Study of heavy baryons in the diquark picture: success and difficulty

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Outline

- 1. Experimental results and theoretical foundation
- 2. Explanation for the heavy baryons in diquark picture
- 3. Summary : success and difficulty

Experimental results and theoretical foundation

Status of charmed baryons

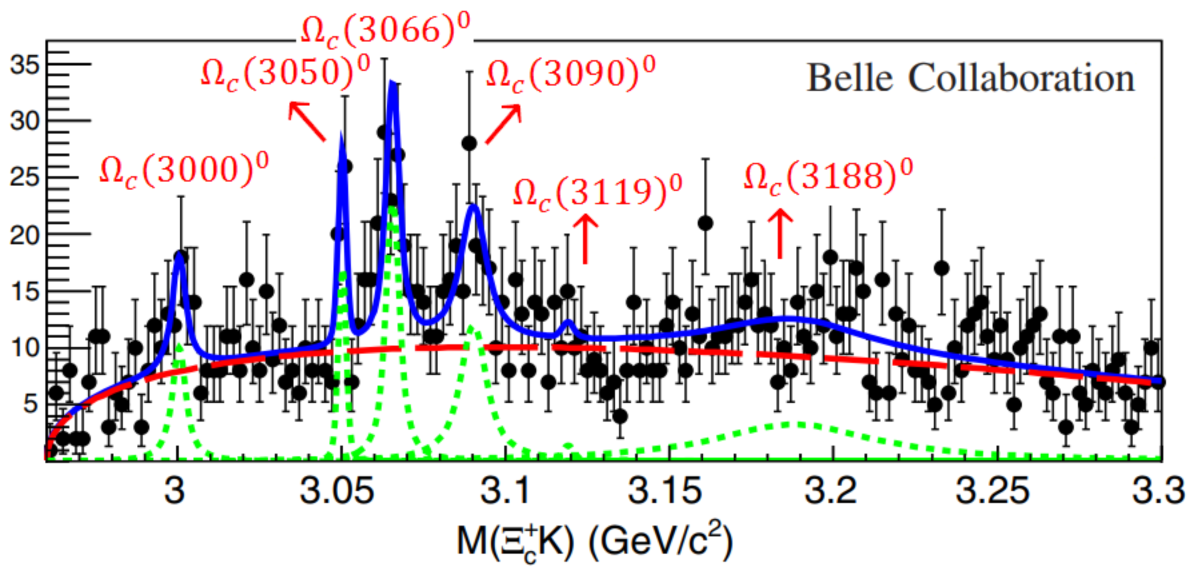
State	Mass	Width	Decay modes
Λ_c^+	2286.46 ± 0.14		Weak
$\Lambda_c(2595)^+$	2592.25 ± 0.28	2.6 ± 0.6	$\Lambda_c\pi\pi, \Sigma_c\pi$
$\Lambda_c(2625)^+$	2628.11 ± 0.19	< 0.97	$\Lambda_c\pi\pi, \Sigma_c^{(*)}\pi$
$\Lambda_c(2765)^+$	2766.6 ± 2.4	50	$\Sigma_c\pi, \Lambda_c\pi\pi$
$\Lambda_c(2860)^+$	$2856.1^{+2.3\dagger}_{-5.9}$	$67.6^{+11.8\dagger}_{-21.6}$	$\Sigma_c^{(*)}\pi, D^0p, D^+n$
$\Lambda_c(2880)^+$	$2881.64 \pm 0.25^\dagger$	$5.6 \pm 0.7^\dagger$	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p, D^+n$
$\Lambda_c(2940)^+$	$2939.8 \pm 1.4^\dagger$	$20 \pm 6^\dagger$	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p, D^+n$
$\Sigma_c(2455)^{++}$	2453.97 ± 0.14	$1.89^{+0.09}_{-0.18}$	$\Lambda_c\pi$
$\Sigma_c(2455)^+$	2452.9 ± 0.4	< 4.6	$\Lambda_c\pi$
$\Sigma_c(2455)^0$	2453.75 ± 0.14	$1.83^{+0.11}_{-0.19}$	$\Lambda_c\pi$
$\Sigma_c(2520)^{++}$	$2518.41^{+0.21}_{-0.19}$	$14.78^{+0.30}_{-0.40}$	$\Lambda_c\pi$
$\Sigma_c(2520)^+$	2517.5 ± 2.3	< 17	$\Lambda_c\pi$
$\Sigma_c(2520)^0$	2518.48 ± 0.20	$15.3^{+0.4}_{-0.5}$	$\Lambda_c\pi$
$\Sigma_c(2800)^{++}$	2801^{+4}_{-6}	75^{+22}_{-17}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
$\Sigma_c(2800)^+$	2792^{+14}_{-5}	62^{+64}_{-44}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
$\Sigma_c(2800)^0$	2806^{+5}_{-7}	72^{+22}_{-15}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$

