激发态单重味重子谱学和衰变的研究

报告人: 罗肆强

兰州大学

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广西●桂林

第八届强子谱和强子结构研讨会



- 1. 研究背景
- 2. 模型方法
- 3. 谱学及衰变研究
- 4. 总结



	Λ_c/Σ_c				
	BNL PRL 34, 1125	Fermilab PRL 37, 882	SKAT JETPL 58, 247	ARGUS PLB 317, 227	CLEO PRL 74, 3331
	$\Sigma_c(2455)$	$\Lambda_c(2286)$	$\Sigma_c(2520)$	$\Lambda_c(2625)$	$\Lambda_c(2595)$
	1975	1976	19	93	1995
	CLEO		BaBar PRL 98, 012001		
	PRL 86, 4479	Belle	Belle	LHCb	Belle
	$\Lambda_c(2880)$ $\Lambda_c(2765)$	PRL 94, 122002 Σ (2800)	PRL 98, 262001	JHEP 05, 030	PRL 130, 031901
	M _c (2703)	$\Delta_{c}(2000)$	$M_c(2)=0$	M _c (2000)	<i>N_c</i> (2)10)
	2000	2004	2006	2017	2022
	$\Xi_c^{(\prime)}$				
	CERN	CLEO	CLEO	CLEO	CLEO
	$\Xi_c(2470)$	$\Xi_c(2645)$	$\Xi'_{c}(2570)$	$\Xi_c(2815)$	$\Xi_c(2790)$
		•			
	1983	1995	1998	1999	2000
	Belle	BaBa	r	LHCb PRL 124, 22	2001
P	RL 97, 162001	$\begin{array}{c} \text{BaBar} \\ 77,021101 \\ 77,021101 \\ 77,021101 \\ 77,021101 \\ 77,021101 \\ 7,021100 \\ 7,021100 \\ 7,021100 \\ 7,021100 \\ 7,021100 \\ 7,021100 \\ 7,0200 \\ 7,0000 \\$	12002 Belle EPJC 78, 252	$\Xi_c(2965)$	5) LHCb
	$\Xi_c(3080)$ PRD $\Xi_c(2970)$ Ξ_c	$(2930) = \Xi_c(305)$	$\begin{array}{l} \text{EPJC 78, 928} \\ \text{55} \\ \Xi_c(2930) \end{array}$	$\Xi_c(293)$	
	2006	2007	2018	2020	2022
	Ω_c				
			LHCb PRL 118, 1	82001	LHCh
	WA62	BaBar	$\Omega_c(3065)$	$\Omega_c(3188)$	PRL 131, 131902
	ZPC 28, 175	PRL 97, 232001	$\Omega_c(3050)$	$\Omega_c(3119)$	$\Omega_c(3185)$
	S2 _c (2700)	$\Omega_{c}(2770)$	≤2 _c (3000)	<u>12_c(3090)</u>	$S_{c}(3327)$
	1985	2006	2017	1	2023 Year

$ \begin{array}{c} \Lambda_b / \Sigma_b \\ \hline CERN R415 \\ LNC 31, 97 \\ \Lambda_b (5620) \\ \hline 1981 \\ \end{array} $	$\begin{array}{c} \text{CDF} \\ \text{PRL 99, 202001} \\ \Sigma_b(5835) \\ \Sigma_b(5815) \\ \hline \\ 2007 \end{array}$	LHCb PRL 109, 172003 $\Lambda_b(5920)$ $\Lambda_b(5912)$	LHCb PRL 122, 012001 Σ _b (6097) 2018	LHCb PRL 123, 152001 $\Lambda_b(6152)$ $\Lambda_b(6146)$ 2019	CMS PLB 803, 135345 LHCb JHEP 06, 136 $\Lambda_b(6072)$
$\Xi_b^{(\prime)}$ DELPHI ZPC 68, 541 $\Xi_c(5795)$	CMS PF PRL 108, 252002	LHCb RL 114, 062004 LF $\Xi_b(5955)^-$ PRL 12.	HCb CMS 1, 072002 PRL 126, 2:	EHCb PRL 128, 1620 52003 $\Xi_b(6333)$	LHCb 01 PRL 131, 171901 $\Xi_b (6095)^0$ $\Xi (6097)^0$
1995	2012	2014 20	2021 2021	2022	2023
Ω_b				Wat	
] PRI 10	D0	EHCb PRL 124, 082002			
$\Omega_b($	6046)		$\Omega_b(6316)$	$\Omega_b(6340)$	
2	008		2	2020	Year

