The Decays of heavy baryons

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Classification

Light baryons

- N and Δ baryons Z. Shah et al., CPC 43, 024106(2019); CPC 45, 023102 (2021)

Singly heavy baryons

- Σ_c^{++}, Σ_c^{+}, Σ_c^{0}, Ξ_c^{+}, Ξ_c^{0}, Λ_c^{+}, Ω_c^{0} [Charm Sector]
  Z. Shah et al., EPJA 52, 313 (2016); CPC 40, 123102 (2016)
- Σ_b^{+}, Σ_b^{-}, Σ_b^{0}, Ξ_b^{+}, Ξ_b^{-}, Λ_b^{-}, Ω_b^{-} [Bottom Sector]
  Nucl. Phys. A 965,57 (2017); Few Body Syst. 59, 112 (2018)

Doubly heavy Baryons

- Ω_{cc}^{+}, Ω_{bb}^{-} and Ω_{bc}^{0} Z. Shah et al., EPJC, **76**, 530 (2016).
- Ξ_{cc}^{+}, Ξ_{bb}^{-}, Ξ_{bc}^{0}, Ξ_{cc}^{++}, Ξ_{bb}^{0} and Ξ_{bc}^{+}
  Z. Shah et al., EPJC, **77**, 129 (2017)

Triply heavy Baryons

- Ω_{ccc}, Ω_{bbb}, Ω_{bbc}, Ω_{ccb}
  Z. Shah et al., EPJA, **53**, 195 (2017); Few-Body Syst. 59, 76 (2018); CPC 42, 053101 (2018)

The Model I

The relevant degrees of freedom for the relative motion of the three constituent quarks are provided by the relative Jacobi coordinates ($\vec{\rho}$ and $\vec{\lambda}$) given in the Hypercentral Constituent Quark Model

$$\vec{\rho} = \frac{1}{\sqrt{2}}(\vec{r_1} - \vec{r_2}) \qquad \vec{\lambda} = \frac{m_1\vec{r_1} + m_2\vec{r_2} - (m_1 + m_2)\vec{r_3}}{\sqrt{m_1^2 + m_2^2 + (m_1 + m_2)^2}} \quad (1)$$

Here m_i and $\vec{r_i}$ (i = 1, 2, 3) denote the mass and coordinate of the i-th constituent quark. The respective reduced masses are given by

$$m_\rho = \frac{2m_1 m_2}{m_1 + m_2} \qquad m_\lambda = \frac{2m_3(m_1^2 + m_2^2 + m_1 m_2)}{(m_1 + m_2)(m_1 + m_2 + m_3)} \quad (2)$$

The confining three-body potential is chosen within a string-like picture, where the quarks are connected by gluonic strings and the potential strings increases linearly with a collective radius r_{3q}. We

The Model II

define hyper radius x and hyper angle ξ in terms of the absolute values ρ and λ of the Jacobi coordinates,

$$x = \sqrt{\rho^2 + \lambda^2} \quad and \quad \xi = arctan\left(\frac{\rho}{\lambda}\right) \tag{3}$$

The hyper radius x is a collective coordinate and therefore the hypercentral potential contains also the three-body effects. The Hamiltonian of three body baryonic system in the hCQM is then expressed as

$$H = \frac{P_x^2}{2m} + V(x) \tag{4}$$

where, $m = \frac{2m_\rho m_\lambda}{m_\rho + m_\lambda}$, is the reduced mass.

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The hypercentral potential V(x)

$$V(x) = V^0(x) + \left(\frac{1}{m_\rho} + \frac{1}{m_\lambda}\right) V^{(1)}(x) + V_{SD}(x) \qquad (5)$$

$$V^{(0)}(x) = \frac{\tau}{x} + \beta x \quad \textit{and} \quad V^{(1)}(x) = -C_F C_A \frac{\alpha_s^2}{4x^2} \qquad (6)$$

$$V_{SD}(x) = V_{SS}(x)(\vec{S_\rho}.\vec{S_\lambda}) + V_{\gamma S}(x)(\vec{\gamma}\cdot\vec{S}) + V_T(x)\left[S^2 - \frac{3(\vec{S}\cdot\vec{x})(\vec{S}\cdot\vec{x})}{x^2}\right] \qquad (7)$$

- The hyper-Coulomb, $\tau = -\frac{2}{3}\alpha_s$
- The Casimir charges of the fundamental and adjoint representation are, $C_F = \frac{4}{3}$ and C_A =3
- m_u=0.338 GeV,m_d=0.350 GeV, m_s=0.500 GeV m_c=1.275 GeV and m_b=4.67 GeV

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Magnetic moments

Table: The magnetic moments of heavy baryons (in terms of nuclear magnaton μ_N)

