

粲强子激发态的理论研究

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湖南 • 长沙

第三届 BESIII-Belle II-LHCb 粲强子物理联合研讨会

报告提纲

1. 研究背景
2. 模型方法
3. 谱学及衰变研究
4. 总结

研究背景

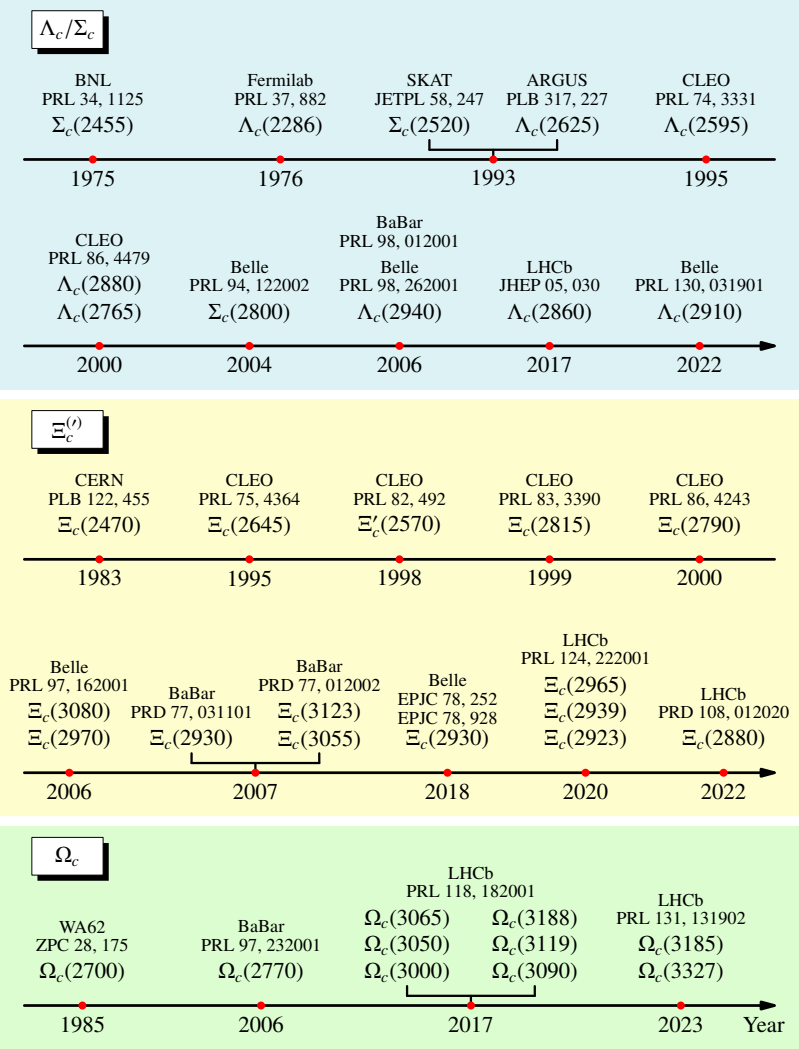
1. 单粲介子

D	$D_0^*(2300)$	$D_0(2550)$	$D_1^*(2600)$	$D(3000)$
D^*	$D_1(2430)$	$D^*(2640)$	$D_2(2740)$	
	$D_1(2420)$	$D_3^*(2750)$	$D_1^*(2760)$	
	$D_2(2460)$			

D_s	$D_{s0}^*(2317)$	$D_{s0}(2590)$	$D_{sJ}^*(3040)$
D_s^*	$D_{s1}(2460)$	$D_{s1}^*(2700)$	
	$D_{s1}(2536)$	$D_{s1}^*(2860)$	
	$D_{s2}(2573)$	$D_{s3}^*(2860)$	