State	Mass	Width	Decay modes
Ξ_c^0	$2470.85^{+0.28}_{-0.40}$		
$\Xi_c'^+$	$2578.3 \pm 0.5^*$		$\Xi_c\gamma$
$\Xi_c'^0$	$2579.2 \pm 0.5^*$		$\Xi_c\gamma$
$\Xi_c(2645)^+$	$2645.7 \pm 0.3^*$	$2.1 \pm 0.2^*$	$\Xi_c\pi$
$\Xi_c(2645)^0$	$2646.3 \pm 0.3^*$	$2.35 \pm 0.22^*$	$\Xi_c\pi$
$\Xi_c(2790)^+$	$2791.5 \pm 0.6^*$	$8.9 \pm 1.0^*$	$\Xi_c'\pi, \Xi_c\pi, \Lambda_c\bar{K}$
$\Xi_c(2790)^0$	$2794.8 \pm 0.6^*$	$10.0 \pm 1.1^*$	$\Xi_c'\pi, \Xi_c\pi, \Lambda_c\bar{K}$
$\Xi_c(2815)^+$	$2816.7 \pm 0.3^*$	$2.43 \pm 0.26^*$	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
$\Xi_c(2815)^0$	$2820.2 \pm 0.3^*$	$2.54 \pm 0.25^*$	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
$\Xi_c(2930)^0$	2931 ± 6	36 ± 13	$\Lambda_c\bar{K}, \Sigma_c\bar{K}, \Xi_c\pi, \Xi_c'\pi$
$\Xi_c(2970)^+$	$2966.7 \pm 0.8^*$	$24.6 \pm 2.0^*$	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, \Xi_c\pi\pi$
$\Xi_c(2970)^0$	$2970.6 \pm 0.8^*$	$29 \pm 3^*$	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, \Xi_c\pi\pi$
$\Xi_c(3055)^+$	3055.1 ± 1.7	11 ± 4	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3055)^0$	3059.0 ± 0.8	6.4 ± 2.4	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3080)^+$	3076.94 ± 0.28	4.3 ± 1.5	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3080)^0$	3079.9 ± 1.4	5.6 ± 2.2	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3123)^+$	3122.9 ± 1.3	4.4 ± 3.8	$\Sigma_c^*\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$

Mass spectra, widths (in units of MeV), and decay modes of the observed charmed baryons

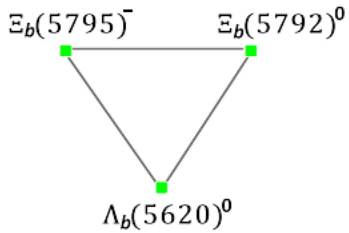
Experimental results and theoretical foundation

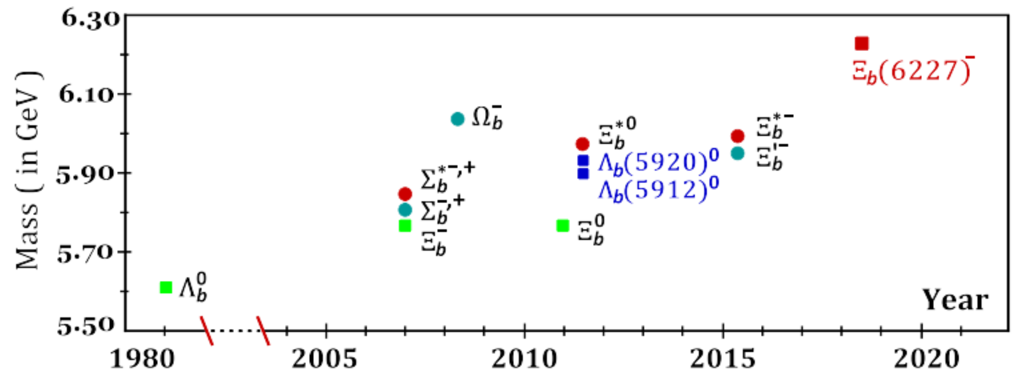
State	Decay mode	Mass (MeV)	Width (MeV)
$\Omega_c(2700)^0$	week	2695.2 ± 1.7	
$\Omega_c(2770)^0$	$\Omega_c^0\gamma$	2765.9 ± 2.0	
$\Omega_c(3000)^0$	$\Xi_c K$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$\Xi_c K$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
$\Omega_c(3066)^0$	$\Xi_c K$, $\Xi_c' K$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$\Xi_c K$, $\Xi_c' K$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$\Xi_c K$, $\Xi_c' K$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
$\Omega_c(3188)^0$	$\Xi_c K$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$

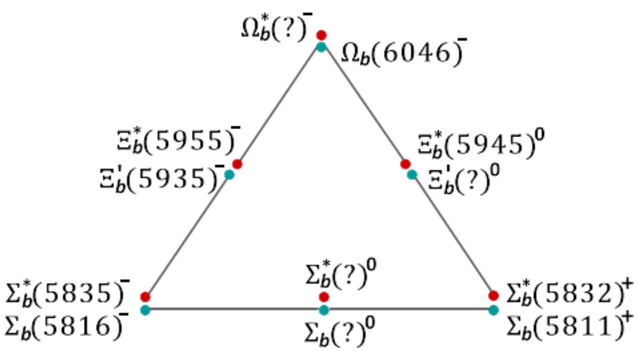


Experimental results and theoretical foundation

Status of bottomed baryons







Names	Status	Mass	Width
$\Lambda_b(5619)^0$	* * *	5619.4 ± 0.6	–
$\Lambda_b(5912)^0$	* * *	5912.0 ± 0.6	< 0.66
$\Lambda_b(5920)^0$	* * *	5919.8 ± 0.8	< 0.63
$\Sigma_b(5815)^-$	* * *	5815.5 ± 1.8	$4.9^{+3.3}_{-2.4}$
$\Sigma_b^*(5835)^-$	* * *	5835.1 ± 1.9	7.5 ± 2.3
$\Xi_b(5790)^-$	* * *	5791.1 ± 2.2	–
$\Xi_b'(5935)^-$	**	5935.02 ± 0.53	< 0.08
$\Xi_b^*(5955)^-$	* * *	5955.33 ± 0.68	1.65 ± 0.41
$\Xi_b^*(6227)^-$		6226.9 ± 2.5	18.1 ± 7.2
$\Omega_b^*(6046)^-$	* * *	6046.1 ± 1.7	1.65 ± 0.41

LHCb

Bing Chen, Ke-wei Wei, Xiang Liu, and Ailin Zhang, arXiv:1805.10826

Mass spectra, widths (in units of MeV), and decay modes of the observed charmed baryons

