Spectroscopy and decays of singly charmed baryons

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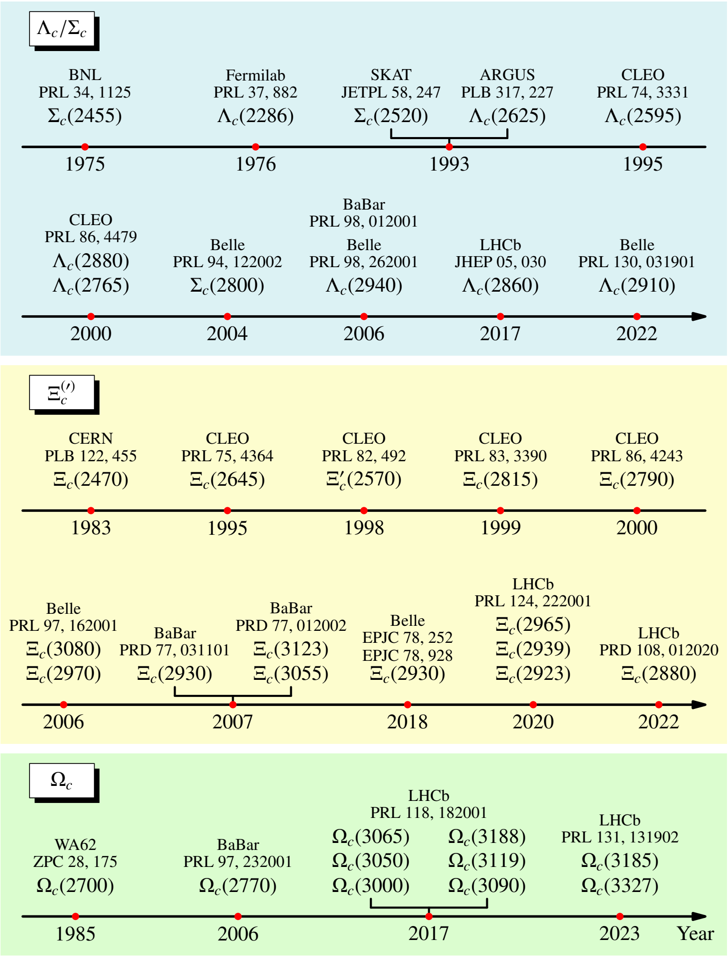
1. Background

Singly Charmed Baryons



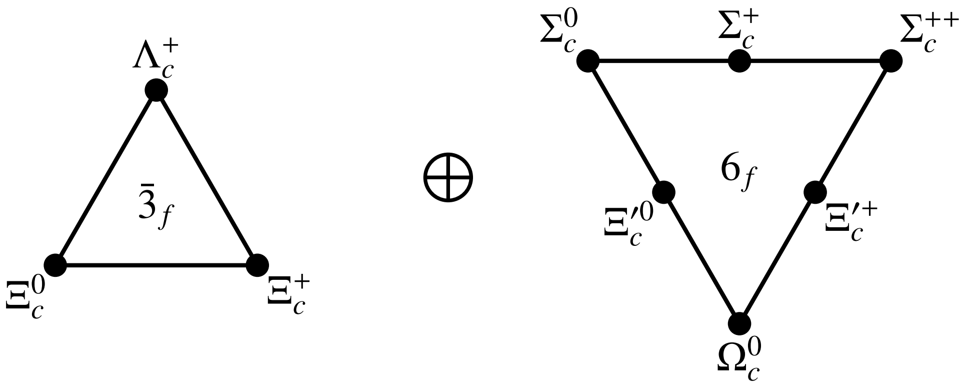
Observed Singly Charmed Baryons in Experiments.

1. In the past about fifty years, over 30 singly charmed baryons were observed.

2. Over half of the number were observed in this centry.

In $SU(3)$ flavor symmetry, the flavor wave functions could be decomposed as

$$3_f \otimes 3_f = \bar{3}_f \oplus 6_f$$



$$\phi^{\text{flavor}}_{\Lambda_c} = \frac{1}{\sqrt{2}}(ud - du)c$$

$$\phi^{\text{flavor}}_{\Xi_c} = \begin{cases} \frac{1}{\sqrt{2}}(us - su)c \\ \frac{1}{\sqrt{2}}(ds - sd)c \end{cases}$$

$$\phi^{\text{flavor}}_{\Sigma_c} = \begin{cases} uuc \\ \frac{1}{\sqrt{2}}(ud + du)c \\ ddQ \end{cases}$$

$$\phi^{\text{flavor}}_{\Xi'_c} = \begin{cases} \frac{1}{\sqrt{2}}(us + su)c \\ \frac{1}{\sqrt{2}}(ds + sd)c \end{cases},$$

$$\phi^{\text{flavor}}_{\Omega_c} = ssc.$$

2. Formalism

Spectroscopy: Three-body

$$H = \sum_{i=1}^{3} \frac{p_i^2}{2m_i} + \sum_{i<j} V_{ij}(\mathbf{r})$$

$$V_{ij} = H_{ij}^{\text{conf}} + H_{ij}^{\text{hyp}} + H_{ij}^{\text{so(cm)}} + H_{ij}^{\text{so(tp)}}$$

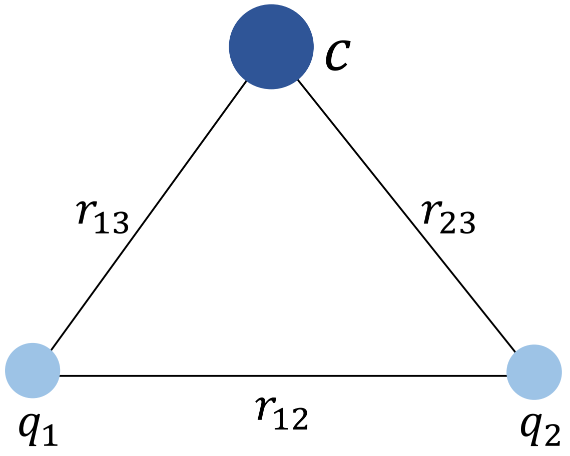
$$H_{ij}^{\text{conf}} = -\frac{2}{3}\frac{\alpha_s}{r_{ij}} + \frac{b}{2} r_{ij} + \frac{1}{2} C$$

$$H_{ij}^{\text{hyp}} = \frac{2\alpha_s}{3m_i m_j}\left[\frac{8\pi}{3}\tilde{\delta}(r_{ij})\mathbf{s}_i \cdot \mathbf{s}_j + \frac{1}{r_{ij}^3} S(\mathbf{r}, \mathbf{s}_i, \mathbf{s}_j)\right]$$

$$H_{ij}^{\text{so(cm)}} = \frac{2\alpha_s}{3r_{ij}^3}\left(\frac{\mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_j}{m_j^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_i - \mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_j}{m_i m_j}\right)$$