[Particle Data Group] Phys. Rev. D 110, 030001 (2024) and 2025 update

2. 单粲重子



- 1. 在过去的大约 50 年里，超过 30 个单粲重子被实验发现；
- 2. 超过一半的数量是本世纪发现的。

3. 双粲重子

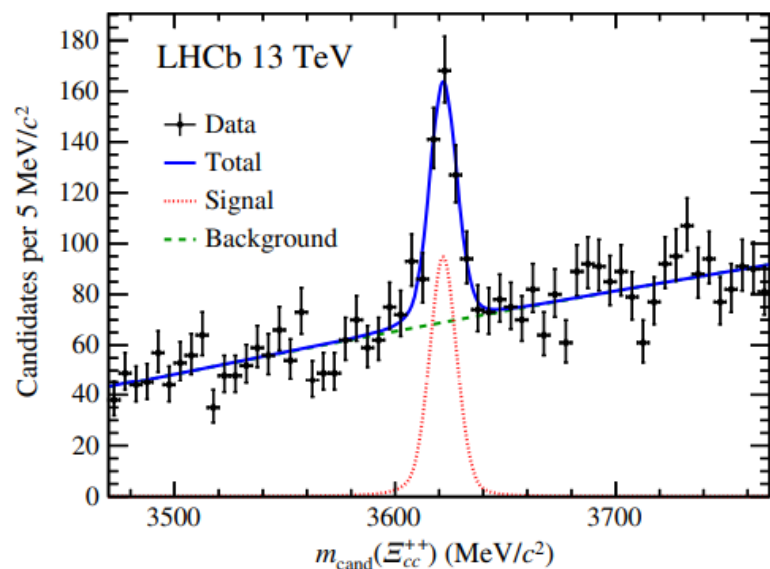


FIG. 3. Invariant mass distribution of $\Lambda_c^+ K^- \pi^+ \pi^+$ candidates with fit projections overlaid.

双粲重子首次由 LHCb 实验组于 2017 年在 $\Lambda_c^+ K^- \pi^+ \pi^+$ 上发现

[LHCb] Phys.Rev.Lett. 119, 112001 (2017)

4. 三粲重子

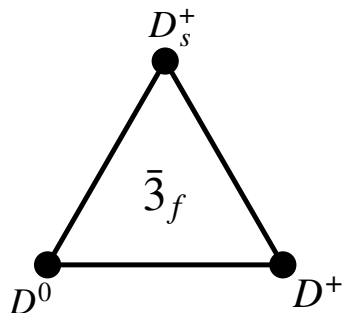
目前尚无三粲重子的候选态，研究主要集中在理论计算

模型方法

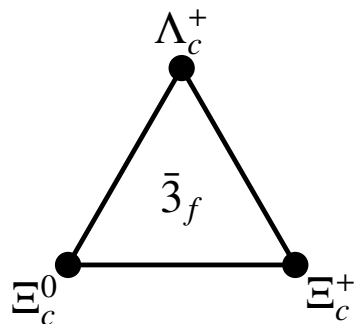
1. $SU(3)$ 对称性

$SU(3)$ 味道对称性下，单重味重子可以进行如下分解

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

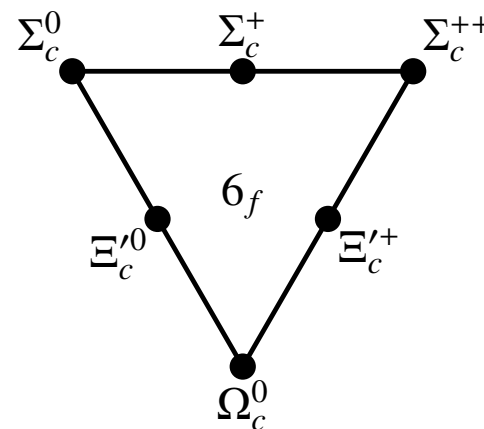


$$\begin{aligned} \phi_{D_s^+}^{\text{flavor}} &= \bar{s}c \\ \phi_D^{\text{flavor}} &= \begin{cases} \bar{u}c \\ \bar{d}c \end{cases} \end{aligned}$$



$$\begin{aligned} \phi_{\Lambda_c^+}^{\text{flavor}} &= \frac{1}{\sqrt{2}}(ud - du)c \\ \phi_{\Xi_c}^{\text{flavor}} &= \begin{cases} \frac{1}{\sqrt{2}}(us - su)c \\ \frac{1}{\sqrt{2}}(ds - sd)c \end{cases} \end{aligned}$$

$\oplus$



$$\begin{aligned} \phi_{\Sigma_c}^{\text{flavor}} &= \begin{cases} uuc \\ \frac{1}{\sqrt{2}}(ud + du)c \\ dd\bar{c} \end{cases} \\ \phi_{\Xi_c'}^{\text{flavor}} &= \begin{cases} \frac{1}{\sqrt{2}}(us + su)c \\ \frac{1}{\sqrt{2}}(ds + sd)c \end{cases}, \\ \phi_{\Omega_c}^{\text{flavor}} &= ssc. \end{aligned}$$