Experimental results and theoretical foundation

Within the diquark picture, the mass difference between the corresponding Ξ_c and Λ_c states is about 180~200 MeV, while the corresponding Ξ_c' and Σ_c states is about 120~130 MeV

doublet	s_l^P	J^P	Λ_c (cud)	Ξ_c (csq)	δ_M
1S	0^+	$\frac{1}{2}^+$	$\Lambda_c(2286)$	$\Xi_c(2470)$	184
2S	0^+	$\frac{1}{2}^+$	$\Lambda_c(2760)$	$\Xi_c(2970)$	200
1P	1^-	$\frac{1}{2}^-$	$\Lambda_c(2595)$	$\Xi_c(2790)$	200
		$\frac{3}{2}^-$	$\Lambda_c(2625)$	$\Xi_c(2815)$	188
1D	2^+	$\frac{3}{2}^+$	$\Lambda_c(2860)$	$\Xi_c(3055)$	201
		$\frac{5}{2}^+$	$\Lambda_c(2880)$	$\Xi_c(3080)$	198
2P	1^-	$\frac{1}{2}^-$			
		$\frac{3}{2}^-$	$\Lambda_c(2940)$	$\Xi_c(3123)$	184

$$\frac{16\pi\alpha}{9m_i m_j}\delta^3(\vec{r}_{ij}^{\,3})\,\vec{S}_i\cdot\vec{S}_j$$

$$\delta_{\text{"good"}} = (m_s - m_q) + \frac{3}{4}\lambda;$$
$$\delta_{\text{"bad"}} = (m_s - m_q) - \frac{1}{4}\lambda;$$

$$m_{\Xi_c'(2930)} - m_{\Sigma_c(2800)} \approx$$
$$m_{\Xi_c'(2570)} - m_{\Sigma_c(2455)} \approx$$
$$m_{\Xi_c'(2645)} - m_{\Sigma_c(2520)} \approx$$
125 MeV

Experimental results and theoretical foundation

Within the diquark picture, the mass difference between the corresponding Ξ_c and Λ_c states is about 180~200 MeV, while the corresponding Ξ_c' and Σ_c states is about 120~130 MeV

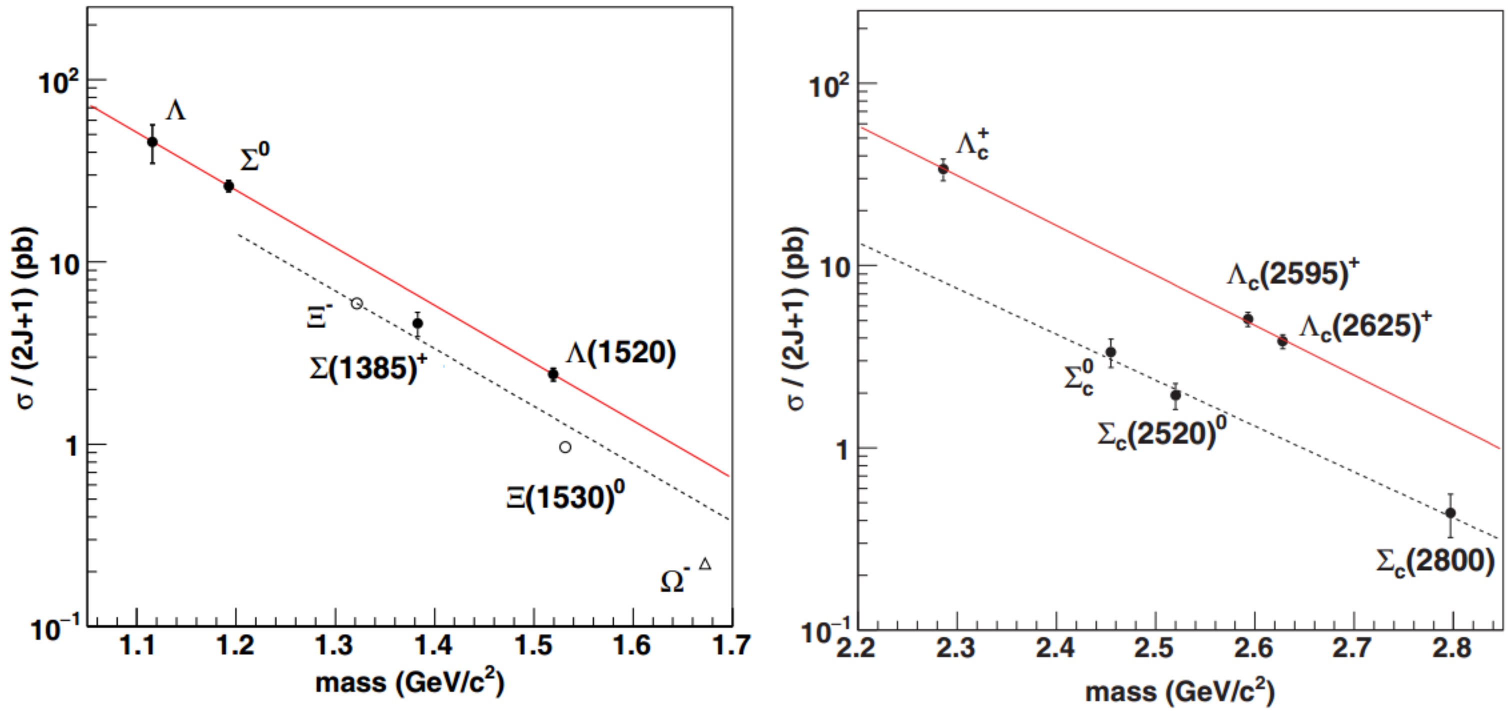
Names	Status	Mass	Width	Names	Status	Mass	Width	ΔM
$\Lambda_c(2286)^+$	* * **	2286.46 ± 0.14	–	$\Xi_c(2468)^0$	* * *	$2470.88^{+0.34}_{-0.80}$	–	$184.42^{+0.37}_{-0.81}$
$\Lambda_c(2595)^+$	* * *	2592.25 ± 0.28	2.6 ± 0.6	$\Xi_c(2790)^0$	* * *	2791.8 ± 3.3	< 12	199.6 ± 3.3
$\Lambda_c(2625)^+$	* * *	2628.11 ± 0.19	< 0.97	$\Xi_c(2815)^0$	* * *	2819.6 ± 1.2	< 6.5	191.5 ± 1.2
$\Lambda_c(2765)^+$	**	$2766.6^{+3.6}_{-7.1}$	≈ 50	$\Xi_c(2980)^0$	* * *	2968.0 ± 2.6	20 ± 7	201.4 ± 3.5
$\Lambda_c(2860)^+$	**	$2856.1^{+3.6}_{-7.1}$	$67.6^{+17.6}_{-29.5}$	$\Xi_c(3055)^+$	**	3054.2 ± 1.3	17 ± 13	198.1
$\Lambda_c(2880)^+$	* * *	2881.53 ± 0.35	5.8 ± 1.1	$\Xi_c(3080)^0$	* * *	3079.9 ± 1.4	5.6 ± 2.2	198.4 ± 1.4
$\Lambda_c(2940)^+$	* * *	$2939.3^{+1.4}_{-1.5}$	17^{+8}_{-6}	$\Xi_c(3123)^+$	*	3122.9 ± 1.3	4 ± 4	$183.6^{+1.9}_{-2.0}$
$\Sigma_c(2455)^0$	* * **	2453.74 ± 0.16	2.16 ± 0.26	$\Xi_c'(2578)^0$	* * *	2577.9 ± 2.9	···	124.2 ± 2.9
$\Sigma_c(2520)^0$	* * *	2518.8 ± 0.6	14.5 ± 1.5	$\Xi_c^*(2645)^0$	* * *	2645.9 ± 0.5	< 5.5	127.1 ± 0.8
$\Sigma_c(2800)^0$	* * *	2806^{+5}_{-7}	72^{+22}_{-15}	$\Xi_c'(2930)^0$	*	2931 ± 6	36 ± 13	125^{+8}_{-9}
$\Lambda_b(5619)^0$	* * *	5619.4 ± 0.6	–	$\Xi_b(5790)^-$	* * *	5791.1 ± 2.2	–	171.7 ± 2.3
$\Lambda_b(5912)^0$	* * *	5912.0 ± 0.6	< 0.66	$\Xi_b(6090)^-$		···	···	
$\Lambda_b(5920)^0$	* * *	5919.8 ± 0.8	< 0.63	$\Xi_b(6100)^-$		···	···	
$\Sigma_b(5815)^-$	* * *	5815.5 ± 1.8	$4.9^{+3.3}_{-2.4}$	$\Xi_b'(5935)^-$	**	5935.02 ± 0.53	< 0.08	120.4 ± 3.0
$\Sigma_b^*(5835)^-$	* * *	5835.1 ± 1.9	7.5 ± 2.3	$\Xi_b^*(5955)^-$	* * *	5955.33 ± 0.68	1.65 ± 0.41	120.4 ± 3.0