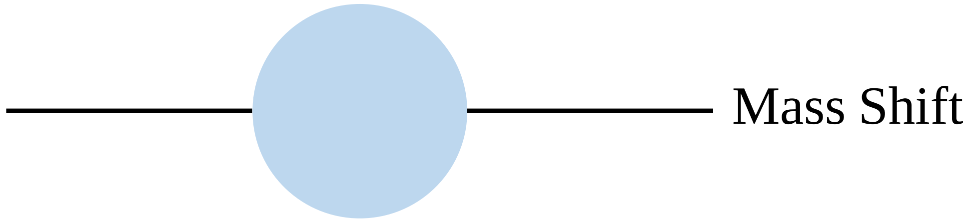
$$H_{ij}^{\text{so(tp)}} = -\frac{1}{2r_{ij}}\frac{\partial H_{ij}^{\text{conf}}}{\partial r_{ij}}\left(\frac{\mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_j}{m_j^2}\right).$$

$$\tilde{\delta}(r) = \frac{\sigma^3}{\pi^{3/2}} \mathrm{e}^{-\sigma^2 r^2} \qquad S(\mathbf{r}, \mathbf{s}_i, \mathbf{s}_j) = \frac{3\mathbf{s}_i \cdot \mathbf{r}_{ij}\mathbf{s}_j \cdot \mathbf{r}_{ij}}{r_{ij}^2} - \mathbf{s}_i \cdot \mathbf{s}_j$$



$q = u, d, s$

Spectroscopy: Coupled-channel effects



In coupled channel effects, the bare state could couple with intermediate channel. Then the physical wave function should be written as

$$|\psi\rangle = c_0 |\psi_A\rangle + c_{BC}(\mathbf{p}) |\psi_{BC}(\mathbf{p})\rangle \,,$$

where $|\psi_A\rangle$ is bare state, $|\psi_{BC}(\mathbf{p})\rangle$ intermediate channel, c_0 and $c_{BC}(\mathbf{p})$ are amplitudes of bare state and intermediate channel, respectively. Then the Hamilton should be rewritten as

$$\hat{H} = \hat{H}_0 + \hat{H}_I + \hat{H}_{BC},$$

where $\hat{H}_0$ is the Hamilton of the bare state, $\hat{H}_{BC}$ is the Hamilton of the intermediate channel, $\hat{H}_I$ is the transition Hamilton between bare state and intermediate channel.

Coupled channel equation:

$$M_0 + \int \frac{|H_{A\to BC}(\mathbf{p})|^2}{M - E_{BC}(p)} \mathrm{d}^3\mathbf{p} = M.$$

Mass shift:

$$\Delta M(M) = \int \frac{|H_{A\to BC}(\mathbf{p})|^2}{M - E_{BC}(p)} \mathrm{d}^3\mathbf{p}.$$

1. M_0: bare mass, calculated by conventional quark model
2. M: physical mass
3. $H_{A\to BC}(\mathbf{p})$: transition matrix element

Decay: QPC model

QPC (quark-pair-creation) model, also called $^3P_0$ model, which transition operator is

$$\hat{\mathcal{T}} = -3\gamma \sum_m \langle 1, m; 1, -m|0, 0\rangle \int \mathrm{d}^3\mathbf{p}_i \mathrm{d}^3\mathbf{p}_j \delta(\mathbf{p}_i + \mathbf{p}_j) \times \mathcal{Y}_1^m\left(\frac{\mathbf{p}_i - \mathbf{p}_j}{2}\right) \omega_0^{(i,j)} \phi_0^{(i,j)} \chi_{1,-m}^{(i,j)} b_i^\dagger(\mathbf{p}_i) d_j^\dagger(\mathbf{p}_j).$$

(Satisfy $^3P_0$ quantum number)

The amplitude of the partial wave is

$$M_{A\to BC}^{SL}(p) = \langle BC, S, L, p|\hat{\mathcal{T}}|A\rangle,$$

S is the relative spin of the final BC, L is the relative orbital angular momentum of BC, P is the momentum of B or C in the center-of-mass of A. The width is calculated by:

$$\Gamma_{A\to BC}^{SL} = 2\pi \frac{E_B(p)E_c(p)}{M_A} p|M_{A\to BC}^{SL}(p)|^2$$

Radiative decay

At the tree level, the Hamiltonian of the coupling of quarks and photon is

$$H_e = -\sum_j e_j \bar{\psi}_j \gamma_\mu^j A^\mu(\boldsymbol{k}, \boldsymbol{r}) \psi_j,$$

In the non-relativistic scheme, the Hamiltonian of the coupling of quarks and photon is given by

$$h_e \simeq \sum_j \left[e_j \boldsymbol{r}_j \cdot \boldsymbol{\epsilon} - \frac{e_j}{2m_j} \boldsymbol{\sigma}_j \cdot (\boldsymbol{\epsilon} \times \hat{\boldsymbol{k}}) \right] e^{-i\boldsymbol{k}\cdot\boldsymbol{r}_j}.$$