2. 两体构型

$$H = \sum_{i=1}^2 \frac{p_i^2}{2m_i} + \sum_{i<j} V_{ij}(\mathbf{r}) \quad i = \text{di}, Q \text{ (重子)} \quad i = q, Q \text{ (介子)}$$

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

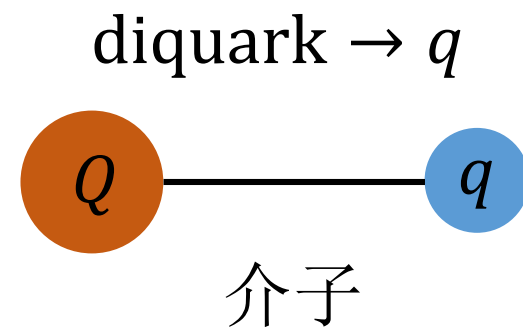
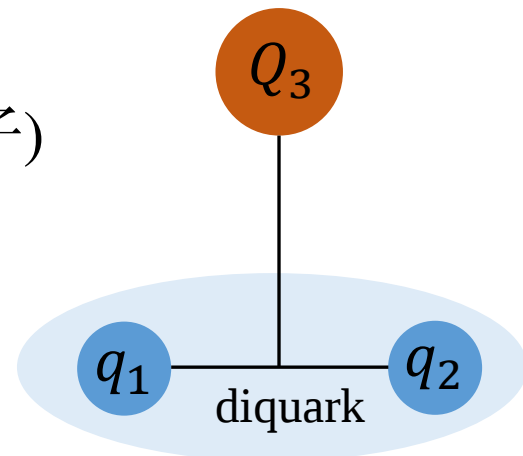
$$H_{ij}^{\text{conf}} = -\frac{4\alpha_s}{3r_{ij}} + br_{ij} + C$$

$$H_{ij}^{\text{hyp}} = \frac{4\alpha_s}{3m_i m_j} \left[\frac{8\pi}{3} \tilde{\delta}(r_{ij}) \mathbf{s}_i \cdot \mathbf{s}_j + \frac{1}{r_{ij}^3} S(\mathbf{r}, \mathbf{s}_i, \mathbf{s}_j) \right]$$

$$H_{ij}^{\text{so(cm)}} = \frac{4\alpha_s}{3r_{ij}^3} \left(\frac{1}{m_i} + \frac{1}{m_j} \right) \left(\frac{\mathbf{s}_i}{m_i} + \frac{\mathbf{s}_j}{m_j} \right) \cdot \mathbf{L}$$

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

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



3. 三体模型

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

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

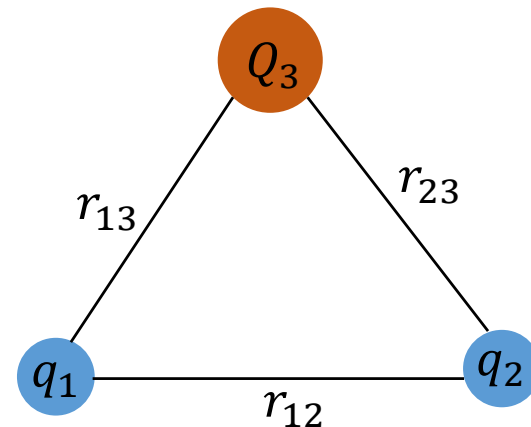
$$H_{ij}^{\text{conf}} = -\frac{2\alpha_s}{3r_{ij}} + \frac{b}{2}r_{ij} + \frac{1}{2}C$$

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

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

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

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



4. 强衰变（QPC）模型

QPC 模型的算符为：

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

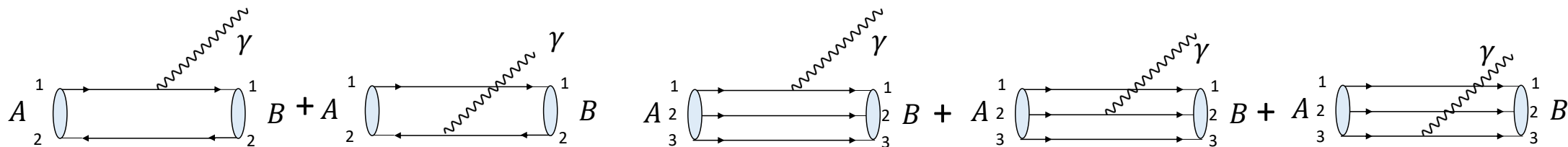
衰变的分波振幅可以写成

$$M_{A \rightarrow BC}^{J_{BC} L_{BC}}(p) = \langle BC, J_{BC}, L_{BC}, p | \hat{\mathcal{T}} | A \rangle,$$

