3}\left(\frac{7}{2}^+\right)$ | 0.15 | 0.012 | 0.011 | $0.35\times10^{-2}$ | $0.41\times10^{-3}$ | 0.18 | 0.0067 | × |
| $\hat{\Xi}_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 27.4 | 21.3 | 14.4 | 2.5 | 0.0 | 0.0 | × |
| $\hat{\Xi}_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 27.4 | 21.3 | 14.4 | 2.5 | 0.0 | 0.0 | × |
| $\hat{\Xi}'_{c1}\left(\frac{1}{2}^+\right)$ | 163 | 18.3 | 3.5 | 9.6 | 0.41 | 205 | 15.5 | × |
| $\hat{\Xi}'_{c1}\left(\frac{3}{2}^+\right)$ | 163 | 4.6 | 8.9 | 2.4 | 1.0 | 205 | 15.5 | × |
| $\hat{\Xi}'_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 41.1 | 15.9 | 21.5 | 1.9 | 0.0 | 0.0 | × |
| $\hat{\Xi}'_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 18.3 | 24.8 | 9.6 | 2.9 | 0.0 | 0.0 | × |
| $\hat{\Xi}'_{c3}\left(\frac{5}{2}^+\right)$ | 105 | 20.9 | 10.1 | 10.9 | 1.2 | 131 | 10.0 | × |
| $\hat{\Xi}'_{c3}\left(\frac{7}{2}^+\right)$ | 105 | 11.7 | 13.7 | 6.1 | 1.6 | 131 | 10.0 | × |
| $\check{\Xi}'^0_{c0}\left(\frac{1}{2}^+\right)$ | 0.0 | 0.23 | 0.46 | 1.9 | 2.9 | 0.0 | 0.0 | |
| $\check{\Xi}^0_{c1}\left(\frac{1}{2}^+\right)$ | 9.8 | 0.30 | 0.15 | 2.6 | 0.95 | 12.4 | 0.60 | |
| $\check{\Xi}^0_{c1}\left(\frac{3}{2}^+\right)$ | 9.8 | 0.075 | 0.38 | 0.65 | 2.4 | 12.4 | 0.60 | |
| $\check{\Xi}'^1_{c1}\left(\frac{1}{2}^+\right)$ | 0.0 | 34.7 | 9.8 | 36.0 | 4.1 | 0.0 | 0.0 | × |
| $\check{\Xi}'^1_{c1}\left(\frac{3}{2}^+\right)$ | 0.0 | 8.7 | 24.4 | 9.0 | 10.3 | 0.0 | 0.0 | × |
| $\check{\Xi}^1_{c0}\left(\frac{1}{2}^+\right)$ | 0.0 | 34.7 | 39.1 | 36.0 | 16.6 | 0.0 | 0.0 | × |
| $\check{\Xi}^1_{c1}\left(\frac{1}{2}^+\right)$ | 97.6 | 17.4 | 4.9 | 18.0 | 2.1 | 122 | 28.2 | × |
| $\check{\Xi}^1_{c1}\left(\frac{3}{2}^+\right)$ | 97.6 | 4.3 | 12.2 | 4.5 | 5.2 | 122 | 28.2 | × |
| $\check{\Xi}^1_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 21.7 | 2.4 | 22.5 | 1.0 | 0.0 | 0.0 | × |
| $\check{\Xi}^1_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 0.0 | 14.7 | 0.0 | 6.2 | 0.0 | 0.0 | |
| $\check{\Xi}'^2_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 8.6 | 4.7 | 12.3 | 1.5 | 0.0 | 0.0 | |
| $\check{\Xi}'^2_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 4.7 | 8.7 | 2.8 | 4.4 | 0.0 | 0.0 | |
| $\check{\Xi}^2_{c1}\left(\frac{1}{2}^+\right)$ | 21.9 | 5.7 | 2.0 | 8.2 | 1.1 | 27.2 | 12.2 | × |
| $\check{\Xi}^2_{c1}\left(\frac{3}{2}^+\right)$ | 21.9 | 1.4 | 4.9 | 2.1 | 2.8 | 27.2 | 12.2 | × |
| $\check{\Xi}^2_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 12.9 | 4.1 | 18.5 | 1.5 | 0.0 | 0.0 | × |
| $\check{\Xi}^2_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 3.2 | 11.7 | 1.9 | 6.3 | 0.0 | 0.0 | |
| $\check{\Xi}^2_{c3}\left(\frac{5}{2}^+\right)$ | 17.4 | 3.6 | 1.9 | 2.2 | 0.41 | 21.9 | 2.1 | × |
| $\check{\Xi}^2_{c3}\left(\frac{7}{2}^+\right)$ | 17.4 | 2.0 | 2.5 | 1.2 | 0.57 | 21.9 | 2.1 | × |

