Spectroscopy of singly heavy flavor baryons

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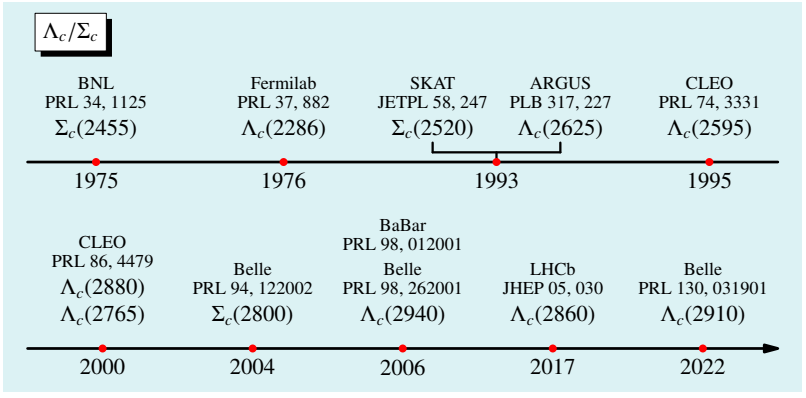
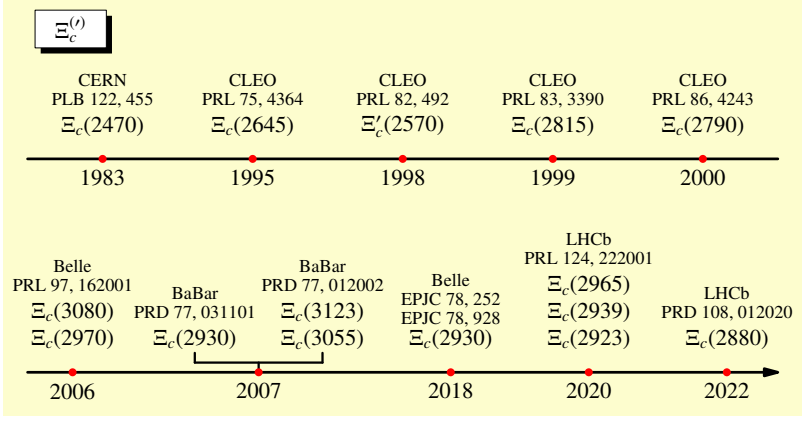
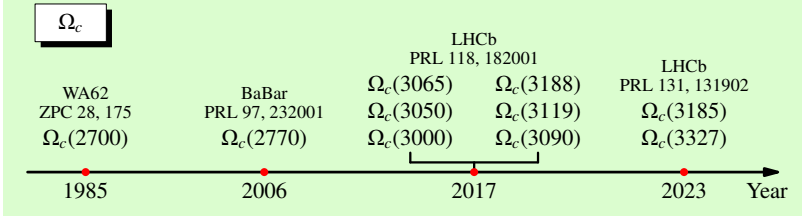
Outline

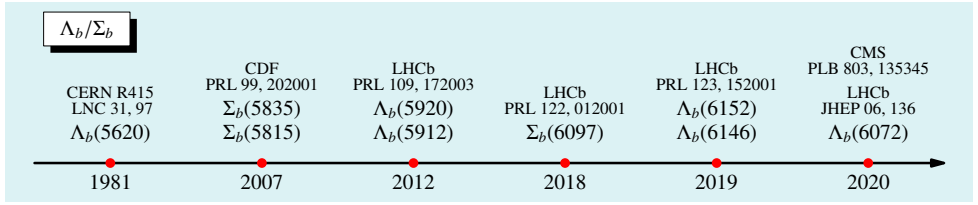
1. Background
2. Formalism
3. Mass spectra and decay behaviors
4. Summary