J_{BC} 是末态 BC 相对自旋， L_{BC} 表示 BC 之间相对轨道角动量， p 是在 A 的质心系中， B 或 C 的动量大小。最终得到的宽度为：

$$\Gamma_{A \rightarrow BC}^{J_{BC} L_{BC}} = 2\pi \frac{E_B(p) E_C(p)}{M_A} p |M_{A \rightarrow BC}^{J_{BC} L_{BC}}(p)|^2$$

5. 辐射衰变



在树图阶下，夸克和光子耦合的 Hamiltonian 为

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

在非相对论近似下，夸克和光子耦合的 Hamiltonian 化简为

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

使用上述的 Hamiltonian，辐射衰变的的振幅可以表示为

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

这里 $|i\rangle$ 和 $|f\rangle$ 分别表示初态和末态的波函数， ω_γ 为末态的光子能量。该辐射衰变的宽度为：

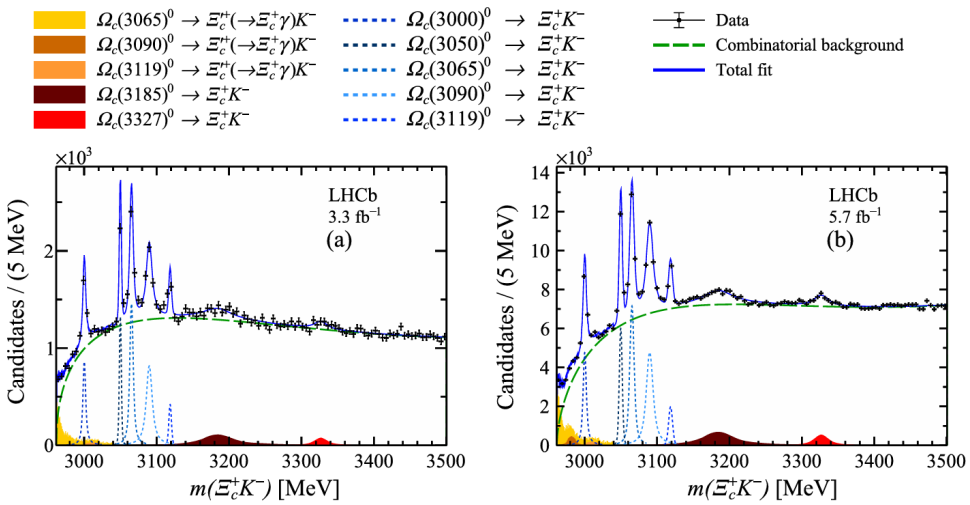
$$\Gamma = \frac{|\mathbf{k}|^2}{\pi} \frac{2}{2J_i + 1} \frac{M_f}{M_i} \sum_{J_{fz}, J_{iz}} |\mathcal{A}_{J_{fz}, J_{iz}}|^2.$$

谱学及衰变研究

1. 单粲重子的分类

$\bar{3}_f$			6_f	
$ 1S, 1/2^+\rangle$			$ 1S, 1/2^+\rangle$	$ 1S, 3/2^+\rangle$
$\Lambda_c(2286)$			$\Sigma_c(2455)$	$\Sigma_c^*(2520)$
$\Xi_c(2470)$			$\Xi'_c(2580)$	$\Xi_c^*(2460)$
			$\Omega_c(2695)$	$\Omega_c^*(2765)$
$ 1P, \frac{1}{2}^-\rangle$	$ 1P, \frac{3}{2}^-\rangle$	$ 2S, \frac{1}{2}^+\rangle$	$1P \sim 2S$	
$\Lambda_c(2595)$	$\Lambda_c(2625)$	$\Lambda_c(2765)$	$\Sigma_c(2800)$	
$\Xi_c(2790)$	$\Xi_c(2815)$	$\Xi_c(2970)$	$\Xi_c(2880) \ \Xi_c(2923) \ \Xi_c(2939) \ \Xi_c(2965)$	
			$\Omega_c(3000) \ \Omega_c(3050) \ \Omega_c(3065) \ \Omega_c(3090)$	
			$\Omega_c(3119) \ \Omega_c(3188)$	
$ 1D, \frac{3}{2}^+\rangle$	$ 1D, \frac{5}{2}^+\rangle$		$1D$	
$\Lambda_c(2860)$	$\Lambda_c(2880)$			
$\Xi_c(3055)$	$\Lambda_c(3080)$			
			$\Omega_c(3327)$	