Table 8. The decay widths of $\Xi_c^+(3123)$ with different $D$-wave assignments. Here we list the results with the typical values $\alpha_\rho = 0.6$ GeV and $\alpha_\lambda = 0.6$ GeV.

| assignment | $\Xi_c^0\pi^+$ | $\Xi_c'^0\pi^+$ | $\Xi_c^{*0}\pi^+$ | $\Sigma_c^{++}K^-$ | $\Sigma_c^{*++}K^-$ | $\Lambda_c^+\bar{K}^0$ | $D^+\Lambda$ | remark |
|---|---|---|---|---|---|---|---|---|
| $\Xi_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 2.8 | 0.43 | 4.5 | 0.49 | 0.0 | 0.0 | |
| $\Xi_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 0.075 | 2.3 | 0.053 | 2.8 | 0.0 | 0.0 | |
| $\Xi'_{c1}\left(\frac{1}{2}^+\right)$ | 8.3 | 1.9 | 0.63 | 3.0 | 0.79 | 10.2 | 5.5 | × |
| $\Xi'_{c1}\left(\frac{3}{2}^+\right)$ | 8.3 | 0.46 | 1.6 | 0.76 | 2.0 | 10.2 | 5.5 | × |
| $\Xi'_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 4.2 | 0.60 | 6.8 | 0.72 | 0.0 | 0.0 | |
| $\Xi'_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 0.050 | 3.4 | 0.035 | 4.3 | 0.0 | 0.0 | |
| $\Xi'_{c3}\left(\frac{5}{2}^+\right)$ | 0.32 | 0.057 | 0.026 | 0.040 | 0.010 | 0.44 | 0.069 | × |
| $\Xi'_{c3}\left(\frac{7}{2}^+\right)$ | 0.32 | 0.032 | 0.035 | 0.023 | 0.013 | 0.44 | 0.069 | × |
| $\hat{\Xi}_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 58.9 | 53.0 | 56.0 | 30.0 | 0.0 | 0.0 | × |
| $\hat{\Xi}_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 58.9 | 53.0 | 56.0 | 30.0 | 0.0 | 0.0 | × |
| $\hat{\Xi}'_{c1}\left(\frac{1}{2}^+\right)$ | 311 | 39.2 | 8.8 | 37.4 | 5.0 | 411 | 85.9 | × |
| $\hat{\Xi}'_{c1}\left(\frac{3}{2}^+\right)$ | 311 | 9.8 | 22.1 | 9.3 | 12.5 | 411 | 85.9 | × |
| $\hat{\Xi}'_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 88.3 | 40.0 | 84.1 | 22.5 | 0.0 | 0.0 | × |
| $\hat{\Xi}'_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 39.2 | 61.8 | 37.4 | 35.0 | 0.0 | 0.0 | × |
| $\hat{\Xi}'_{c3}\left(\frac{5}{2}^+\right)$ | 200 | 44.8 | 25.2 | 42.7 | 14.3 | 264 | 55.3 | × |
| $\hat{\Xi}'_{c3}\left(\frac{7}{2}^+\right)$ | 200 | 25.2 | 34.0 | 24.0 | 19.3 | 264 | 55.3 | × |
| $\check{\Xi}'^0_{c0}\left(\frac{1}{2}^+\right)$ | 0.0 | 4.3 | 0.35 | 0.015 | 2.5 | 0.0 | 0.0 | |
| $\check{\Xi}^0_{c1}\left(\frac{1}{2}^+\right)$ | 36.5 | 5.8 | 0.12 | 0.020 | 0.82 | 52.7 | 1.8 | × |
| $\check{\Xi}^0_{c1}\left(\frac{3}{2}^+\right)$ | 36.5 | 1.4 | 0.29 | 0.005 | 2.0 | 52.7 | 1.8 | × |
| $\check{\Xi}'^1_{c1}\left(\frac{1}{2}^+\right)$ | 0.0 | 54.3 | 17.0 | 80.2 | 18.3 | 0.0 | 0.0 | × |
| $\check{\Xi}'^1_{c1}\left(\frac{3}{2}^+\right)$ | 0.0 | 13.6 | 42.6 | 20.1 | 45.8 | 0.0 | 0.0 | × |
| $\check{\Xi}^1_{c0}\left(\frac{1}{2}^+\right)$ | 0.0 | 54.3 | 68.2 | 80.2 | 73.3 | 0.0 | 0.0 | × |
| $\check{\Xi}^1_{c1}\left(\frac{1}{2}^+\right)$ | 139 | 27.1 | 8.5 | 40.1 | 9.2 | 175 | 73.3 | × |
| $\check{\Xi}^1_{c1}\left(\frac{3}{2}^+\right)$ | 139 | 6.8 | 21.3 | 10.0 | 22.9 | 175 | 73.3 | × |
| $\check{\Xi}^1_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 33.9 | 4.3 | 50.1 | 4.6 | 0.0 | 0.0 | × |
| $\check{\Xi}^1_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 0.0 | 25.6 | 0.0 | 27.5 | 0.0 | 0.0 | × |
| $\check{\Xi}'^2_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 10.5 | 10.0 | 21.3 | 8.1 | 0.0 | 0.0 | × |
| $\check{\Xi}'^2_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 9.9 | 13.9 | 9.8 | 16.9 | 0.0 | 0.0 | × |
| $\check{\Xi}^2_{c1}\left(\frac{1}{2}^+\right)$ | 21.6 | 7.0 | 2.8 | 14.2 | 4.0 | 25.2 | 21.1 | × |
| $\check{\Xi}^2_{c1}\left(\frac{3}{2}^+\right)$ | 21.6 | 1.7 | 7.1 | 3.6 | 10.0 | 25.2 | 21.1 | × |
| $\check{\Xi}^2_{c2}\left(\frac{3}{2}^+\right)$ | 0.0 | 15.7 | 8.1 | 32.0 | 7.4 | 0.0 | 0.0 | × |
| $\check{\Xi}^2_{c2}\left(\frac{5}{2}^+\right)$ | 0.0 | 6.6 | 17.7 | 6.6 | 23.2 | 0.0 | 0.0 | × |
| $\check{\Xi}^2_{c3}\left(\frac{5}{2}^+\right)$ | 32.7 | 7.5 | 4.4 | 7.5 | 3.0 | 43.1 | 10.1 | × |
| $\check{\Xi}^2_{c3}\left(\frac{7}{2}^+\right)$ | 32.7 | 4.2 | 5.9 | 4.2 | 4.1 | 43.1 | 10.1 | × |