Baryon	J^P	**M.m.**	**Baryon**	J^P	**M.m.**
N	$\frac{1}{2}^+$	-1.997	Δ	$\frac{3}{2}^+$	4.56
Ξ_{cc}^+	$\frac{1}{2}^+$	0.784	Ξ_{cc}^+	$\frac{3}{2}^+$	0.068
Ξ_{cc}^{++}	$\frac{1}{2}^+$	0.031	Ξ_{cc}^{++}	$\frac{3}{2}^+$	2.218
Ξ_{bb}^-	$\frac{1}{2}^+$	0.196	Ξ_{bb}^-	$\frac{3}{2}^+$	-1.737
Ξ_{bb}^0	$\frac{1}{2}^+$	-0.663	Ξ_{bb}^0	$\frac{3}{2}^+$	-1.607
Ω_{cc}^+	$\frac{1}{2}^+$	0.692	Ω_{cc}^+	$\frac{3}{2}^+$	0.285
Ω_{bb}^-	$\frac{1}{2}^+$	0.108	Ω_{bb}^-	$\frac{3}{2}^+$	-1.239
Ξ_{bc}^0	$\frac{1}{2}^+$	0.527	Ξ_{bc}^0	$\frac{3}{2}^+$	-0.448
Ξ_{bc}^+	$\frac{1}{2}^+$	-0.304	Ξ_{bc}^+	$\frac{3}{2}^+$	2.107

Transition Magnetic moment I

The radiative transition moment can be expressed as,

$$\mu_{B^* \to B\gamma} = \langle B^* | \mu_{B^* \to B\gamma} | B \rangle \tag{8}$$

The transition magnetic moment (μ_i) of the constituent quarks are computed using the spin flavour wave functions of the initial and final baryons are [1, 2]

$$\mu_i = \langle \phi_{sf} | \frac{e_i}{2m_i^{eff}} \sigma_{iz} | \phi_{sf} \rangle \tag{9}$$

Here, m_i^{eff} is the effective mass of the constituent quarks within the baryons. In order to evaluate the $B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\gamma$ transition magnetic moments, we take the geometric mean of effective quark masses of the constituent quarks of initial and final states baryons.

$$m_i^{eff} = \sqrt{m_{i(B^*)}^{eff} m_{i(B)}^{eff}} \tag{10}$$

Transition Magnetic moment II

The spin-3/2 to spin-1/2 doubly heavy baryon transition magnetic moments in the quark model can be determined as follows [4]

- $\Delta \rightarrow N$, $\frac{2\sqrt{2}}{3}(\mu_d - \mu_u)$
- $\Sigma_c^{*0} \rightarrow \Sigma_c^0$, $\frac{2\sqrt{2}}{3}(\mu_d - \mu_c)$
- $\Xi_c^{*0} \rightarrow \Xi_c^0$, $\frac{\sqrt{2}}{\sqrt{3}}(\mu_d - \mu_s)$
- $\Omega_c^{*0} \rightarrow \Omega_c^0$, $\frac{2\sqrt{2}}{3}(\mu_c - \mu_s)$
- For doubly charmed baryons, $\frac{4}{3\sqrt{2}}(\mu_Q - \mu_q)$
- For doubly bottom baryons, $\frac{2\sqrt{2}}{3}(\mu_Q - \mu_q)$
- For doubly charm-bottom baryons, $\frac{\sqrt{2}}{3}(\mu_Q + \mu_Q - 2\mu_q)$

The decay width can be expressed as

$$\Gamma = \frac{k^3}{4\pi}\frac{2}{2J+1}\frac{e^2}{m_p^2}\mu^2_{B^*\rightarrow B} \tag{11}$$

Transition Magnetic moment III

Table: Transision Magnetic Moments of doubly charm, doubly bottom and doubly charm-bottom baryons (in units of μ_N).

Process	Our results	[4]	[5]	[3]	[6]	[7]
$\Xi_{cc}^{++*} \rightarrow \Xi_{cc}^{++}$	-1.01	-1.40	0.17	-0.47	1.35	-0.787
$\Xi_{cc}^{+*} \rightarrow \Xi_{cc}^{+}$	1.048	1.23	0.86	0.98	1.06	0.945
$\Omega_{cc}^{+*} \rightarrow \Omega_{cc}^{+}$	0.96	0.90	0.84	0.59	0.88	0.789
$\Xi_{bb}^{0*} \rightarrow \Xi_{bb}^{0}$	-1.69	-1.81				
$\Xi_{bb}^{-*} \rightarrow \Xi_{bb}^{-}$	0.73	0.81				
$\Omega_{bb}^{-*} \rightarrow \Omega_{bb}^{-}$	0.48	0.48				
$\Xi_{bc}^{+*} \rightarrow \Xi_{bc}^{+}$	-1.39	-1.61				
$\Xi_{bc}^{0*} \rightarrow \Xi_{bc}^{0}$	0.94	1.02				
$\Omega_{bc}^{0*} \rightarrow \Omega_{bc}^{0}$	0.71	0.69				

Table: Radiative decay widths of heavy baryons.