- 1. 在过去的大约 50 年里,超过 30 个单粲重子被实验发现;
- 2. 在过去的大约 40 年里,超过 20 个单底重子被实验发现;
- 3. 超过一半的数量是本世纪发现的。



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

$$\begin{aligned} V_{ij} &= H_{ij}^{\text{conf}} + H_{ij}^{\text{hyp}} + H_{ij}^{\text{so}(\text{cm})} + H_{ij}^{\text{so}(\text{tp})} \\ H_{ij}^{\text{conf}} &= -\frac{2\alpha_s}{3r_{ij}} + \frac{b}{2}r_{ij} + \frac{1}{2}C \\ H_{ij}^{\text{hyp}} &= \frac{2\alpha_s}{3m_i m_j} \left[\frac{8\pi}{3} \tilde{\delta}(r_{ij}) \mathbf{s}_i \cdot \mathbf{s}_j + \frac{1}{r_{ij}^3} S(\mathbf{r}, \mathbf{s}_i, \mathbf{s}_j) \right] \\ H_{ij}^{\text{so}(\text{cm})} &= \frac{2\alpha_s}{3r_{ij}^3} \left(\frac{\mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_j}{m_j^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_i - \mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_j}{m_i m_j} \right] \\ H_{ij}^{\text{so}(\text{tp})} &= -\frac{1}{2r_{ij}} \frac{\partial H_{ij}^{\text{conf}}}{\partial r_{ij}} \left(\frac{\mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_j}{m_j^2} \right). \\ \tilde{\delta}(r) &= \frac{\sigma^3}{\pi^{3/2}} e^{-\sigma^2 r^2} \quad S(\mathbf{r}, \mathbf{s}_i, \mathbf{s}_j) = \frac{3\mathbf{s}_i \cdot \mathbf{r}_{ij}\mathbf{s}_j \cdot \mathbf{r}_{ij}}{r_{ij}^2} - \mathbf{s}_i \cdot \mathbf{s}_j \end{aligned}$$



2. 求解三体薛定谔方程-高斯展开法

三体 Schrödinger 方程:

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

波函数 $\Psi_{JM}(\rho, \lambda)$ 的展开形式为

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

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

 $C_{n_{\rho}n_{\lambda}}$ 通过 Rayleigh-Ritz 变分法进行求解:

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

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



高斯参数: $\nu_{n_{\rho}} = \frac{1}{\rho_{n_{\rho}}^{2}}, \rho_{n_{\rho}} = \stackrel{雅可比坐标}{\rho_{1}a^{n_{\rho}}} (n_{\rho} = 1 - n_{\max}^{\rho})$ $\nu_{n_{\lambda}} = \frac{1}{\lambda_{n_{\lambda}}^{2}}, \lambda_{n_{\lambda}} = \lambda_{1}b^{n_{\lambda}-1} (n_{\lambda} = 1 - n_{\max}^{\lambda})$

3. QPC 模型-强衰变

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

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

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:

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

4. 辐射衰变



在树图阶下,夸克和光子耦合的 Hamiltonian 为

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

在非相对论近似下,夸克和光子耦合的 Hamiltonian 化简为

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

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* > 和 |*f* > 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:

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



1. 单重味重子的分类

单粲重子

	$\bar{3}_{f}$		6 _{<i>f</i>}
$ 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$	$1P \sim 2S$
$\Lambda_c(2595)$	$\Lambda_c(2625)$	$\Lambda_c(\bar{2765})$	$\Sigma_c(2800)$
$\Xi_c(2790)$	$\Xi_{c}(2815)$	$\Xi_c(2970)$	$\Xi_c(2880) \Xi_c(2923) \Xi_c(2939) \Xi_c(2965)$
			$\Omega_c(3000) \ \Omega_c(3050) \ \Omega_c(3065) \ \Omega_c(3090)$
			$\Omega_c(3119) \ \Omega_c(3188)$
$ 1D,\frac{3}{2}^+\rangle$	$ 1D,\frac{5}{2}^+\rangle$		1 <i>D</i>
$\Lambda_c(2\tilde{8}60)$	$\Lambda_c(2\bar{8}80)$		
$\Xi_c(3055)$	$\Lambda_c(3080)$		
			$\Omega_c(3327)$

—————————————————————————————————————						
	3_f		6_f			
$ 1S, 1/2^+\rangle$			$ 1S, 1/2^+\rangle$ $ 1S, 3/2^+\rangle$			
$\Lambda_b(5620)$			$\Sigma_b(5815)$ $\Sigma_b^*(5835)$			
$\Xi_b(5795)$			$\Xi_{h}^{\prime}(5935)$ $\Xi_{h}^{*}(5955)$			
			$\Omega_b(6046)$			
$ 1P,\frac{1}{2}\rangle$	$ 1P,\frac{3}{2}\rangle$	$ 2S,\frac{1}{2}^+\rangle$	$1P \sim 2S$			
$\overline{\Lambda_b(5912)}$	$\Lambda_b(\bar{5920})$	$\Lambda_b(\bar{6072})$	$\Sigma_b(6097)$			
$\Xi_b(6087)$	$\Xi_b(6095)$		$\Xi_b(6227)$			
			$\Omega_b(6316) \ \Omega_b(6340) \ \Omega_b(6330) \ \Omega_b(6350)$			
$ 1D,\frac{3}{2}^+\rangle$	$ 1D,\frac{5}{2}^+\rangle$		1 <i>D</i>			
$\overline{\Lambda_b(6146)}$	$\Lambda_b(\bar{6152})$					
$\Xi_c(6327)$	$\Xi_b(6333)$					

单底重子

2. D 波单重味重子的研究



 $\Omega_c(3327)$ 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)



衰变:

Decay channels	$\Omega_{c1}(1D,1/2^+)$	$\Omega_{c1}(1D,3/2^+)$	$\Omega_{c2}(1D,3/2^+)$	$\Omega_{c2}(1D,5/2^+)$	$\Omega_{c3}(1D,5/2^+)$	$\Omega_{c3}(1D,7/2^+)$
$\overline{\Xi_c(2470)\bar{K}}$	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
$\Xi_{c}^{\prime}(2580)\bar{K}$	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]	

 $\Lambda_b(1D)$ 和 $\Xi_b(1D)$ 的研究

	$\Lambda_b(0140)$ 相 $\Lambda_b(0152)$ 的理论	2.用作手
衰变道	$\Lambda_b(6146)(1D, \frac{3}{2}^+)$	$\Lambda_b(6152)(1D, \frac{5^+}{2})$
$\overline{\Sigma_b(5815) \pi}$	3.25^{p}	0.22^{f}
$\Sigma_{b}^{*}(5835) \pi$	$0.65^p, \ \ 0.28^f$	$4.03^p, 0.14^f$
总宽度	4.18	4.39
实验值[1]	$2.9 \pm 1.3 \pm 0.3$	$2.1 \pm 0.8 \pm 0.3$

Λ_b(6146) 和 Λ_b(6152) 的理论解释

[1] [LHCb] Phys. Rev. Lett. 123, 152001 (2019)