With the above Hamiltonian, the radiative decay amplitude is expressed as

$$\mathcal{A} = -i\sqrt{\frac{\omega_\gamma}{2}} \langle f | h_e | i \rangle,$$

where $|i\rangle$ and $|f\rangle$ are the wave functions of the initial and final baryons, respectively. The ω_γ is the energy of photon. Finally, the general expression of the radiative decay width of single-charm baryon is

$$\Gamma = \frac{|\boldsymbol{k}|^2}{\pi} \frac{2}{2J_i + 1} \frac{M_f}{M_i} \sum_{J_{fz}, J_{iz}} |\mathcal{A}_{J_{fz}, J_{iz}}|^2.$$

Numerical method: GEM

Three-body Schrödinger equation:

$$\left(\sum_{i=1}^{3}\frac{p_i^2}{2m_i}+\sum_{i<j}V_{ij}(\mathbf{r})\right)|\Psi_{JM}\rangle = E|\Psi_{JM}\rangle$$

the wave function $\Psi_{JM}(\boldsymbol{\rho},\boldsymbol{\lambda})$ is expanded as

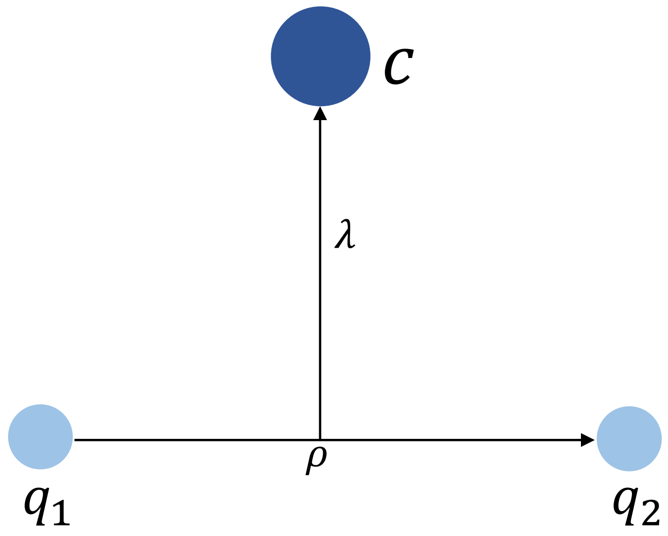
$$\Psi_{JM}(\boldsymbol{\rho},\boldsymbol{\lambda}) = \sum_{n_\rho,n_\lambda} C_{n_\rho n_\lambda}\phi^{\text{color}}\phi^{\text{flavor}}$$

$$\times [[[s_{q_1}s_{q_2}]_{s_\ell}[\phi_{n_\rho l_\rho}(\boldsymbol{\rho})\phi_{n_\lambda l_\lambda}(\boldsymbol{\lambda})]_L]_{j_\ell}]_{JM}$$

$C_{n_\rho n_\lambda}$ is calculated by Rayleigh-Ritz variational method:

$$\phi_{n_\rho l_\rho m_\rho}(\boldsymbol{\rho}) = N_{n_\rho l_\rho}\rho^{l_\rho}\mathrm{e}^{-\nu_{n_\rho}^{\rho}\rho^2}Y_{l_\rho m_\rho}(\hat{\boldsymbol{\rho}})$$

$$\phi_{n_\lambda l_\lambda m_\lambda}(\boldsymbol{\lambda}) = N_{n_\lambda l_\lambda}\lambda^{l_\lambda}\mathrm{e}^{-\nu_{n_\lambda}^{\lambda}\lambda^2}Y_{l_\lambda m_\lambda}(\hat{\boldsymbol{\lambda}})$$



Jacobi-coordinate of the singly charmed baryons.

Gaussian parameters:

$$\nu_{n_\rho} = \frac{1}{\rho_{n_\rho}^2},\ \rho_{n_\rho} = \rho_1 a^{n_\rho - 1}\ (n_\rho = 1 - n_{\max}^{\rho})$$

$$\nu_{n_\lambda} = \frac{1}{\lambda_{n_\lambda}^2},\ \lambda_{n_\lambda} = \lambda_1 b^{n_\lambda - 1}\ (n_\lambda = 1 - n_{\max}^{\lambda})$$

3. Spectroscopy and decays of singly charmed baryons

$1S$ states

$\bar{3}_f$	6_f	
$\Lambda_c(2286)$	$\Sigma_c(2455)$	$\Sigma_c^*(2520)$
$\Xi_c(2470)$	$\Xi_c'(2580)$	$\Xi_c^*(2460)$
	$\Omega_c(2695)$	$\Omega_c^*(2765)$

$1P$-$2S$ candinates

$\bar{3}_f$			6_f
$\|1P,\frac{1}{2}^-\rangle$	$\|1P,\frac{3}{2}^-\rangle$	$\|2S,\frac{1}{2}^+\rangle$	$1P\sim 2S$
$\Lambda_c(2595)$	$\Lambda_c(2625)$	$\Lambda_c(2765)$	$\Sigma_c(2800)$
$\Xi_c(2790)$	$\Xi_c(2815)$	$\Xi_c(2970)$	$\Xi_c(2880)$ $\Xi_c(2923)$ $\Xi_c(2939)$ $\Xi_c(2965)$
			$\Omega_c(3000)$ $\Omega_c(3050)$ $\Omega_c(3065)$ $\Omega_c(3090)$ $\Omega_c(3119)$ $\Omega_c(3188)$

D-wave candinates

$\Lambda_c(1D)$: $\Lambda_c(2860)$ $\Lambda_c(2880)$

$\Xi_c(1D)$: $\Xi_c(3055)$ $\Lambda_c(3080)$

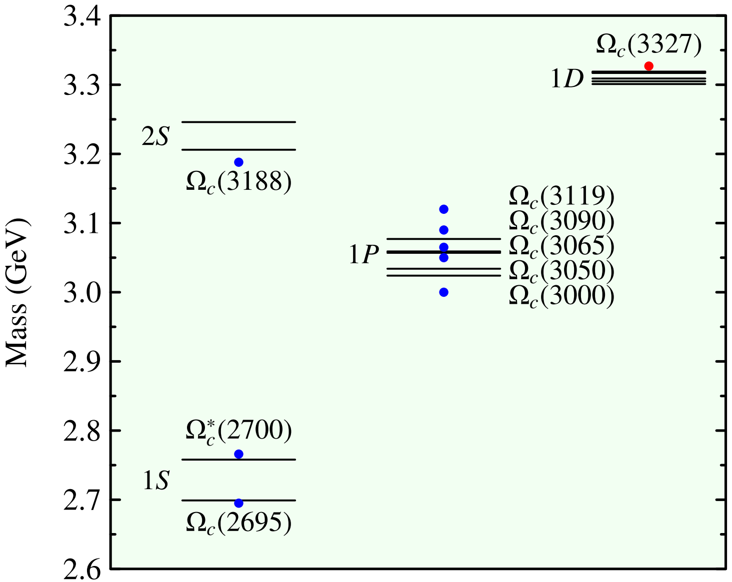
$\Omega_c(1D)$: $\Omega_c(3327)$

In 2023, the LHCb Collaboration [1] observed a new state $\Omega_c(3327)$ in $\Xi_c K$ channel, which mass and width are