2. $\Omega(3327)$ 的发现及理论解释

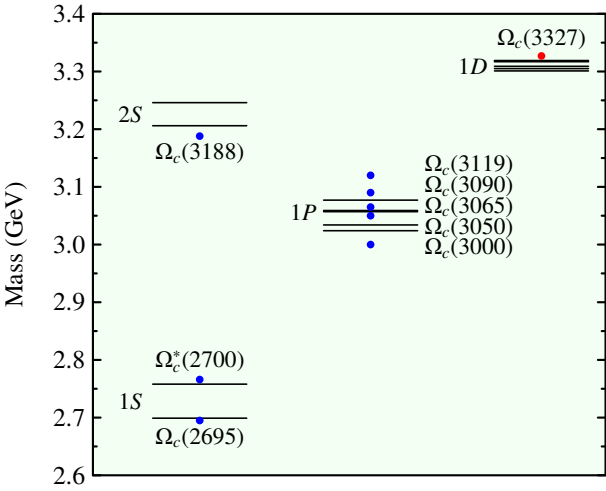


$$M_{\Omega_c(3327)} = 3327.1 \pm 1.2^{+0.1}_{-1.3} \pm 0.2 \text{ MeV},$$

$$\Gamma_{\Omega_c(3327)} = 20 \pm 5^{+13}_{-1} \text{ MeV}.$$

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

谱学:



衰变:

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]					

3. F 波单粲重子的理论研究

现状:

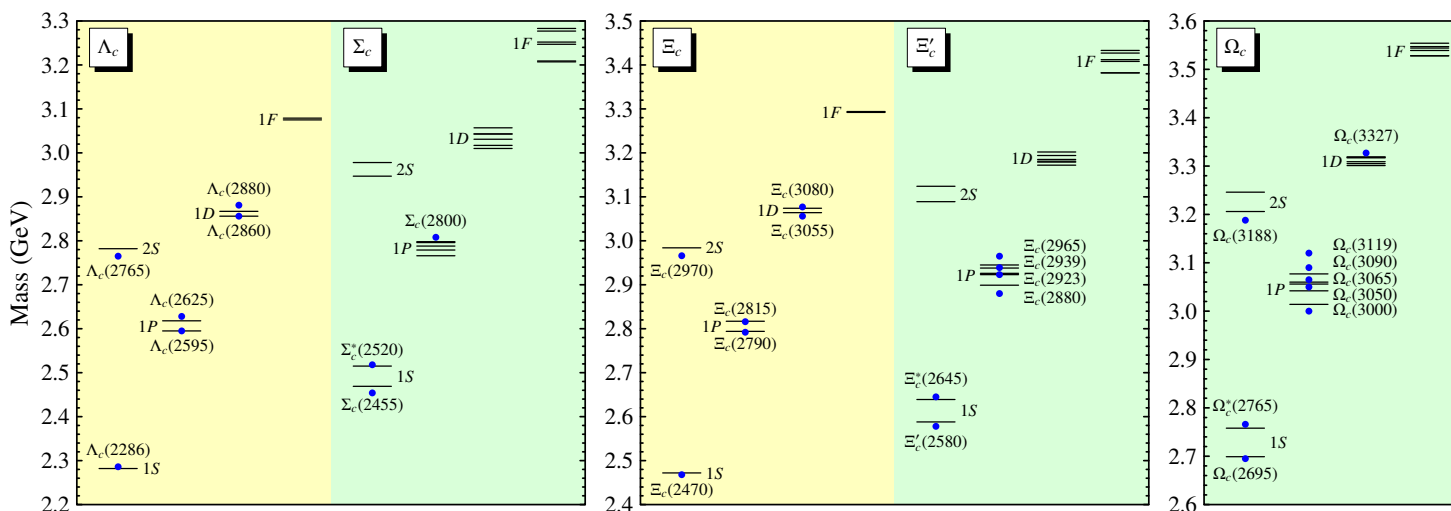
谱学:

✓ 完备的 $1S$ 态

✓ 大量的 $1P$ 、 $2S$ 候选态

✓ 若干 $1D$ 、 $2P$ 候选态

? 尚未发现 $1F$ 候选态



衰变:

$\bar{3}_f$:

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
...		1.0	0.8
Total		43.3	63.3