Experimental results and theoretical foundation

PHYSICAL REVIEW D **97**, 072005 (2018)

Production cross sections of hyperons and charmed baryons from e^+e^- annihilation near $\sqrt{s} = 10.52$ GeV

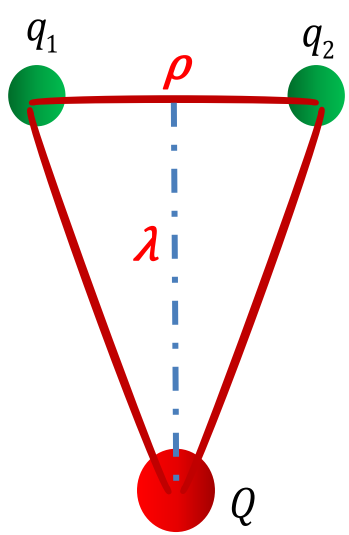
(Belle Collaboration)



This observation supports the theory that the diquark production is the main process of charmed baryon production from e^+e^- annihilation and that the diquark structure exists in the ground state and low-lying excited states of Λ_c^+ baryons.

Experimental results and theoretical foundation

If we assume that two light quarks in the charmed baryon systems develop into a quark cluster, then the mass differences between Ξ_c and Λ_c states can be understood well. In the quark cluster picture (or diquark picture), the degree of freedom of two light quarks in a diquark system is frozen. Only the degree of freedom between the center of mass of two light quarks and the c quark can be excited.



$$H_0 = \sum_{i=1}^{3} \frac{p_i^2}{2m_i} + \sum_{i<j} \left(\frac{1}{2}\kappa r_{ij}^2 + U(r_{ij}) \right) - \frac{\sum_i p_i^2}{2M}$$

In terms of Jacobi relative coordinates

$$\vec{\rho} = \frac{1}{\sqrt{2}}(\vec{r}_2 - \vec{r}_1); \quad \vec{\lambda} = \frac{1}{\sqrt{6}}(\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)$$

$$H_0 = \frac{p_\rho^2}{2m_\rho} + \frac{p_\lambda^2}{2m_\lambda} + \frac{1}{2}m_\rho \omega_\rho^2 \rho^2 + \frac{1}{2}m_\lambda \omega_\lambda^2 \lambda^2 + \langle U \rangle$$