$$M_{\Omega_c(3327)} = 3327.1 \pm 1.2^{+0.1}_{-1.3} \pm 0.2\,\text{MeV},$$
$$\Gamma_{\Omega_c(3327)} = 20 \pm 5^{+13}_{-1}\,\text{MeV}.$$

[1] [LHCb] Phys. Rev. Lett. 131, 131902 (2023)

Spescstroscopy:



Decay:

Decay channels	$\Omega_{c1}(1D,1/2^+)$	$\Omega_{c1}(1D,3/2^+)$	$\Omega_{c2}(1D,3/2^+)$	$\Omega_{c2}(1D,5/2^+)$	$\Omega_{c3}(1D,5/2^+)$	$\Omega_{c3}(1D,7/2^+)$
$\Xi_c(2470)\bar{K}$	2.7	2.7	×	×	13.4	13.4
$\Xi_c(2790)\bar{K}$	125.0	0.5	1.1	0.4	3.6	0.0
$\Xi_c(2815)\bar{K}$	0.0	114.1	0.0	0.1	0.0	0.3
$\Xi_c'(2580)\bar{K}$	3.9	0.9	8.7	2.6	3.0	1.7
$\Xi_c^*(2645)\bar{K}$	2.7	6.7	5.2	15.8	2.2	3.0
$\Omega_c(2695)\eta$	0.4	0.1	1.0	0.0	0.0	0.0
$\Omega_c(2765)\eta$	0.0	0.0	0.0	0.1	0.0	0.0
ΞD	244.9	15.3	137.8	31.3	2.2	80.6
ΞD^*	5.6	16.3	3.8	10.2	0.0	0.0
Total	385.2	156.6	157.6	60.5	24.4	99.0
Exp.					$20 \pm 5^{+13}_{-1}$ [1]	

$\Omega_c(3327)$ is a good D-wave Ω_c candidate

Predictions of $1F$ singly charmed baryons

Present

✓ Complete $1S$ states

✓ Many $1P$-$2S$ candinates

✓ Several $1D$、$2P$ candinates

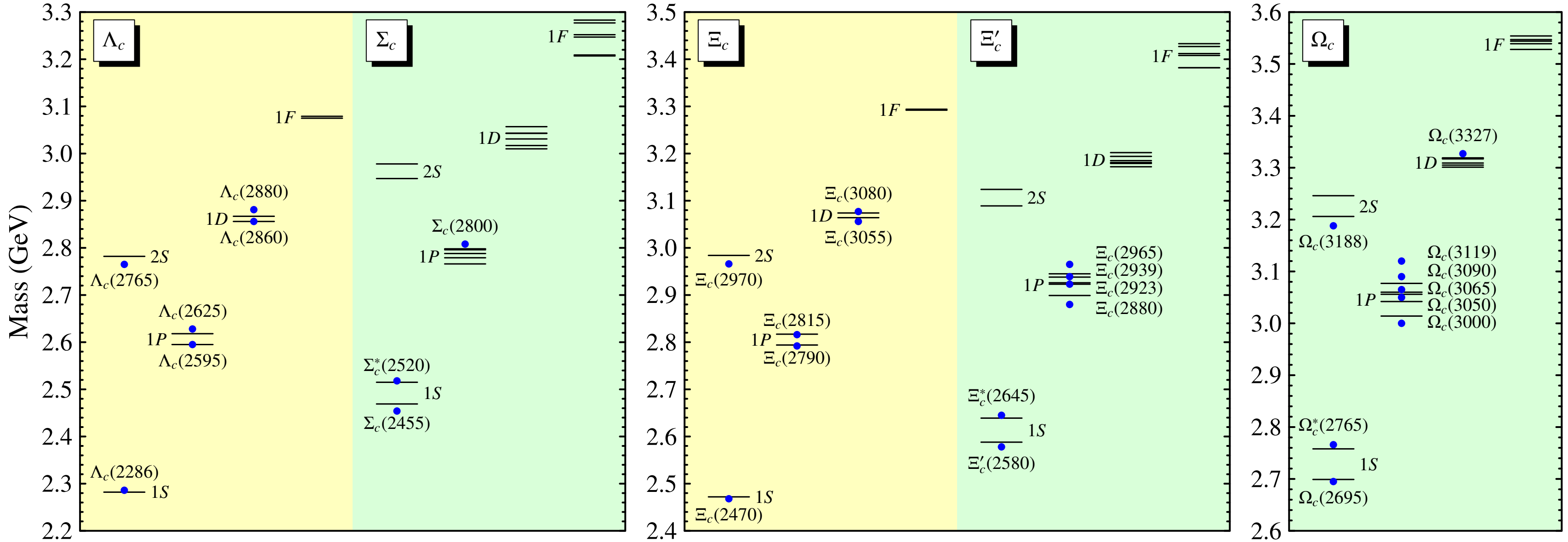
？There are no $1F$ candidates

- The methods have been tested in $1S$, $1P$, $1D$, and $2S$.
- $1F$ is higher wave, our model is not tested in $1F$.