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
...		0.9	0.9
Total		51.7	90.1

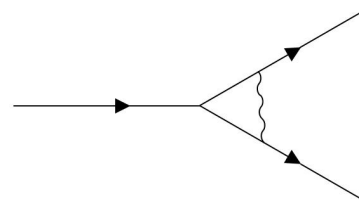
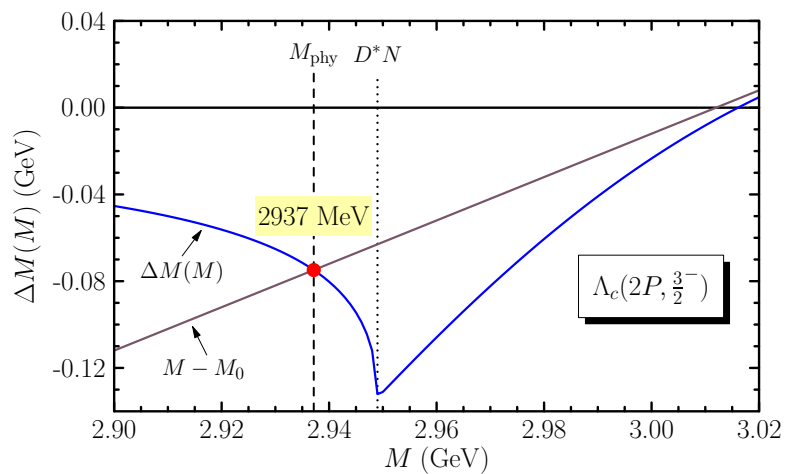
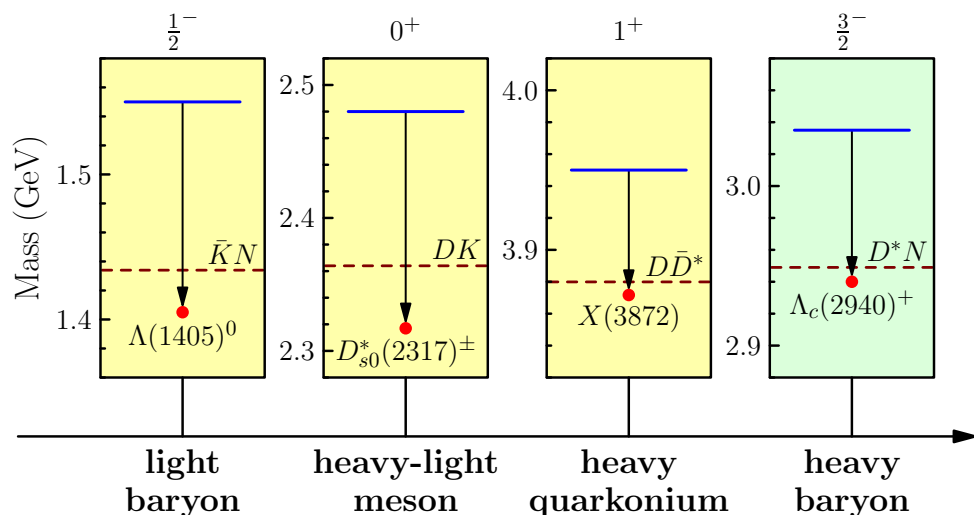
6_f :

	Mode I	Mode II
$\Sigma_c(1F)$	$\Sigma_c(1P)\pi$	ΔD
	$\Sigma_c(1D)\pi$	...
	$\Lambda_c\pi\pi$	
	...	
$\Xi'_c(1F)$	$\Sigma_c(1P)\bar{K}$	Σ^*D
	$\Sigma_c(1D)\bar{K}$	...
	$\Lambda_c\bar{K}\pi$	
	...	
$\Omega_c(1F)$	...	Ξ^*D
		ΞD^*