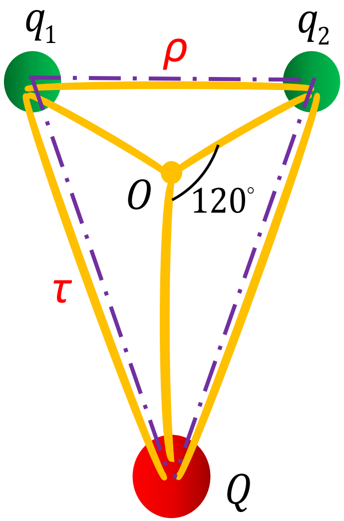
$$E_{\rho,\lambda} = \left(2n_\rho + l_\rho + \frac{3}{2}\right)\omega_\rho + \left(2n_\lambda + l_\lambda + \frac{3}{2}\right)\omega_\lambda$$

Experimental results and theoretical foundation

Since the oscillator frequencies ω_ρ and ω_λ are different in the charmed baryons ($m_Q \gg m_q$)

$$\frac{\omega_\lambda}{\omega_\rho} = \sqrt{\frac{1}{3}\left(1+\frac{2m_q}{m_Q}\right)} < 1$$

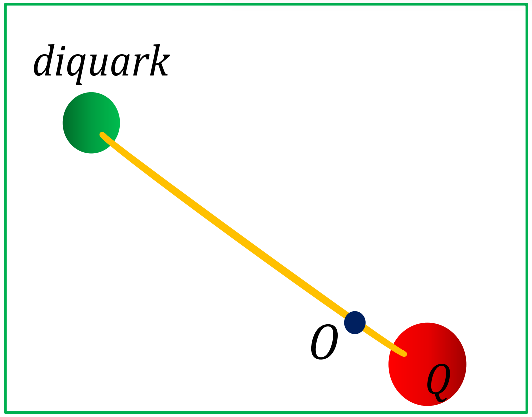
which indicates that the λ mode excited charmed baryons would have lower excited energies.



$$\begin{bmatrix} -\frac{\nabla_\rho^2}{2m_\rho} + \left(-\frac{2}{3}\frac{\alpha}{\rho} + \sqrt{\frac{3}{4}}b\rho\right) + \frac{16\pi\alpha}{9m^2}\vec{s}_1\cdot\vec{s}_2\delta^3(\vec{\rho}) \\ -\frac{\nabla_\lambda^2}{2m_\lambda} + \left(-\frac{4}{3}\frac{\alpha}{\sqrt{\lambda^2+\frac{\rho^2}{4}}} + b\lambda\right) + \frac{16\pi\alpha}{9mm_Q}\vec{s}_{di}\cdot\vec{s}_Q\delta^3(\vec{\tau}) \end{bmatrix}\Psi(\vec{\rho},\vec{\lambda}) = E\Psi(\vec{\rho},\vec{\lambda})$$

Masses and decays of charmed baryons in diquark picture

"Assignments of Λ_Q and Ξ_Q baryons in the heavy quark-light diquark picture",
Bing Chen, Ke-Wei Wei, and Ailin Zhang
Eur. Phys. J. A **51**, 82 (2015)



In the relativistic flux tube (RFT) model, Selem and Wilczek have obtained the following mass formula,

$$E = M + \sqrt{\frac{\sigma L}{2}} + 2^{1/4}\kappa L^{-1/4}\mu^{3/2}$$

A. Selem, F. Wilczek, arXiv:hep-ph/ 0602128

We have extended equation above to the radial excited heavy baryons as

Chew-Frautschi formula

$$(\varepsilon_{nL} - m_Q)^2 = \frac{1}{2}\sigma(\kappa n + L) + (m_l + \zeta_Q)^2$$

where $\zeta_Q = m_Q u_1^2$。

Finally, we added the $\vec{s}_Q \cdot \vec{L}$ couplings term as

$$H_{nL}^{so} = \frac{1}{3\times 2^{5/2}} \frac{\alpha_s}{(u_1+u_2)^3} \left(\frac{\sigma}{\kappa n+L}\right)^{3/2} \frac{1}{m_l m_Q} \vec{s}_Q \cdot \vec{L}$$

Masses and decays of charmed baryons in diquark picture

Results of the excited Λ_c^+ and Ξ_c excited states:

Bing Chen, Ke-Wei Wei, Ailin Zhang,
Eur.Phys.J. A **51** (2015) 82

$J^P(nL)$	Exp. [1]	This work	Ref. [9]	Ref. [50]	Ref. [51]
$\frac{1}{2}^+(1S)$	2286.86	2286	2286	2286	2265
$\frac{1}{2}^+(2S)$	2766.6	2766	2769	2791	2775
$\frac{1}{2}^+(3S)$		3112	3130	3154	3170
$\frac{1}{2}^+(4S)$		3397	3437		
$\frac{1}{2}^-(1P)$	2592.3	2591	2598	2625	2630
$\frac{3}{2}^-(1P)$	2628.1	2629	2627	2636	2640
$\frac{1}{2}^-(2P)$	2939.3	2989	2983		[2780]
$\frac{3}{2}^-(2P)$		耦合道效应 3000	3005		[2840]
$\frac{1}{2}^-(3P)$		3296	3303		[2830]
$\frac{3}{2}^-(3P)$		3301	3322		[2885]
$\frac{3}{2}^+(1D)$		2857	2874	2887	2910
$\frac{5}{2}^+(1D)$	2881.53	2879	2880	2887	2910
$\frac{3}{2}^+(2D)$		3188	3189	3120	3035
$\frac{5}{2}^+(2D)$		3198	3209	3125	3140
$\frac{5}{2}^-(1F)$		3075	3097	[2872]	[2900]
$\frac{7}{2}^-(1F)$		3092	3078		3125
$\frac{7}{2}^+(1G)$		3267	3270		3175
$\frac{9}{2}^+(1G)$		3280	3284		