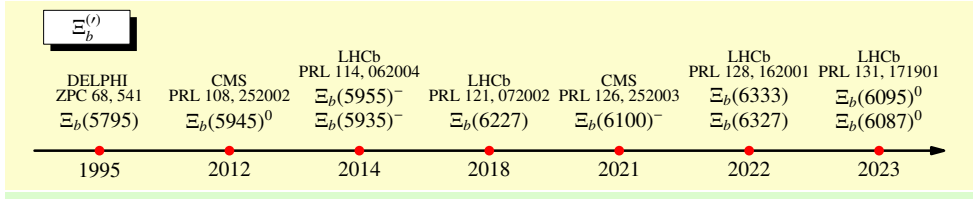
1. Background

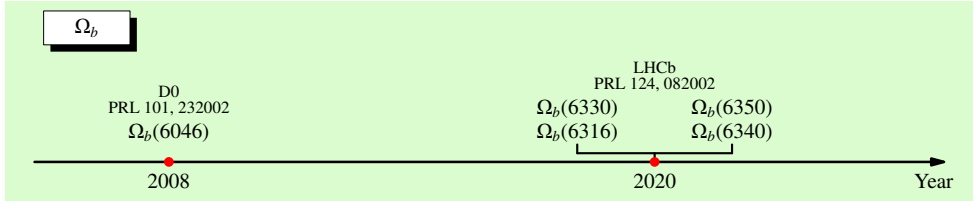












1. In the past about 50 years, over 30 singly charmed baryons were observed.
2. In the past about 40 years, over 20 singly bottom baryons were observed.
3. Over half of the singly heavy flavor baryons were observed in this century.

2. Formalism

1. Potential model

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

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

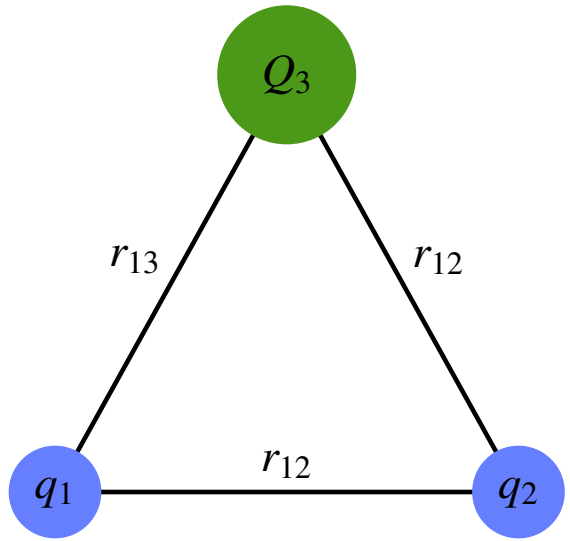
$$H_{ij}^{\text{conf}} = -\frac{2\alpha_s}{3r_{ij}} + \frac{b}{2} r_{ij} + \frac{1}{2} C$$

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

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

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

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



Interaction

2. The method for solving three-body Schrödinger equation

Three-body Schrödinger equation:

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

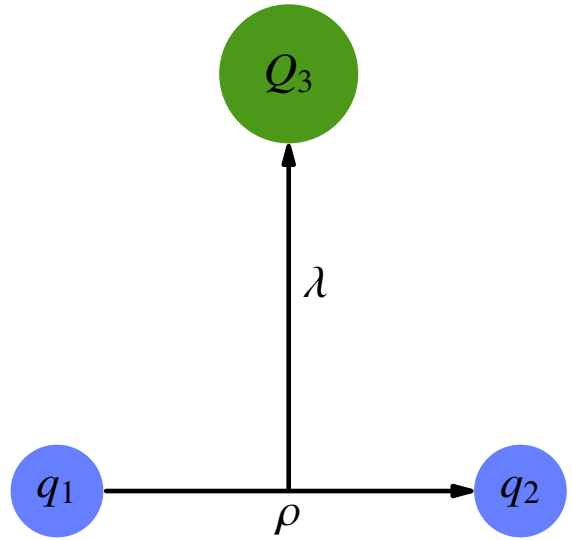
The expansion of $\Psi_{JM}(\boldsymbol{\rho},\boldsymbol{\lambda})$:

$$\Psi_{JM}(\boldsymbol{\rho},\boldsymbol{\lambda}) = \sum_{n_\rho,n_\lambda} C_{n_\rho n_\lambda}\phi^{\text{color}}\phi^{\text{flavor}} \times [[[s_{q_1}s_{q_2}]_{s_\ell}[\phi_{n_\rho l_\rho}(\boldsymbol{\rho})\phi_{n_\lambda l_\lambda}(\boldsymbol{\lambda})]_L]_{j_\ell}s_{Q_3}]_{JM}$$