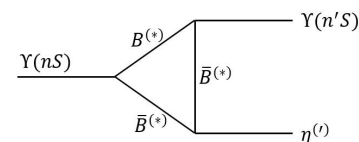
质量更高, 衰变更为复杂

4. 耦合道效应

$\Lambda_c(2940)$ 的低质量疑难



反常磁矩



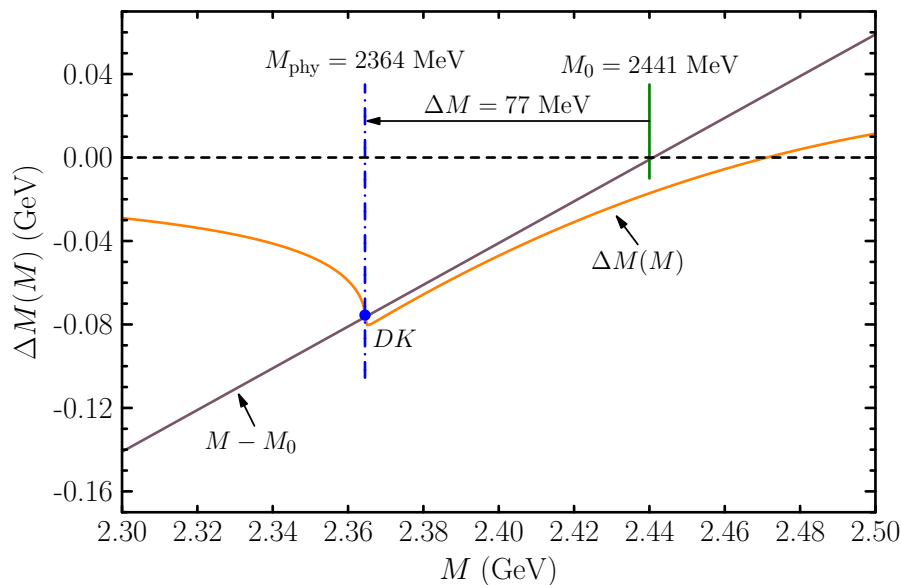
OZI 压低过程



质量修正

1. 在耦合道模型下， $\Lambda_c(2940)$ 的质量可以得到很好的解释；
 2. 文献 [1] 考虑了强子-强子间的相互作用，得到的质量更低。
- [1] Z. L. Zhang, Z. W. Liu, S. Q. Luo, F. L. Wang, B. Wang and H. Xu, Phys. Rev. D 107, 034036 (2023)

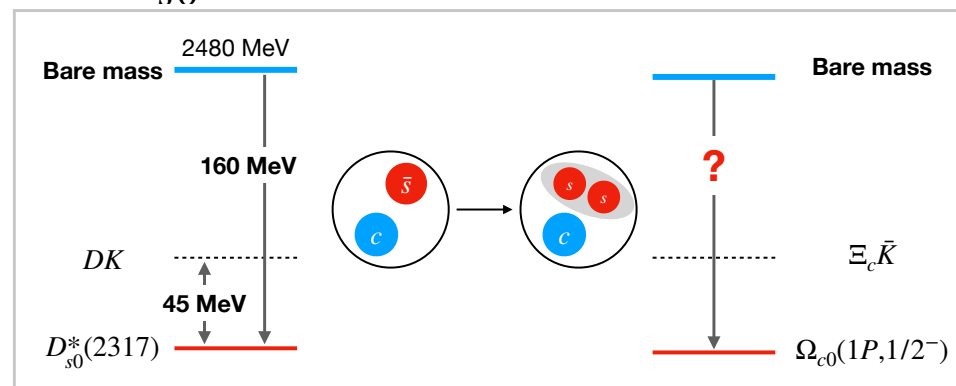
$\Omega_c(1P)$ 中的耦合道效应



$$\Delta M^0(M) = \text{Re} \int_0^\infty p^2 dp \frac{|\mathcal{M}_{\Omega_{c0} \rightarrow \Xi_c \bar{K}}(p)|^2}{M - \sqrt{M_{\Xi_c}^2 + p^2} - \sqrt{M_K^2 + p^2}},$$

$$\Delta M^1(M) = \text{Re} \int_0^\infty p^2 dp \frac{|\mathcal{M}_{\Omega_{c1} \rightarrow \Xi'_c \bar{K}}(p)|^2}{M - \sqrt{M_{\Xi'_c}^2 + p^2} - \sqrt{M_K^2 + p^2}}.$$

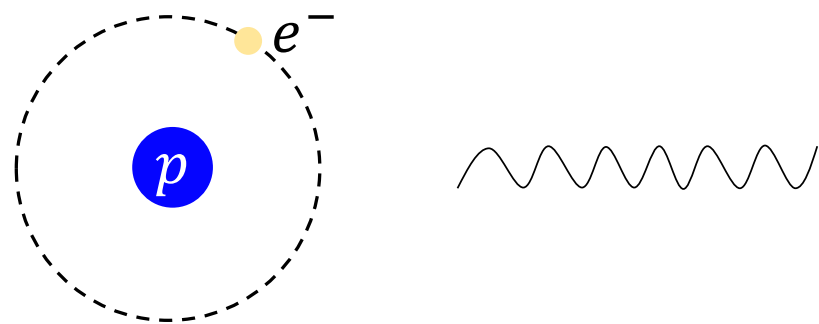
$$D_{s0}^*(2317) \rightarrow \Omega_{c0}(1P, 1/2^-)$$