$J^P(nL)$	Exp. [1]	This work	Ref. [9]	Ref. [50]
$\frac{1}{2}^+(1S)$	2470.88	2467	2476	2466
$\frac{1}{2}^+(2S)$	2968.0	2959	2959	2924
$\frac{1}{2}^+(3S)$		3325	3323	[3183]
$\frac{1}{2}^+(4S)$		3629	3632	
$\frac{1}{2}^-(1P)$	2791.8	2779	2792	2773
$\frac{3}{2}^-(1P)$	2819.6	2814	2819	2783
$\frac{1}{2}^-(2P)$	3122.9	3195	3179	
$\frac{3}{2}^-(2P)$		3204	3201	
$\frac{1}{2}^-(3P)$		3521	3500	
$\frac{3}{2}^-(3P)$		3525	3519	
$\frac{3}{2}^+(1D)$	3054.2	3055	3059	3012
$\frac{5}{2}^+(1D)$	3079.9	3076	3076	3004
$\frac{3}{2}^+(2D)$		3407	3388	
$\frac{5}{2}^+(2D)$		3416	3407	
$\frac{5}{2}^-(1F)$		3286	3278	
$\frac{7}{2}^-(1F)$		3302	3292	
$\frac{7}{2}^+(1G)$		3490	3469	
$\frac{9}{2}^+(1G)$		3503	3483	

Masses and decays of charmed baryons in diquark picture

LHCb Collaboration (R. Aaij (CERN) *et al.*), **JHEP 1705 (2017) 030**

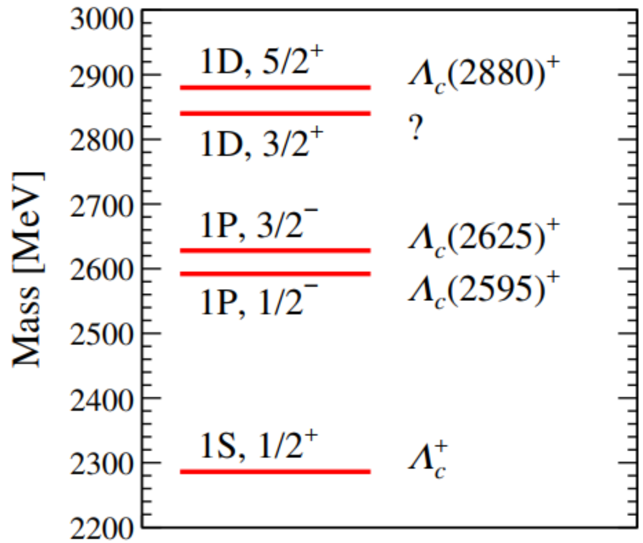


Figure 1. Expected spectrum of the Λ_c^+ ground state and its orbital excitations from a study based on the nonrelativistic heavy quark-light diquark model [21], along with the observed resonances corresponding to those states [23].

$\frac{3}{2}^+$

$$m(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\ \text{MeV},$$

$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\ \text{MeV}$$

Masses and decays of charmed baryons in diquark picture

Bing Chen, Ke-Wei Wei, Xiang Liu, Takayuki Matsuki, Eur. Phys. J. C **77**, 154 (2017)
Bing Chen, Xiang Liu, and Ailin Zhang, Phys. Rev. D **95**, 074022 (2017)
Bing Chen, Xiang Liu, Phys. Rev. D **95**, 074022 (2017)

doublet	s_l^P	J^P	Λ_c (cud)	Ξ_c (csq)	Λ_b (bud)	Ξ_b (bsq)	comment
1S	0^+	$1/2^+$	$\Lambda_c(2286)$	$\Xi_c(2470)$	$\Lambda_b(5620)$	$\Xi_b(5795)$	****
2S	0^+	$1/2^+$	$\Lambda_c(2760)$	$\Xi_c(2980)$			*
1P	1^-	$1/2^-$	$\Lambda_c(2595)$	$\Xi_c(2790)$	$\Lambda_b(5912)$		***
		$3/2^-$	$\Lambda_c(2625)$	$\Xi_c(2815)$	$\Lambda_b(5920)$		
1D	2^+	$3/2^+$	$\Lambda_c(2860)$	$\Xi_c(3055)$			**~***
		$5/2^+$	$\Lambda_c(2880)$	$\Xi_c(3080)$			
2P	1^-	$1/2^-$					*~**
		$3/2^-$	$\Lambda_c(2940)$	$\Xi_c(3123)$			

Masses and decays of charmed baryons in diquark picture

Bing Chen, Ke-Wei Wei, Xiang Liu, Takayuki Matsuki, Eur. Phys. J. C **77**, 154 (2017)
Bing Chen, Xiang Liu, and Ailin Zhang, Phys. Rev. D **95**, 074022 (2017)
Bing Chen, Xiang Liu, Phys. Rev. D **95**, 074022 (2017)