Spectroscopy:

Symmetry	States	J	s_ℓ	l_ρ	l_λ	L	j_ℓ
$\bar{3}_f$	$\Lambda_c/\Xi_c(nF, 5/2^-)$	$\frac{5}{2}$	0	0	3	3	3
	$\Lambda_c/\Xi_c(nF, 7/2^-)$	$\frac{7}{2}$	0	0	3	3	3
6_f	$\Sigma_{c2}/\Xi'_{c2}/\Omega_{c2}(nF, 3/2^-)$	$\frac{3}{2}$	1	0	3	3	2
	$\Sigma_{c2}/\Xi'_{c2}/\Omega_{c2}(nF, 5/2^-)$	$\frac{5}{2}$	1	0	3	3	2
	$\Sigma_{c3}/\Xi'_{c3}/\Omega_{c3}(nF, 5/2^-)$	$\frac{5}{2}$	1	0	3	3	3
	$\Sigma_{c3}/\Xi'_{c3}/\Omega_{c3}(nF, 7/2^-)$	$\frac{7}{2}$	1	0	3	3	3
	$\Sigma_{c4}/\Xi'_{c4}/\Omega_{c4}(nF, 7/2^-)$	$\frac{7}{2}$	1	0	3	3	4
	$\Sigma_{c4}/\Xi'_{c4}/\Omega_{c4}(nF, 9/2^-)$	$\frac{9}{2}$	1	0	3	3	4

System	α_s	b (GeV^2)	σ (GeV)	C (GeV)
Λ_c/Σ_c	0.560	0.122	1.600	−0.633
$\Xi_c^{(\prime)}$	0.560	0.140	1.600	−0.693
Ω_c	0.578	0.144	1.732	−0.688
meson	0.578	0.144	1.028	−0.685
$m_{u/d} = 0.370$ GeV $m_s = 0.600$ GeV $m_c = 1.880$ GeV				



Decay:

$\bar{3}_f$:

Decay channels	M_f (MeV)	$\Lambda_c(1F,5/2^-)$	$\Lambda_c(1F,7/2^-)$
$\Sigma_c(1S,3/2^+)\pi$	2520	0.5	0.8
$\Sigma_{c2}(1P,3/2^-)\pi$	2779	9.5	0.2
$\Sigma_{c2}(1P,5/2^-)\pi$	2796	0.8	9.5
ND		9.9	11.8
ND^*		21.6	40.2
$\cdots$		1.0	0.8
Total		43.3	63.3

Br $[\Lambda_c(1F,5/2^-) \to ND^*] \approx$49.9%,
Br $[\Lambda_c(1F,7/2^-) \to ND^*] \approx$63.5%.

Decay channels	M_f (MeV)	$\Xi_c(1F,5/2^-)$	$\Xi_c(1F,7/2^-)$
$\Xi'_{c2}(1P,3/2^-)\pi$	2926	1.5	0.1
$\Xi'_{c2}(1P,5/2^-)\pi$	2945	0.2	1.6
$\Sigma_c(1S,1/2^+)\bar{K}$	2455	0.7	0.7
$\Sigma_c(1S,3/2^+)\bar{K}$	2520	1.2	1.7
$\Sigma_{c2}(1P,3/2^-)\bar{K}$	2779	4.4	0.0
$\Sigma_{c2}(1P,5/2^-)\bar{K}$	2796	0.0	0.6
ΛD		0.5	2.1
ΣD		10.0	22.9
ΛD^*		4.0	5.2
ΣD^*		28.3	54.3
$\cdots$		0.9	0.9
Total		51.7	90.1

Br $[\Xi_c(1F,5/2^-) \to \Sigma D^*] \approx$54.7%,
Br $[\Xi_c(1F,7/2^-) \to \Sigma D^*] \approx$60.2%.

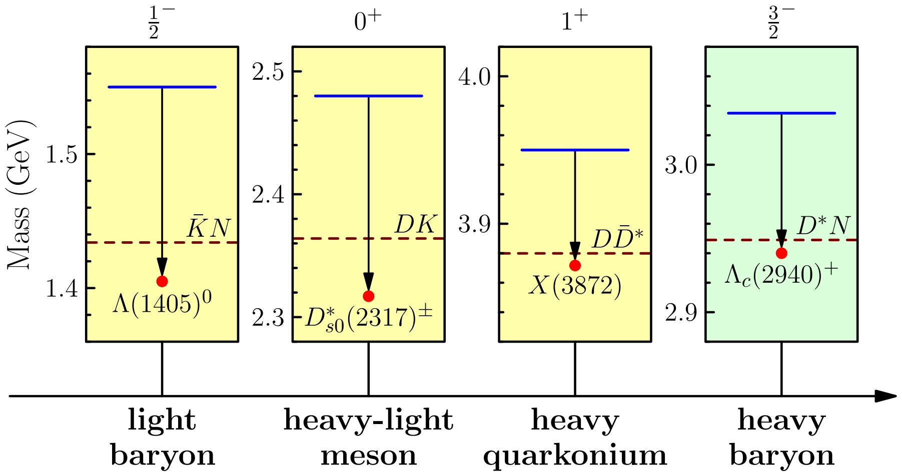
6_f:

Some typical decay channels in theoretical calculations

	$\Sigma_c(1F)$	$\Xi'_c(1F)$	$\Omega_c(1F)$
Singly charmed baryon	$\Sigma_c(1P)\pi$	$\Sigma_c(1P)\bar{K}$	Small predicted branching ratios
+ light flavor meson	$\Sigma_c(1D)\pi$	$\Lambda_c(1P)\bar{K}$	
	$\Lambda_c\pi\pi$	$\Lambda_c\bar{K}\pi$	
	$\dots$	$\dots$	
Light flavor baryon	ΔD	$\Sigma^* D$	Br $[\Omega_{c2}(1F, 3/2^-) \to \Xi^* D] \approx 30.8\%$
+ Singly charmed meson			Br $[\Omega_{c2}(1F, 3/2^-) \to \Xi D^*] \approx 42.2\%$
	$\dots$	$\dots$	$\dots$