理论与实验一致

	至 。 宽度的理论计算	
衰变道	$\Xi_b(6327)(1D,\frac{3}{2}^+)$	$\Xi_b(6330)(1D, \frac{5^+}{2})$
$\Xi_{b}^{\prime}(5935) \pi$	0.39^{p}	0.09^{f}
$\Sigma_b(5815) \ \bar{K}$	1.73^{p}	0.00^{f}
$\Xi_{b}^{*}(5955) \pi$	$0.09^p, \ 0.15^f$	$0.51^p, \ 0.07^f$
$\Sigma_b^*(5835) \ \bar{K}$	$0.02^p, \ \ 0.00^f$	$0.09^p, \ 0.00^f$
总宽度	2.38	0.76

[2] [LHCb] Phys. Rev. Lett. 128, 162001 (2022) $m[\Xi_b(6327)^0] = 6327.28^{+0.23}_{-0.21}$ MeV, $m[\Xi_b(6333)^0] = 6332.69^{+0.17}_{-0.18}$ MeV, $\Gamma[\Xi_b(6327)^0] = 0.93^{+0.74}_{-0.60}$ MeV, $\Gamma[\Xi_b(6333)^0] = 0.25^{+0.58}_{-0.25}$ MeV,

理论被实验证实

3. F 波单重味重子的理论研究

谱学:

现状:

√较为完备的 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: 3_f:____

F 波单粲重子

 6_{f} :

Decay channels	M_f (MeV)	$\Lambda_c(1F, 5/2^-)$	$\Lambda_c(1F,7/2^-)$
$\overline{\Sigma_c(1S,3/2^+)\pi}$	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)	$\Xi_c(1F, 5/2^-)$	$\Xi_c(1F, 7/2^-)$
$\overline{\Xi_{c2}'(1P,3/2^{-})\pi}$	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

	Mode I	Mode II
	$\Sigma_c(1P)\pi$	ΔD
Σ (1 E)	$\Sigma_c(1D)\pi$	
$\Delta_c(1\Gamma)$	$\Lambda_c \pi \pi$	
	$\Sigma_c(1P)\bar{K}$	Σ^*D
$\nabla (1E)$	$\Sigma_c(1D)ar{K}$	
$\Xi_c(1\Gamma)$	$\Lambda_c ar{K} \pi$	
O(1E)		Ξ^*D
$\Sigma_{\mathcal{L}}^2(1\Gamma)$		ΞD^*

质量更高,衰变更为复杂

F 波单底重子 6_f:

$\bar{3}_f$:

 $\Lambda_b(1F,7/2^-)$ Decay channels M_f (MeV) $\Lambda_b(1F, 5/2^-)$ $\Sigma_b(1S, 1/2^+)\pi$ 5816 0.6 0.3 $\Sigma_b(1S, 3/2^+)\pi$ 5835 0.6 1.0 $\Sigma_{b2}(1P, 3/2^{-})\pi$ 6082 11.7 0.2 $\Sigma_{b2}(1P, 5/2^{-})\pi$ 6089 1.0 12.3 $N\bar{B}$ 5.9 24.9 $N\bar{B}^*$ 20.2 43.9 . . . 0.4 0.4 Total 59.4 64.0

Decay channels	M_f (MeV)	$\Xi_b(1F, 5/2^-)$	$\Xi_b(1F, 7/2^-)$
$\overline{\Xi_{b2}'(1P, 3/2^{-})\pi}$	6211	2.0	0.1
$\Xi_{b2}'(1P, 5/2^{-})\pi$	6220	0.2	2.2
$\Sigma_b(1S, 1/2^+)\bar{K}$	5816	1.4	0.5
$\Sigma_b(1S, 3/2^+)\bar{K}$	5835	1.1	2.2
$\Lambda ar{B}$		2.8	1.1
$\Sigma ar{B}$		27.0	1.9
$\Lambda ar{B}^*$		3.1	6.0
$\Sigma ar{B}^*$		1.1	5.4
		0.5	0.5
Total		39.2	19.9