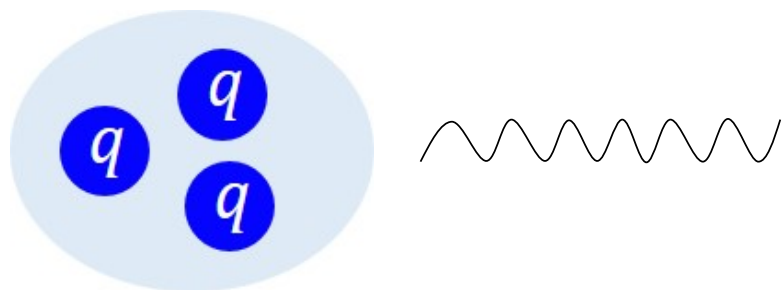
$$\begin{pmatrix} M^{j\ell=0} + \Delta M^0(M) & \tilde{V}^{\text{spin}} \\ \tilde{V}^{\text{spin}} & M^{j\ell=1} + \Delta M^1(M) \end{pmatrix} \begin{pmatrix} c_0 \\ c_1 \end{pmatrix} = M \begin{pmatrix} c_0 \\ c_1 \end{pmatrix},$$

$\Omega_{c0}^d(1P, 1/2^-)$ 的物理质量理论值为 2945 MeV，下降了大约 97 MeV。

5. 辐射衰变



辐射衰变 → 氢原子能级结构



辐射衰变 → 强子结构

实验上观察到的单粲重子的辐射衰变

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

$\bar{3}_f$:

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

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

6. 对称性

- 奇异数不同的系统质量劈裂近似相等

$nL(J^P)$	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
	$\Sigma_b^*(5835)^+/\Xi_b^*(5955)^-/\Omega_b^-(\dots)$	125.0/...
$1P(\frac{3}{2}^- \text{ or } \frac{5}{2}^-)$	$\Sigma_c(2800)^{++}/\Xi'_c(2939)^0/\Omega_c(3065)^0$	137.6/127.0
	$\Sigma_b(6097)^-/\Xi'_b(6227)^-/\Omega_b(6350)^-$	128.9/123.0

$$m_{\Omega_c} - m_{\Xi'_c} \approx m_{\Xi'_c} - m_{\Sigma_c}$$

- 同一轨道激发中， Λ_Q 和 Ξ_Q 拥有相似的自旋劈裂

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

- ρ 模和 λ 模谱学行为不同

λ 模激发的 $\Lambda_c/\Sigma_c/\Xi_c^{(\prime)}$

$\Lambda_c(2286)$	$\Lambda_c(2765)$	$\Lambda_c(2595)$	$\Lambda_c(2625)$	$\Lambda_c(2860)$	$\Lambda_c(2880)$
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 模激发 $\Lambda_c/\Sigma_c/\Xi_c^{(\prime)}$

	$ 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			
$\Xi'_c{}^\rho(1P)$	3005	3027			
ΔM	151	153			

$$m_{u/d} = 310 \text{ MeV}, m_s = 450 \text{ MeV}, m_c = 1650 \text{ MeV}$$

$$m_{\Xi_c^\rho} - m_{\Lambda_c^\rho} \approx 150 \text{ MeV}$$

$$m_{\Xi'_c{}^\rho} - m_{\Sigma_c{}^\rho} \approx 150 \text{ MeV}$$

$$m_s - m_{u/d} = 140 \text{ MeV}$$

质量劈裂与 $m_s - m_{u/d}$ 差值和接触项高度关联

质量与劈裂与 $m_s - m_{u/d}$ 差值高度关联

4. 总结

- 大部分的单粲重子在传统的夸克模型下可以得到很好的解释；
- 部分特殊的态（如 $D_{s0}^*(2317)$ 、 $\Lambda_c(2940)$ 、 $\Omega_c(1P)$ 等）可能存低质量疑难，可以借助强子的耦合道效应来研究；
- 部分单粲重子可以基于辐射衰变来寻找；
- 单粲重子的谱学存在较高的对称性。

谢谢各位批评指正