For bottom-strange baryons,

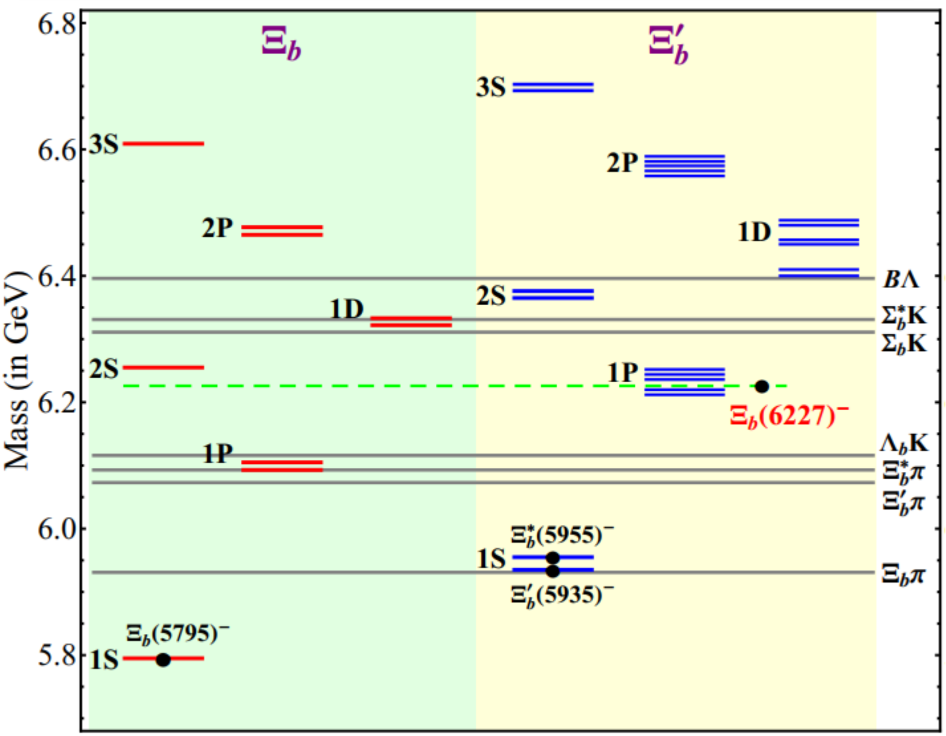
Bing Chen, Ke-wei Wei, Xiang Liu, and Ailin Zhang, arXiv:1805.10826

n*L*	**1*S***		**1*P***					**2*S***	
J^P	$1/2^+$	$3/2^+$	$1/2^-$	$1/2'^-$	$3/2^-$	$3/2'^-$	$5/2^-$	$1/2^+$	$3/2^+$
Σ_c	$\Sigma_c(2455)$	$\Sigma_c(2520)$				$\Sigma_c(2800)$			
Ξ'_c	$\Xi'_c(2570)$	$\Xi'_c(2645)$				$\Xi'_c(2930)$			
Ω_c	$\Omega_c(2700)$	$\Omega_c(2760)$	$\Omega_c(3000)$	$\Omega_c(3090)$	$\Omega_c(3050)$	$\Omega_c(3119)$	$\Omega_c(3066)$	$\Omega_c(3188)$	
Σ_b	$\Sigma_b(5815)$	$\Sigma_b(5835)$							
Ξ'_b	$\Xi'_b(5935)$	$\Xi'_b(5955)$				$\Xi'_b(6227)^-$			
Ω_b	$\Omega_b(6045)$								

Masses and decays of charmed baryons in diquark picture

Bing Chen, Ke-wei Wei, Xiang Liu, and Ailin Zhang, arXiv:1805.10826

$$M = 6226.9 \pm 2.0(\text{stat}) \pm 0.3(\text{syst}) \pm 0.2(\Lambda_b^0)\ \text{MeV},$$
$$\Gamma = 18.1 \pm 5.4(\text{stat}) \pm 1.8(\text{syst})\ \text{MeV}.$$



Decay channels	Prediction	Experiments [PDG]
$\Sigma_b(5815)^- \to \Lambda_b^0\pi^-$	5.12	$4.9^{+3.3}_{-2.4}$
$\Sigma_b(5835)^- \to \Lambda_b^0\pi^-$	9.13	7.5 ± 2.3
$\Xi_b'(5935)^- \to \Xi_b\pi$	0.05	< 0.08, CL=95%
$\Xi_b^*(5955)^- \to \Xi_b\pi$	1.09	1.65 ± 0.33

Decay	$1/2^-$		$3/2^-$		$5/2^-$
modes	$\Xi_{b0}'(6249)$	$\Xi_{b1}'(6239)$	$\Xi_{b1}'(6244)$	$\Xi_{b2}'(6213)$	$\Xi_{b2}'(6217)$
Λ_bK	9.1	×	×	10.2	11.0
$\Xi_b\pi$	0.2	×	×	11.4	11.7
$\Xi_b'(5935)\pi$	×	15.1	0.9	1.0	0.5
$\Xi_b^*(5955)\pi$	×	2.0	23.7	1.0	1.7
$\Xi_b(6096)\pi$	0.3	0.1	0.1	–	–
$\Xi_b(6102)\pi$	0.3	–	0.1	–	–
Theory	9.9	17.2	24.8	23.6	24.9
Expt. [9]				$18.1 \pm 5.4 \pm 1.8$	

The measured branching ratios

Belle [2007]
Phys. Rev. Lett. 98, 262001 (2007)

$$\frac{\boldsymbol{B(\Lambda_c(2880)\to\Sigma_c(2520)\pi)}}{\boldsymbol{B(\Lambda_c(2880)\to\Sigma_c(2455)\pi)}} = \mathbf{0.225} \pm 0.062 \pm 0.025;$$

BABAR [2008]
Phys. Rev. D **77**, 012002 (2008)

$$\frac{B(\Xi_c(3080)\to\Sigma_c(2520)K)}{B(\Xi_c(3080)\to\Sigma_c(2455)K)} = \frac{0.55\pm0.05\pm0.05}{0.45\pm0.05\pm0.05} = 0.82 \sim 1.86;$$

Belle [2016]
Phys. Rev. D **94**, 032002 (2016)

$$\frac{B(\Xi_c(3080)\to\Sigma_c(2520)K)}{B(\Xi_c(3080)\to\Sigma_c(2455)K)} = 1.07 \pm 0.27 \pm 0.04;$$

$$\frac{B(\Xi_c(3080)\to\Lambda D)}{B(\Xi_c(3080)\to\Sigma_c(2455)K)} = 1.29 \pm 0.30 \pm 0.15;$$

$$\frac{B(\Xi_c(3055)\to\Lambda D)}{B(\Xi_c(3055)\to\Sigma_c(2455)K)} = 5.09 \pm 1.01 \pm 0.76;$$