	Mode I	Mode II
	$\Sigma_b(1P)\pi$	
$\Sigma_{\rm c}(1F)$	$\Sigma_b(1D)\pi$	
$\Delta_b(11^{\circ})$	$\Lambda_b \pi \pi$	
	$\Sigma_b(1P)ar{K}$	
$\Xi'(1F)$	$\Sigma_b(1D)ar{K}$	
$\underline{-}_{b}(1\Gamma)$	$\Lambda_b ar{K} \pi$	
O(1E)	•••	Ξ^*D
$\Sigma_b(1\Gamma)$		ΞD^*

质量更高,衰变更为复杂

5. 辐射衰变

·	实验上观察到的单粲重子的辐射衰变					
	Processes	Status				
	$\Xi_c^{\prime +} \to \Xi_c^+ \gamma$	\checkmark				
辐射衰变 → 氢原子能级结构	$\Xi_c^{\prime 0} o \Xi_c^0 \gamma$	\checkmark				
	$\Omega_c^{*0} o \Omega_c^0 \gamma$	\checkmark				
	$\Xi_c^0(2790) \to \Xi_c^0 \gamma$	\checkmark				
	$\Xi_c^0(2815) \to \Xi_c^0 \gamma$	\checkmark				
	$\Xi_c^+(2790) \rightarrow \Xi_c^+ \gamma$	Upper limits				
辐射衰变 → 强子结构	$\frac{\Xi_c^+(2815)\to \Xi_c^+\gamma}{}$	Upper limits				



Drogoss	Our	Ref.	Ref.	Drooos	Our	Ref.	Ref.	Expt.
FIOCESS	Our	[1]	[2]	PIOCESS	Oui	[1]	[2]	[3]
$\overline{\Lambda_c^+(1P, \frac{1}{2}^-) \to \Lambda_c^+(1S, \frac{1}{2}^+) \gamma}$	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
$\Lambda_c^+(1P, \frac{\overline{1}}{2}) \to \Sigma_c^+(1S, \frac{\overline{1}}{2}) \gamma$	0.3	0.45	1.0	$\Xi_c^0(1P, \overline{\underline{1}}^-) \to \Xi_c^{\prime 0}(1S, \overline{\underline{1}}^+) \gamma$	0.0	0.0	0.0	•••
$\Lambda_c^+(1P, \overline{\underline{1}}^-) \to \Sigma_c^{*+}(1S, \overline{\underline{3}}^+)\gamma$	0.0	0.05	0.0	$\Xi_c^0(1P, \overline{\frac{1}{2}}) \to \Xi_c^{*0}(1S, \overline{\frac{3}{2}}) \gamma$	0.0	0.0	0.0	•••
$\Lambda_c^+(1P, \frac{3}{2}) \to \Lambda_c^+(1S, \frac{1}{2}) \gamma$	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	• • •
$\Lambda_c^+(1P, \frac{3}{2}) \to \Sigma_c^{*+}(1S, \frac{3}{2}) \gamma$	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	•••
				$\Xi_c^+(1P, \frac{1}{2}) \rightarrow \Xi_c^+(1S, \frac{1}{2}) \gamma$	1.7	4.65	7.4	< 350
				$\Xi_c^+(1P, \frac{1}{2}) \to \Xi_c^{\prime+}(1S, \frac{1}{2}) \gamma$	1.2	1.43	1.3	•••
				$\Xi_c^+(1P, \frac{1}{2}) \to \Xi_c^{*+}(1S, \frac{3}{2}) \gamma$	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
				$\Xi_c^+(1P, \frac{3}{2}) \to \Xi_c^{\prime+}(1S, \frac{1}{2}) \gamma$	2.1	2.32	2.9	•••
				$\Xi_c^+(1P, \frac{3}{2}) \to \Xi_c^{*+}(1S, \frac{3}{2}) \gamma$	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).