Decay	Our results	[8]	[7]	[10]	[11]
$\Gamma(\Delta \to N\gamma$	2.6199				
$\Gamma(\Sigma_c^{*0} \to \Sigma_c^0\gamma)$	1.553				
$\Gamma(\Xi_c^{*0} \to \Xi_c^0\gamma)$	0.906				
$\Gamma\Omega_c^{*0} \to \Omega_c^0\gamma)$	1.441				
$\Gamma(\Sigma_b^{*+} \to \Sigma_b^+\gamma)$	0.13				
$\Gamma(\Xi_b^{*0} \to \Xi_b^0\gamma)$	0.99				
$\Gamma\Omega_b^{*0} \to \Omega_b^0\gamma)$	0.219				
$\Gamma(\Xi_{cc}^* \to \Xi_{cc}\gamma)$	1.4823	1.649	2.08		3.90
$\Gamma(\Omega_{cc}^* \to \Omega_{cc}^+\gamma)$	0.0190	0.326	0.949		
$\Gamma(\Xi_{bb}^* \to \Xi_{bb}\gamma)$	0.0325	0.022	0.0031		
$\Gamma(\Omega_{bb}^* \to \Omega_{bb})$	0.022	0.001			0.04
$\Gamma(\Xi_{bc}^* \to \Xi_{bc})$	1.276	0.316	0.612	0.209	
$\Gamma(\Omega_{bc}^* \to \Omega_{bc})$	0.336	0.002		0.0031	

Study of $\Omega_c(3000)^0 \to \Xi_c^+ K^-$ decay

- In 2017, the LHCb Collaboration observed five narrow excited Ω_c states such as $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$ and $\Omega_c(3120)^0$ in the $\Xi_c^+ K^-$ mass spectrum [12]. The quantum numbers of excited states of Ω_c baryonic states are still unknown in PDG [13].
- Our attempt is to assign a possible spin-parity to the recently observed $\Omega_c(3000)^0$ baryon [12, 14]. The PDG reported its world-average mass 3000.41 MeV, which is close to the theoretical predictions of $1P$-wave states obtained in various potential models [15, 17, 18, 19].
- Here, we want to analyze the decay $\Omega_c(3000)^0 \to \Xi_c^+ K^-$ into each possible quantum state of $1P$-wave.
- And, we try to compare the decay width of our calculation with the experimental value 4.5 ± 0.6 (stat) $\pm$ 0.3 (syst) MeV, measured with first statistical and second systematic uncertainties [12].
- That can be used to confirm or reject the quantum number assignment of this newly observed $\Omega_c(3000)^0$ baryon.

Methodology I

- The strong decays of excited charmed baryons are most conveniently described by HHChPT, into which heavy-quark symmetry and chiral symmetry are incorporated [25, 26].
- In this approach, the partial decay widths are [24]

$$\Gamma(\Omega_{c1}^0(1/2^-) \to \Xi_c^+ K^-) = \frac{h_4^2}{4\pi f_\pi^2} \frac{m_{\Xi_c^+}}{m_{\Omega_{c1}^0}} E_K^2 p_K, \qquad (12)$$

$$\Gamma(\Omega_{c1}^0(3/2^-) \to \Xi_c^+ K^-) = \frac{h_9^2}{9\pi f_\pi^2} \frac{m_{\Xi_c^+}}{m_{\Omega_{c1}^0}} p_K^5, \qquad (13)$$

derived from the Lagrangian terms [21]. Here p_K is the center-of-mass momentum of the kaon, $f_\pi = 130.2$ MeV is the pion decay constant [13], and $E_K = \frac{m_{\Omega_{c1}^0}^2 - m_{\Xi_c^+}^2 + m_K^2}{2m_{\Omega_{c1}^0}}$.

Conclusion

- An experimental observed decay width 4.5 $\pm$ 0.6 (stat) $\pm$ 0.3 (syst) MeV of $\Omega_c(3000)^0$ is obtained with coupling $h_4^2 \approx 0.16$, which is smaller by 8, 5, 10, and 10 times than the predictions of Pirjol and Yan [21], Cheng and Chua [22], Cheng [23] and the CDF measurement [28], respectively.
- On the other hand, the decay width is obtained with coupling $h_9^2 \approx 0.13 \times 10^{-4}$ MeV^{-2}, it is in agreement with the result $\leq 0.13 \times 10^{-4}$ MeV^{-2} of Refs. [21, 23].
- Therefore, the $\Omega_c(3000)^0$ is more appropriate assigned as $\Omega_{c1}^0(3/2^-)$ quantum state rather than $\Omega_{c1}^0(1/2^-)$.
- We forsee to extend this scheme to analyze the strong decays of its ($\Omega_c(3000)^0$) experimentally observed sister states such as $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3120)^0$ [12, 14].

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