Hai-Yang Cheng, Chun-Khiang Chua, Phys.Rev. D **75** (2007) 014006
Bing Chen, Xiang Liu, and Ailin Zhang, Phys.Rev. D **95**, 074022 (2017)
Ya-Xiong Yao, Kai-Lei Wang, Xian-Hui Zhong, arXiv:1803.00364

Summary : success and difficulty

$\Lambda_c(2940)^+$

states	Expt.	CWLM	EFG	CWZ	CI
$\|2P,1/2^-\rangle$	——	2980	2983	2989	3030
$\|2P,3/2^-\rangle$	2939.3	**3004**	**3005**	**3000**	**3035**

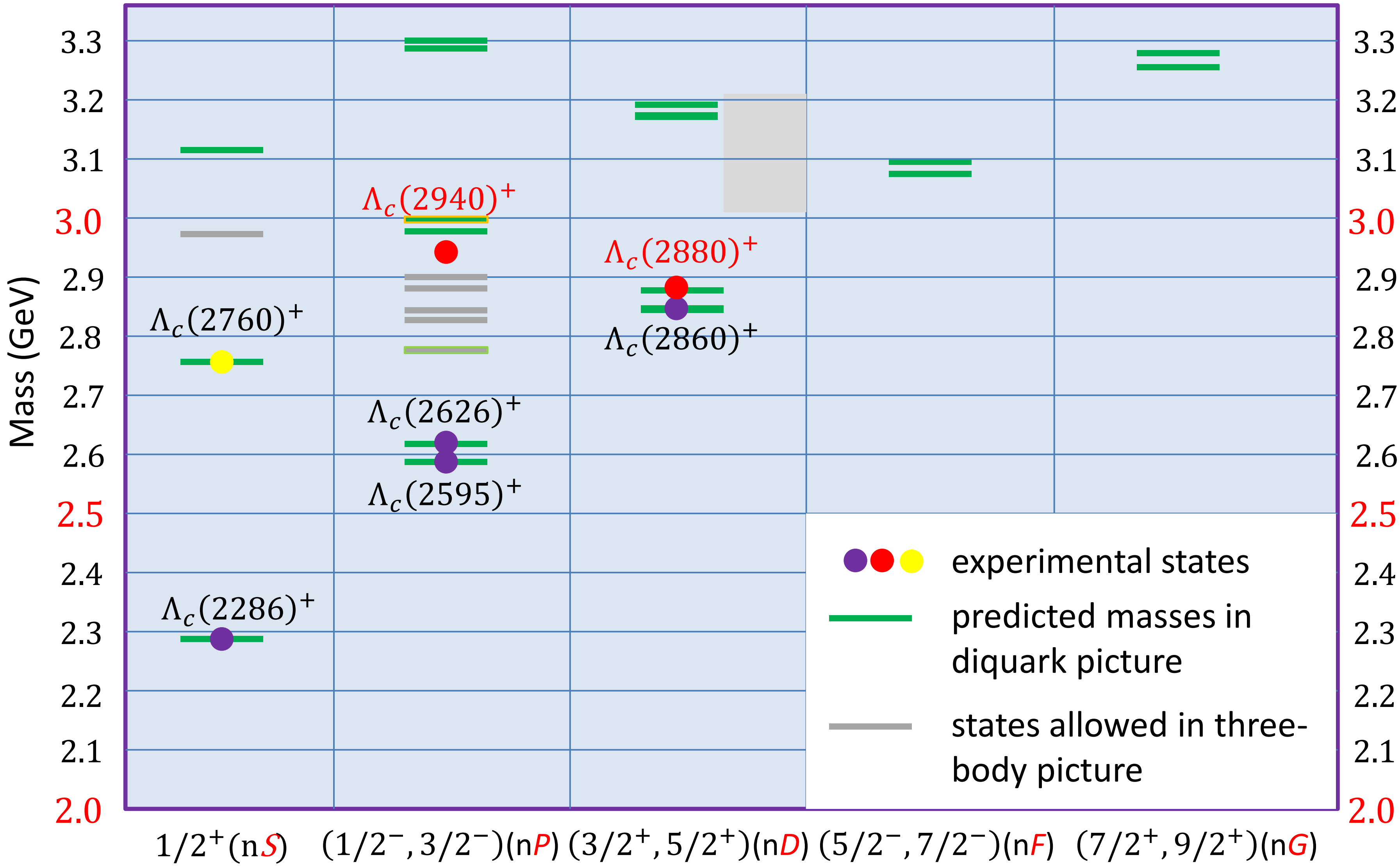
Mass (in MeV)

Some thresholds in an S wave plays an important dynamical role in making the $|2P,3/2^-\rangle$ state a notable mass shift.

$D^* p$	$D^* n$
2950	**2950**

So the coupled-channel effects should be considered for the $2P$ Λ_c^+states.

Summary : success and difficulty



Summary : success and difficulty

In the heavy quark-light diquark picture, most of the observed charmed baryon states can be explained including their mass spectrum and strong decays. As discussed above, however, there are some questions which should be investigated deeply.

(1) The branching ratios of $\Lambda_c(2880)^+$and $\Xi_c(3080)$ pose challenges to the diquark picture,

(2) The coupled-channel effects should be studied for the $2P$ Λ_c^+ states,

(3) The spin-parity of $\Lambda_c(2760)^+$ [or a $\Sigma_c(2760)^+$ state] and $\Xi_c^{(\prime)}(2980)$ should be measured,

(4) We may ask why no ρ-mode excited heavy baryon state has been detected by any experiment. If they exist, how are we going to find them?

Thank you !