$C_{n_\rho n_\lambda}$ could be obtained 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

Gaussian parameters:

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

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

E. Hiyama, Y. Kino, and M. Kamimura, Prog. Part. Nucl. Phys. 51, 223–307 (2003).

3. Strong decays: Quark-Pair-Creation (QPC) model

The transition operator of QPC model is

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

Partial amplitude of the decay is

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

J_{BC} is the relative spin of the final BC, L_{BC} is the relative orbital angular momentum of BC, the P is the momentum of B or C in the center-of-mass frame of A. Then the decay width is

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

3. Mass spectra and decay behaviors

1. Possible assignments of the singly heavy flavor baryons

Singly charmed baryons

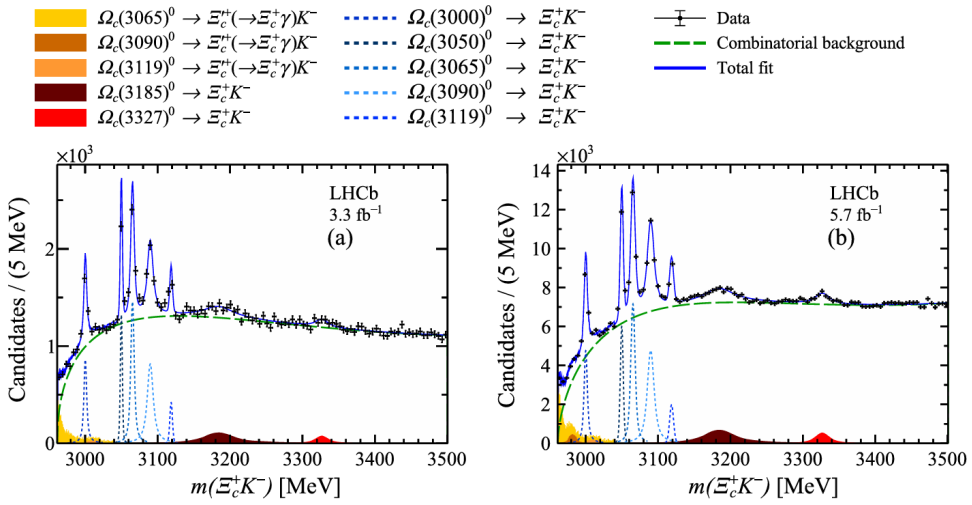
$\bar{3}_f$			6_f	
$\|1S, 1/2^+\rangle$			$\|1S, 1/2^+\rangle$	$\|1S, 3/2^+\rangle$
$\Lambda_c(2286)$			$\Sigma_c(2455)$	$\Sigma_c^*(2520)$
$\Xi_c(2470)$			$\Xi_c'(2580)$	$\Xi_c^*(2460)$
			$\Omega_c(2695)$	$\Omega_c^*(2765)$
$\|1P, \frac{1}{2}^-\rangle$	$\|1P, \frac{3}{2}^-\rangle$	$\|2S, \frac{1}{2}^+\rangle$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

Singly bottom baryons

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

2. *D*-wave singly heavy flavor baryons

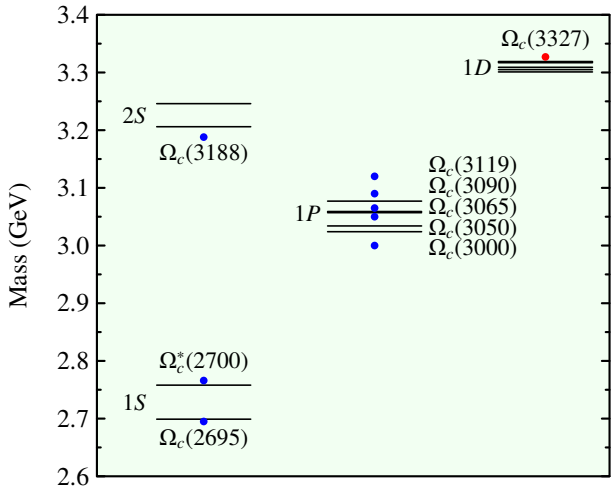
Observation and interpretation of $\Omega_c(3327)$