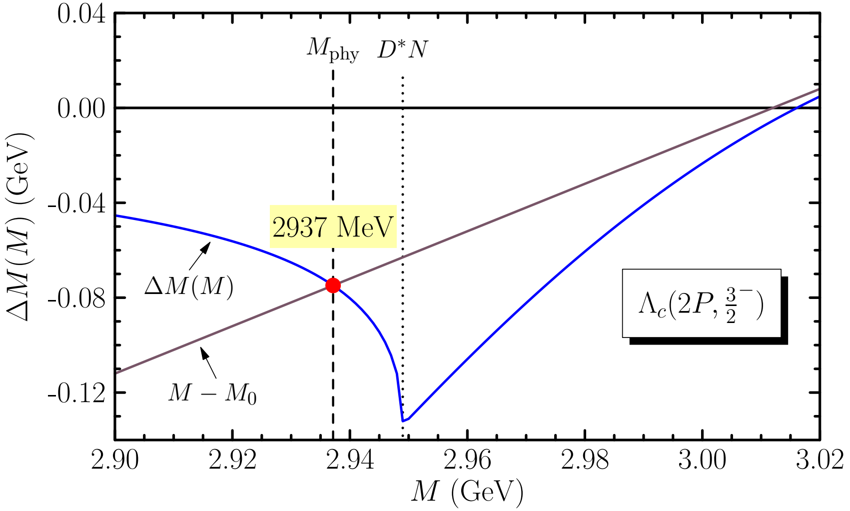
Coupled-channel effects

Low mass puzzle of $\Lambda_c(2940)$



1. Most hadrons could be well interpreted in conventional quark model.
2. Masses of $\Lambda(1405)$, $D^*_{s0}(2317)$, $X(3872)$, etc. are about 100 MeV less than the quark model predictions.
3. $\Lambda_c(2940)$ is the first charmed baryon which has abnormal mass.

Numerical results

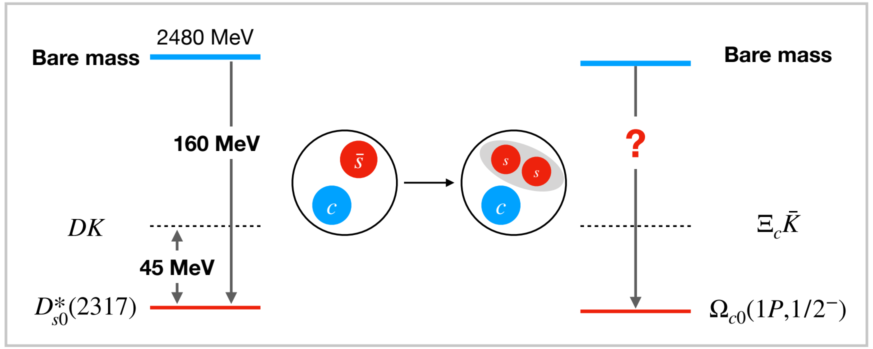


✓ In the framework of coupled channel, the mass $\Lambda_c(2940)$ could be well interpreted.

✓ In Ref. [1], the authors introduce hadron-hadron interaction in the loop and obtained lower masses then this work.

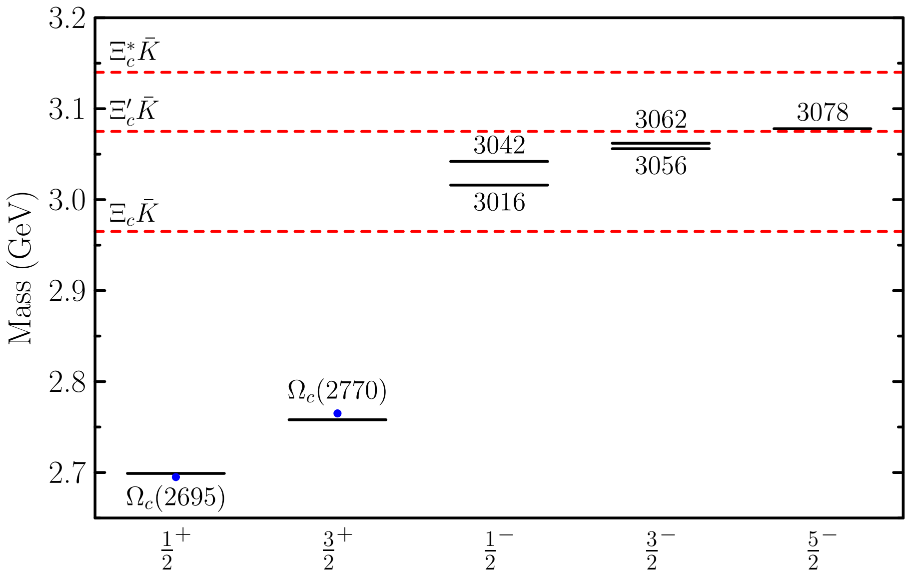
[1] Z. L. Zhang, Z. W. Liu, S. Q. Luo, F. L. Wang, B. Wang and H. Xu, Phys. Rev. D 107, 034036 (2023)

Hadron loop in Ω_c



- There exist significant coupled channel effect in $D^*_{s0}(2317)$.

- We replace $\bar{s}$ with ss, then how coupled channel effect affect Ω_c.



- The physical mass of $\Omega^d_{c0}(1P, 1/2^-)$ are predicted as 2945 MeV, which mass shift is about 97 MeV.

- We suggest search for $\Omega^d_{c0}(1P, 1/2^-)$ in Belle II, LHCb, and so on.