Process	Our	Ref.	Ref.	Ref.	Process	Our	Ref.	Ref.	Ref.
		[1]	[2]	[3]			[1]	[2]	[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	$\Xi_c^{\prime 0}(1S, \frac{1}{2}^+) \longrightarrow \Xi_c^0(1S, \frac{1}{2}^+) \gamma$	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	$\Xi_c^{*0}(1S, \tfrac{3}{2}^+) \longrightarrow \Xi_c^0(1S, \tfrac{1}{2}^+) \gamma$	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	$\Xi_c^{*0}(1S, \frac{3}{2}^+) \longrightarrow \Xi_c^{\prime 0}(1S, \frac{1}{2}^+)\gamma$	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	$\Xi_c^{\prime+}(1S, \frac{1}{2}^+) \to \Xi_c^+(1S, \frac{1}{2}^+) \gamma$	14.9	42.3	20.6	21.38
$\Sigma_c^{*++}(1S, \frac{3}{2}^+) \rightarrow \Sigma_c^{++}(1S, \frac{1}{2}^+)\gamma$	1.7	3.94	2.1	1.483	$\Xi_c^{*+}(1S, \tfrac{3}{2}^+) \longrightarrow \Xi_c^+(1S, \tfrac{1}{2}^+) \gamma$	52.7	139	74.2	81.9
					$\Xi_c^{*+}(1S, \frac{3}{2}^+) \rightarrow \Xi_c^{\prime+}(1S, \frac{1}{2}^+)\gamma$	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).



Process	Our	Ref. [1]	Ref. [2]	Process	Our	Ref. [1]	Ref. [2]
$\overline{\Lambda_{b}^{0}(1P, \frac{1}{2})} \rightarrow \Lambda_{b}^{0}(1S, \frac{1}{2}) \gamma$	47.0	50.2	40.7	$\Xi_b^-(1P, \frac{1}{2}) \rightarrow \Xi_b^-(1S, \frac{1}{2}) \gamma$	79.1	135	91.5
$\Lambda_b^{\bar{0}}(1P, \frac{\bar{1}}{2}) \to \Sigma_b^{\bar{0}}(1S, \frac{\bar{1}}{2}) \gamma$	0.1	0.14	0.2	$\Xi_b^{-}(1P, \overline{\frac{1}{2}}) \to \Xi_b^{\prime-}(1S, \overline{\frac{1}{2}}) \gamma$	0.0	0.0	0.0
$\Lambda_b^0(1P, \frac{1}{2}) \rightarrow \Sigma_b^{*0}(1S, \frac{3}{2}) \gamma$	0.1	0.09	0.0	$\Xi_b^{-}(1P, \frac{1}{2}) \to \Xi_b^{*-}(1S, \frac{3}{2}) \gamma$	0.0	0.0	0.0
$\Lambda_b^0(1P, \frac{3}{2}) \to \Lambda_b^0(1S, \frac{1}{2}) \gamma$	49.1	52.8	43.4	$\Xi_b^-(1P, \frac{3}{2}) \to \Xi_b^-(1S, \frac{1}{2}) \gamma$	84.5	147	96.1
$\Lambda_b^0(1P, \frac{3}{2}) \to \Sigma_b^0(1S, \frac{1}{2}) \gamma$	0.1	0.21	0.3	$\Xi_b^-(1P, \frac{3}{2}) \to \Xi_b^{\prime-}(1S, \frac{1}{2}) \gamma$	0.0	0.0	0.0
$\Lambda_b^0(1P, \frac{3}{2}) \rightarrow \Sigma_b^{*0}(1S, \frac{3}{2}) \gamma$	0.1	0.15	0.0	$\Xi_b^{-}(1P, \frac{3}{2}) \to \Xi_b^{*-}(1S, \frac{3}{2}) \gamma$	0.0	0.0	0.0
				$\overline{\Xi_b^0(1P, \frac{1}{2})} \to \Xi_b^0(1S, \frac{1}{2}) \gamma$	33.9	63.6	83.1
				$\Xi_b^0(1P, \frac{1}{2}) \to \Xi_b^{\prime 0}(1S, \frac{1}{2}) \gamma$	0.4	1.32	0.6
				$\Xi_b^0(1P, \frac{1}{2}) \to \Xi_b^{*0}(1S, \frac{3}{2}) \gamma$	0.5	2.04	0.1
				$\Xi_b^0(1P, \frac{3}{2}) \to \Xi_b^0(1S, \frac{1}{2}) \gamma$	35.2	68.3	88.9
				$\Xi_b^0(1P, \frac{3}{2}) \to \Xi_b^{\prime 0}(1S, \frac{1}{2}) \gamma$	0.6	1.68	0.7
				$\Xi_b^0(1P, \frac{3}{2}) \to \Xi_b^{*0}(1S, \frac{3}{2}) \gamma$	0.6	2.64	0.2