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

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

Spectrum



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.					$20 \pm 5^{+13}_{-1}$	

The $\Omega_c(3327)$ is a good $\Omega_c(1D)$ candidate.

$\Lambda_b(1D)$ and $\Xi_b(1D)$

Interpretations of $\Lambda_b(6146)$ and $\Lambda_b(6152)$

Decay Channels	$\Lambda_b(6146)(1D,\frac{3}{2}^+)$	$\Lambda_b(6152)(1D,\frac{5}{2}^+)$
$\Sigma_b(5815)\,\pi$	3.25^p	0.22^f
$\Sigma_b^*(5835)\,\pi$	0.65^p, 0.28^f	4.03^p, 0.14^f
Total	4.18	4.39
Expt. [1]	$2.9 \pm 1.3 \pm 0.3$	$2.1 \pm 0.8 \pm 0.3$

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

The numerical results are consistent with the experiments

Theoretical widths of $\Xi_b(1D)$

Decay channels	$\Xi_b(6327)(1D,\frac{3}{2}^+)$	$\Xi_b(6330)(1D,\frac{5}{2}^+)$
$\Xi_b'(5935)\,\pi$	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
Total	2.38	0.76

[2] [LHCb] Phys. Rev. Lett. 128, 162001 (2022)

$m[\Xi_b(6327)^0] = 6327.28^{+0.23}_{-0.21} \pm 0.12 \pm 0.24$ MeV,
$m[\Xi_b(6333)^0] = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22$ 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.

The theoretical results were confirmed by experiments

3. F-wave singly heavy flavor baryons

Status:

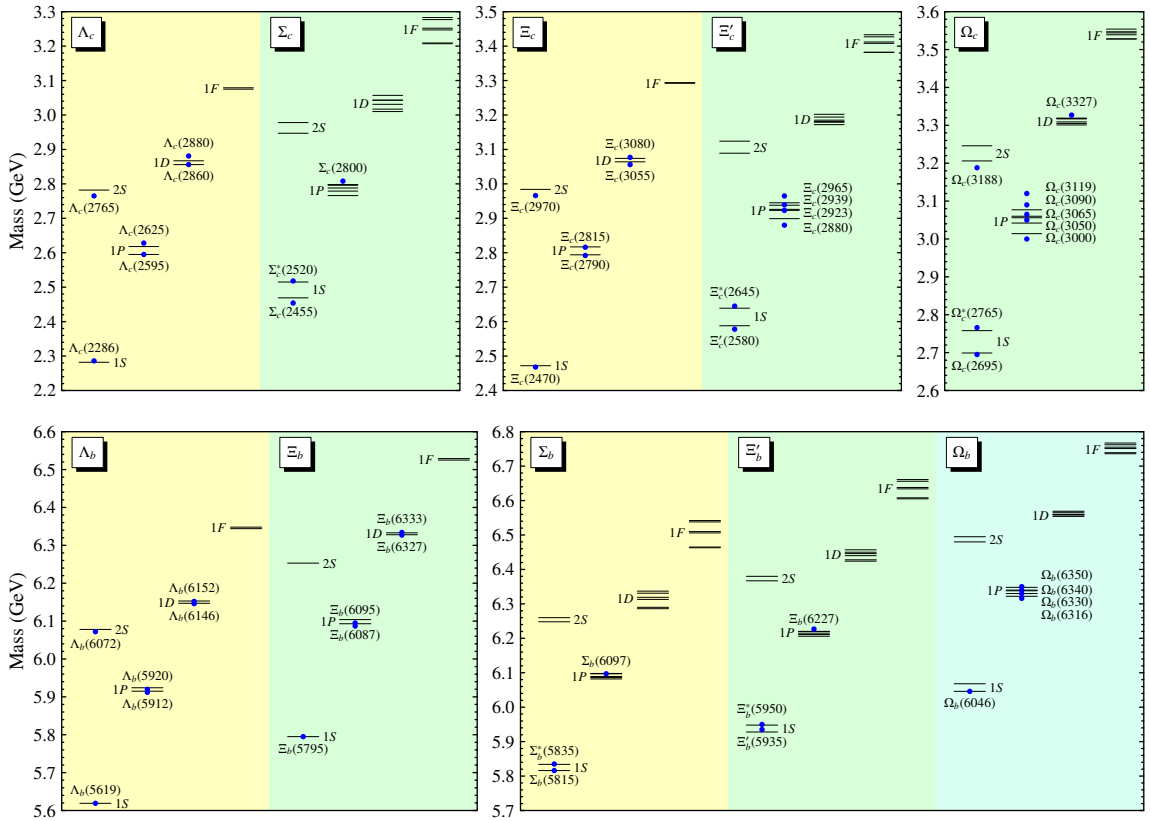
✓ Nearly complete $1S$ states

✓ Many $1P$ and $2S$ candidates

✓ Several $1D$ and $2P$ candidates

? **No $1F$ candidates**

Spectra:



The studies of the missing $1F$ candidates could provide some clues to search for them.

Decay: F-wave singly charmed baryons

$\bar{3}_f$:

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

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

6_f:

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

We suggest:

1. search for $\Lambda_c(1F)$ in $ND^{(*)}$ channels
2. search for $\Xi_b(1F)$ in $\Sigma\bar{B}^{(*)}$ channels
3. search for $6_f - 1F$ states in three-body channels, light flavor baryon + singly heave flavor meson, and channels contain orbital excited wave singly heavy flavor baryons.

F-wave singly bottom baryons

$\bar{3}_f$:

Decay channels	M_f (MeV)	$\Lambda_b(1F,5/2^-)$	$\Lambda_b(1F,7/2^-)$
$\Sigma_b(1S,1/2^+)\pi$	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
$N\bar{B}$		24.9	5.9
$N\bar{B}^*$		20.2	43.9
$\cdots$		0.4	0.4
Total		59.4	64.0

Decay channels	M_f (MeV)	$\Xi_b(1F,5/2^-)$	$\Xi_b(1F,7/2^-)$
$\Xi'_{b2}(1P,3/2^-)\pi$	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
$\Lambda\bar{B}$		2.8	1.1
$\Sigma\bar{B}$		27.0	1.9
$\Lambda\bar{B}^*$		3.1	6.0
$\Sigma\bar{B}^*$		1.1	5.4
$\cdots$		0.5	0.5
Total		39.2	19.9

6_f:

	Mode I	Mode II
$\Sigma_b(1F)$	$\Sigma_b(1P)\pi$ $\Sigma_b(1D)\pi$ $\Lambda_b\pi\pi$ $\cdots$	$\cdots$
$\Xi'_b(1F)$	$\Sigma_b(1P)\bar{K}$ $\Sigma_b(1D)\bar{K}$ $\Lambda_b\bar{K}\pi$ $\cdots$	$\cdots$
$\Omega_b(1F)$	$\cdots$	$\Xi\bar{B}^{(*)}$

We suggest:

1. search for $\Lambda_b(1F)$ in $N\bar{B}^{(*)}$ channels
2. search for $\Xi_b(1F)$ in $\Sigma\bar{B}^{(*)}$ channels
3. search for $6_f - 1F$ states in three-body channels, light flavor baryon + singly heave flavor meson, and channels contain orbital excited wave singly heavy flavor baryons.

4. Summary

- Until now, there exist nearly complete $1S$ states and many candidates of $1P$ and $2S$ excited singly heavy flavor baryons.
- The $1D$ candidates are also established step by step.
- For the $1F$ states, we studied their spectra and decay behaviors, which may provide some suggestions for experiments.

Thank you for attentions.