Radiative decays

Observed radiative decays of singly charmed baryons

Processes	Status
$\Xi_c'^+ \to \Xi_c^+\gamma$	✓
$\Xi_c'^0 \to \Xi_c^0\gamma$	✓
$\Omega_c^{*0} \to \Omega_c^0\gamma$	✓
$\Xi_c^0(2790) \to \Xi_c^0\gamma$	✓
$\Xi_c^0(2815) \to \Xi_c^0\gamma$	✓
$\Xi_c^+(2790) \to \Xi_c^+\gamma$	Upper limits
$\Xi_c^+(2815) \to \Xi_c^+\gamma$	Upper limits

$\bar{3}_f$:

Process	Our	Ref. [1]	Ref. [2]	Process	Our	Ref. [1]	Ref. [2]	Expt. [3]
$\Lambda_c^+(1P,\frac{1}{2}^-)\to\Lambda_c^+(1S,\frac{1}{2}^+)\gamma$	0.1	0.26	0.1	$\Xi_c^0(1P,\frac{1}{2}^-)\to\Xi_c^0(1S,\frac{1}{2}^+)\gamma$	217.5	263	202.5	800 ± 320
$\Lambda_c^+(1P,\frac{1}{2}^-)\to\Sigma_c^+(1S,\frac{1}{2}^+)\gamma$	0.3	0.45	1.0	$\Xi_c^0(1P,\frac{1}{2}^-)\to\Xi_c^{\prime 0}(1S,\frac{1}{2}^+)\gamma$	0.0	0.0	0.0	$\cdots$
$\Lambda_c^+(1P,\frac{1}{2}^-)\to\Sigma_c^{*+}(1S,\frac{3}{2}^+)\gamma$	0.0	0.05	0.0	$\Xi_c^0(1P,\frac{1}{2}^-)\to\Xi_c^{*0}(1S,\frac{3}{2}^+)\gamma$	0.0	0.0	0.0	$\cdots$
$\Lambda_c^+(1P,\frac{3}{2}^-)\to\Lambda_c^+(1S,\frac{1}{2}^+)\gamma$	0.8	0.30	0.7	$\Xi_c^0(1P,\frac{3}{2}^-)\to\Xi_c^0(1S,\frac{1}{2}^+)\gamma$	243.1	292	292.6	$320\pm 45^{+45}_{-80}$
$\Lambda_c^+(1P,\frac{3}{2}^-)\to\Sigma_c^+(1S,\frac{1}{2}^+)\gamma$	0.9	1.17	2.5	$\Xi_c^0(1P,\frac{3}{2}^-)\to\Xi_c^{\prime 0}(1S,\frac{1}{2}^+)\gamma$	0.0	0.0	0.1	$\cdots$
$\Lambda_c^+(1P,\frac{3}{2}^-)\to\Sigma_c^{*+}(1S,\frac{3}{2}^+)\gamma$	0.2	0.26	0.2	$\Xi_c^0(1P,\frac{3}{2}^-)\to\Xi_c^{*0}(1S,\frac{3}{2}^+)\gamma$	0.0	0.0	0.0	$\cdots$
				$\Xi_c^+(1P,\frac{1}{2}^-)\to\Xi_c^+(1S,\frac{1}{2}^+)\gamma$	1.7	4.65	7.4	<350
				$\Xi_c^+(1P,\frac{1}{2}^-)\to\Xi_c^{\prime +}(1S,\frac{1}{2}^+)\gamma$	1.2	1.43	1.3	$\cdots$
				$\Xi_c^+(1P,\frac{1}{2}^-)\to\Xi_c^{*+}(1S,\frac{3}{2}^+)\gamma$	0.5	0.44	0.1	$\cdots$
				$\Xi_c^+(1P,\frac{3}{2}^-)\to\Xi_c^+(1S,\frac{1}{2}^+)\gamma$	1.0	2.8	4.8	<80
				$\Xi_c^+(1P,\frac{3}{2}^-)\to\Xi_c^{\prime +}(1S,\frac{1}{2}^+)\gamma$	2.1	2.32	2.9	$\cdots$
				$\Xi_c^+(1P,\frac{3}{2}^-)\to\Xi_c^{*+}(1S,\frac{3}{2}^+)\gamma$	1.2	0.99	0.3	$\cdots$

[1] K. L. Wang, Y. X. Yao, X. H. Zhong, and Q. Zhao, Phys. Rev. D 96, 116016 (2017).

[2] E. Ortiz-Pacheco and R. Bijker, Phys. Rev. D 108, 054014 (2023).

[3] [Belle Collaboration] Phys. Rev. D 102, 071103 (2020).

6_f:

Process	Our	Ref. [1]	Ref. [2]	Ref. [3]	Process	Our	Ref. [1]	Ref. [2]	Ref. [3]
$\Sigma_c^{*0}(1S,\frac{3}{2}^+) \to \Sigma_c^0(1S,\frac{1}{2}^+)\,\gamma$	1.3	3.43	1.8	1.378	$\Xi_c'^0(1S,\frac{1}{2}^+) \to \Xi_c^0(1S,\frac{1}{2}^+)\gamma$	0.3	0.0	0.4	0.342
$\Sigma_c^{+}(1S,\frac{1}{2}^+) \to \Lambda_c^+(1S,\frac{1}{2}^+)\,\gamma$	59.2	80.6	87.2	93.5	$\Xi_c^{*0}(1S,\frac{3}{2}^+) \to \Xi_c^0(1S,\frac{1}{2}^+)\gamma$	1.1	0.0	1.6	1.322
$\Sigma_c^{*+}(1S,\frac{3}{2}^+) \to \Lambda_c^+(1S,\frac{1}{2}^+)\,\gamma$	132.8	373	199.4	231	$\Xi_c^{*0}(1S,\frac{3}{2}^+) \to \Xi_c'^0(1S,\frac{1}{2}^+)\gamma$	1.0	3.03	1.4	1.262
$\Sigma_c^{*+}(1S,\frac{3}{2}^+) \to \Sigma_c^+(1S,\frac{1}{2}^+)\,\gamma$	0.0	0.004	0.0	0.00067	$\Xi_c'^+(1S,\frac{1}{2}^+) \to \Xi_c^+(1S,\frac{1}{2}^+)\gamma$	14.9	42.3	20.6	21.38
$\Sigma_c^{*++}(1S,\frac{3}{2}^+) \to \Sigma_c^{++}(1S,\frac{1}{2}^+)\gamma$	1.7	3.94	2.1	1.483	$\Xi_c^{*+}(1S,\frac{3}{2}^+) \to \Xi_c^+(1S,\frac{1}{2}^+)\gamma$	52.7	139	74.2	81.9
					$\Xi_c^{*+}(1S,\frac{3}{2}^+) \to \Xi_c'^+(1S,\frac{1}{2}^+)\gamma$	0.1	0.004	0.1	0.029
					$\Omega_c^{*0}(1S,\frac{3}{2}^+) \to \Omega_c^0(1S,\frac{1}{2}^+)\gamma$	0.9	0.89	1.0	1.14

[1] K. L. Wang, Y. X. Yao, X. H. Zhong, and Q. Zhao, Phys. Rev. D 96, 116016 (2017).