We find that the only possible assignment of $\Lambda_c(2880)^+$ is $\check{\Lambda}^2_{c3}\left(\frac{5}{2}^+\right)$ after considering both its total decay width and the ratio $\Gamma(\Sigma_c^*\pi^\pm)/\Gamma(\Sigma_c\pi^\pm)$, which agrees very well with the indication from the Belle experiment that $\Lambda_c(2880)^+$ favors $J^P = \frac{5}{2}^+$ by the analysis of the angular distribution[15].

Because $\Lambda_c(2940)^+$ is observed in the invariant mass spectrum of $D^0p$[14] and the first radial excitation of $\Lambda_c$ does not decay into $D^0p$ from the $^3P_0$ model, results out the possibility of $\Lambda_c(2940)^+$ being a radial excitation. From their calculated decay widths, we can only exclude some $D$-wave assignments which are marked with crosses in Table 4. Furthermore the decay width ratios of $\Lambda_c(2940)^+$ model will be useful in the identification of its quantum numbers in the future.

Finally for determining the quantum numbers of $\Xi_c(2980, 3077, 3055, 3123)^+$, the following suggestions are made:

1) Search for other possible decay modes of $\Xi_c(2980, 3077, 3055, 3123)^+$. From Tables 5—8, one finds that there exist the forbidden decay modes for $\Xi_c(2980, 3077, 3055, 3123)^+$ in some assignments of quantum number, which will be the hint for excluding and confirming the quantum number of $\Xi_c(2980, 3077, 3055, 3123)^+$.

2) Measure the ratios of $\Xi_c^0\pi^+ : \Xi_c'(0)\pi^+ : \Xi_c^{*0}\pi^+ : \Sigma_c^{++}K^- : \Lambda_c^+K^0 : D^+\Lambda$. Our numerical results show that the ratios of $\Xi_c^0\pi^+ : \Xi_c'(0)\pi^+ : \Xi_c^{*0}\pi^+ : \Sigma_c^{++}K^- : \Lambda_c^+K^0 : D^+\Lambda$ are different for different assignment. Thus one urges our experimental colleagues to search for other decay modes of $\Xi_c(2980, 3077, 3055, 3123)^+$. These information will be helpful to finally determine the properties of $\Xi_c(2980, 3077, 3055, 3123)^+$ in future.

## 4 Conclusion

Accompanying with a series of observations of new heavy flavor hadrons, the studies of heavy flavor physics enters a new era. The unknown properties of these states, i.e. their quantum numbers, have attracted great interest of both theorists and experimentalists in high energy physics. Study on the strong decay of these heavy flavor hadrons is a very important topic which would be helpful to shed light on our understanding of the their properties.

In this proceeding, one retrospects on the research of strong decay of these new charmed hadrons, especially introduces our work in the past one year. By the experimental information, we can exclude and confirm some assignments for these charmed hadrons. Meanwhile we give some useful suggestions for the future experiments.

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