[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).



Process Our	Ref.	Ref.	Ref.	Process	Our	Ref.	Ref.	Ref.	
		[1]	[2]	[3]			[1]	[2]	[3]
$\Sigma_b^{*-}(1S, \frac{3}{2}^+) \rightarrow \Sigma_b^-(1S, \frac{1}{2}^+)\gamma$	0.0	0.06	0.0	0.0144	$\Xi_b^{\prime-}(1S, \frac{1}{2}^+) \to \Xi_b^-(1S, \frac{1}{2}^+) \gamma$	0.6	0.0	0.6	0.707
$\Sigma_b^0(1S, \frac{1}{2}^+) \rightarrow \Lambda_b^0(1S, \frac{1}{2}^+) \gamma$	94.7	130	128.1	151.9	$\Xi_b^{*-}(1S, \tfrac{3}{2}^+) \to \Xi_b^-(1S, \tfrac{1}{2}^+) \gamma$	0.8	0.0	1.0	1.044
$\Sigma_b^{*0}(1S, \frac{3}{2}^+) \to \Lambda_b^0(1S, \frac{1}{2}^+)\gamma$	120.2	335	168.8	198.8	$\Xi_b^{*-}(1S, \frac{3}{2}^+) \rightarrow \Xi_b^{\prime-}(1S, \frac{1}{2}^+)\gamma$	0.0	15.0	0.0	0.0122
$\Sigma_b^{*0}(1S, \frac{3}{2}^+) \rightarrow \Sigma_b^0(1S, \frac{1}{2}^+)\gamma$	0.0	0.02	0.0	0.0059	$\Xi_b^{\prime 0}(1S, \frac{1}{2}^+) \to \Xi_b^0(1S, \frac{1}{2}^+) \gamma$	28.0	84.6	28.4	46.9
$\Sigma_b^{*+}(1S, \frac{3}{2}^+) \rightarrow \Sigma_b^+(1S, \frac{1}{2}^+)\gamma$	0.1	0.25	0.1	0.080	$\Xi_b^{*0}(1S, \frac{3}{2}^+) \to \Xi_b^0(1S, \frac{1}{2}^+) \gamma$	40.8	104	45.2	65.0
					$\Xi_b^{*0}(1S, \frac{3}{2}^+) \to \Xi_b^{\prime 0}(1S, \frac{1}{2}^+) \gamma$	0.0	5.19	0.0	0.0069
					$\Omega_b^{*-}(1S, \frac{3}{2}^+) \rightarrow \Omega_b^-(1S, \frac{1}{2}^+)\gamma$	0.0	0.1	0.0	0.056

- [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).



- 目前,实验上已经发现了大量的单重味重子激发态的候选态,它
 们在传统的夸克模型上可以得到很好的解释;
- 我们建议通过 ND^(*)、ΣD^(*)、NB^(*)、ΣB^(*)、部分三体衰变等过
 程寻找 F 波单重味重子;
- •辐射衰变也可以用于研究单重味重子的结构。

谢谢各位批评指正