[2] E. Ortiz-Pacheco and R. Bijker, Phys. Rev. D 108, 054014 (2023).

[3] A. Hazra, S. Rakshit, and R. Dhir, Phys. Rev. D 104, 053002 (2021).

Symmetry

1. Hadrons with different numbers of strange quarks have similar excited energies

$nL(J^P)$	States	Masses	Gaps
$1S(1/2^+)$	$\Lambda_c(2286)^+/\Xi_c(2470)^+$	2286.5/2467.9	181.4
$1P(1/2^-)$	$\Lambda_c(2595)^+/\Xi_c(2790)^+$	2592.3/2792.4	200.1
$1P(3/2^-)$	$\Lambda_c(2625)^+/\Xi_c(2815)^+$	2628.1/2816.7	188.6
$2S(1/2^+)$	$\Lambda_c(2765)^+/\Xi_c(2970)^+$	2766.6/2966.3	199.7
$1D(3/2^+)$	$\Lambda_c(2860)^+/\Xi_c(3055)^+$	2856.1/3055.9	199.8
$1D(5/2^+)$	$\Lambda_c(2880)^+/\Xi_c(3080)^+$	2881.6/3077.2	195.6

$$m_{\Xi_c} - m_{\Lambda_c} \approx \text{const}$$

$nL(J^P)$	States	Gaps
$1S(1/2^+)$	$\Sigma_c(2455)^{++}/\Xi_c'(2570)^+/\Omega_c(2695)^0$	124.4/116.8
	$\Sigma_b(5815)^+/\Xi_b'(5935)^-/\Omega_b(6046)^-$	124.4/111.1
$1S(3/2^+)$	$\Sigma_c^*(2520)^{++}/\Xi_c^*(2645)^+/\Omega_c(2765)^0$	127.2/120.3
	$\Sigma_b^*(5835)^+/\Xi_b^*(5955)^-/\Omega_b^-(\cdots)$	125.0/ $\cdots$
$1P(\frac{3}{2}^- \text{ or } \frac{5}{2}^-)$	$\Sigma_c(2800)^{++}/\Xi_c'(2939)^0/\Omega_c(3065)^0$	137.6/127.0
	$\Sigma_b(6097)^-/\Xi_b'(6227)^-/\Omega_b(6350)^-$	128.9/123.0

$$m_{\Omega_c} - m_{\Xi_c'} \approx m_{\Xi_c'} - m_{\Sigma_c}$$

2. Λ_Q and Ξ_Q have similar mass splits with orbital excited doublet

Λ_Q	Mass splits	Ξ_Q	Mass splits
$\Lambda_c(2595)^+/\Lambda_c(2625)^+$	35.8	$\Xi_c(2790)^+/\Xi_c(2815)^+$	24.3
$\Lambda_c(2860)^+/\Lambda_c(2880)^+$	25.5	$\Xi_c(3055)^+/\Xi_c(3080)^+$	21.3

3. ρ- and λ-mode excited singly charmed baryons have different behaviour

λ-mode excited $\Lambda_c/\Sigma_c/\Xi_c^{(\prime)}$

$\Lambda_c(2286)$	$\Lambda_c(2765)$	$\Lambda_c(2595)$	$\Lambda_c(2625)$	$\Lambda_c(2860)$	$\Lambda_c(2880)$
2286.5	2766.6	2592.3	2628.1	2856.1	2881.6
2286	2788	2595	2620	2858	2871
$\Xi_c(2468)$	$\Xi_c(2970)$	$\Xi_c(2790)$	$\Xi_c(2815)$	$\Xi_c(3055)$	$\Xi_c(3080)$
2467.9	2966.3	2792.4	2816.7	3055.9	3077.2
2466	2985	2786	2811	3060	3071
$\Sigma_c(2455)$	$\Sigma_c(2520)$	$\Sigma_c(2800)$			
2454.0	2518.4	2801.0			
2463	2511	2791			
$\Xi_c'(2580)$	$\Xi_c'(2645)$	$\Xi_c'(2923)$	$\Xi_c'(2939)$	$\Xi_c'(2965)$	
2578.4	2645.6	2923.0	2938.6	2964.9	
2595	2648	2928	2949	2934	

ρ-mode excited $\Lambda_c/\Sigma_c/\Xi_c^{(\prime)}$

	$\|1/2^-\rangle_L$	$\|1/2^-\rangle_H$	$\|3/2^-\rangle_L$	$\|3/2^-\rangle_H$	$\|5/2^-\rangle$
$\Lambda_c^\rho(1P)$	2862	2868	2834	2891	2863
$\Xi_c^\rho(1P)$	3010	3016	2988	3048	3021
ΔM	148	148	154	157	158
	$\|1/2^-\rangle$	$\|3/2^-\rangle$			
$\Sigma_c^\rho(1P)$	2854	2874			
$\Xi_c^{\prime\rho}(1P)$	3005	3027			
ΔM	151	153			

$$m_{u/d} = 310 \text{ MeV}, m_s = 450 \text{ MeV}, m_c = 1650 \text{ MeV}$$
$$m_{\Xi_c^\rho} - m_{\Lambda_c^\rho} \approx 150 \text{ MeV}$$
$$m_{\Xi_c^{\prime\rho}} - m_{\Sigma_c^{\prime\rho}} \approx 150 \text{ MeV}$$
$$m_s - m_{u/d} = 140 \text{ MeV}$$

Mass Gaps are related to both m_s-$m_{u/d}$ and contact term.

Mass Gaps are mainly related to m_s-$m_{u/d}$.

Summary

- Most observed singly charmed baryons are consistent with the theoretical calculations.
- Some abnormal spectra could be explained by hadron loop.
- We suggest study some states with radiative decays.
- Singly charmed baryons have high symmetry.

谢谢各位批评指正