Quark clusters in heavy hadrons — What, Where and How —

保坂 淳 Atsushi Hosaka

RCNP/Osaka & JAEA/Tokai & RIKEN

新学術クラスター階層研究会 hosted by TITech via Zoom

- 1. Introduction
- 2. Unsolved and new problems
 - 2.1 Roper and analogues: Light diquarks in heavy baryons
 - 2.2 Pc: Hadronic clusters for molecules
 - 2.3 Doubly heavy: Heavy diquarks in tetra and hexaquarks
- 3. Summary

1. Introduction

rpp2019-qtab-mesons

Particle Data Group

rpp2019-qtab-baryons

LIGHT UNFLAVORED	STRANGE	CHARMED, STRANGE	$c\overline{c}$ continued	$1/2^+$	**** A(1	232) 3/2+ ****	5+	1/2+ ;	**** =0	1/2+ ****	Λ^+	1/2+ ****
$ [S = C = B = 0] $ $ [G(J^{PC}) \qquad \qquad I^{G}(J^{PC}) $	$(S = \pm 1, C = B = 0)$ I(P)	$(C = S = \pm 1)$		$n = \frac{1}{2}$	**** $\Delta(1)$	600) 3/2 ⁺ ****	Σ^0	1/2+ 3	**** = =-	1/2+ ****	$\Lambda_{c}(2595)^{+}$	1/2 ***
π^{\pm} 1 0 1 $\bullet \pi_{2}(1670)$ 1 $-(2^{-+})$.(°) • K± 1/200	• D^{\pm} 0(0 ⁻)	• $\psi(25) = 0 (1)$ • $\psi(3770) = 0^{-}(1)$	N(1440) 1/2 ⁺	**** \(\Delta\)	620) 1/2 ⁻ ****	Z	1/2+	**** Ξ(1530)	3/2+ ****	$\Lambda_{c}(2625)^{+}$	3/2 ***
• π^0 1 ⁻ (0 ⁻⁺) • ϕ (1680) 0 ⁻ (1)	• K ⁰ 1/2(0 ⁻)	• $D_c^{*\pm}$ 0(??)	• $\psi_2(3823)$ 0 ⁻ (2)	N(1520) 3/2-	**** <i>\D</i> (1	700) 3/2 ⁻ ****	Σ(1385)	3/2+ 3	**** <i>Ξ</i> (1620)	*	$\Lambda_{c}(2765)^{+}$	*
• η 0 ⁺ (0 ⁻⁺), • $\rho_3(1690)$ 1 ⁺ (3)	• K§ 1/2(0 ⁻)	• $D_{s0}^{*}(2317)^{\pm} 0(0^{+})$	xto(3860) 0 ⁺ (0 ⁺ ⁺)	N(1535) 1/2 ⁻	**** \Delta(1	750) 1/2 ⁺ *	Σ(1480)	;	* <i>Ξ</i> (1690)	***	$\Lambda_{c}(2860)^{+}$	3/2+ ***
• $f_0(500)$ 0+(0++) • $\rho(1700)$ 1+(1)	• K_L^0 1/2(0 ⁻)	• $D_{s1}(2460)^{\pm} = 0(1^{+})$	• $\chi_{c1}(38/2)$ 0 (1 + +)	N(1650) 1/2 ⁻	**** \\ \Delta(1)	900) 1/2 ***	Σ(1560)	;	** <i>Ξ</i> (1820)	3/2" ***	$\Lambda_{c}(2880)^{+}$	5/2 ⁺ ***
• $\rho(70)$ 1 (1) • $\delta_2(170)$ 1 (2 · ·) • $\omega(782)$ 0 - (1) • $f_0(1710)$ 0 + (0 + +)	• $K_0^*(700)$ 1/2(0 ⁺) • $K^*(892)$ 1/2(1)	• $D_{s1}(2536)^{\pm} 0(1^{\pm})$	• $Z_c(3900)$ 1 (1) • $X(3915)$ 0 (0/2)	N(1675) 5/2 ⁻	**** $\Delta(1)$	905) 5/2 ⁺ ****	$\Sigma(1580)$	3/2- *	* <u>=</u> (1950)	*** 57	$\Lambda_{c}(2940)^{+}$	3/2 ***
• $\eta'(958)$ 0 ⁺ (0 ⁻⁺) $\eta(1760)$ 0 ⁺ (0 ⁻⁺)	• $K_1(1270)$ 1/2(1+)	• $D_{52}^{\pm}(2700)^{\pm}$ 0(1 ⁻)	• $\chi_{c2}(3930) 0^+(2^{++})$	N(1680) 5/2 ⁺	**** \D(1)	910) $1/2^+$ ****	$\Sigma(1620)$	$1/2^{-2}$	* <u>=(2030)</u>	$\geq \frac{5}{2}$: ***	$\Sigma_c(2455)$	1/2+ ****
• $f_0(980)$ 0 ⁺ (0 ⁺⁺) • $\pi(1800)$ 1 ⁻ (0 ⁻⁺)	• K1(1400) 1/2(1+)	$D_{s1}^*(2860)^{\pm} 0(1^{-})$	X(3940) ? [?] (? ^{??})	N(1700) = 3/2 $N(1710) = 1/2^{\pm}$	**** \	920) 3/2 *** 020) 5/2 ***	$\Sigma(1660)$	1/2 ' '		*	$\Sigma_{c}(2520)$	3/2****
• $a_0(980)$ 1 ⁻ (0 ⁺⁺) $f_2(1810)$ 0 ⁺ (2 ⁺⁺) • $d(1020)$ 0 ⁻ (1) $Y(1925)$ 2 [?] (0 ⁻⁺)	• $K^*(1410)$ 1/2(1 ⁻¹)	$D_{53}^{*}(2860)^{\pm} 0(3^{-})$	• $X(4020)$ 1 ⁺ (?: ⁻)	$N(1710) = 1/2^{+}$ $N(1720) = 3/2^{+}$	**** \ \ \ (1)	930) 3/2 *** 940) 3/2 **	$\Sigma(1670)$	3/2	$\pm (2250)$	**	$\Sigma_c(2800)$	1/2+ ***
• $\phi(1020)$ 0 (1) $\chi(1035)$ (0) • $h_1(1170)$ 0 $-(1+-)$ • $\phi_2(1850)$ 0 $-(3)$	• $K_0^*(1430)$ 1/2(0 ⁺) • $K^*(1430)$ 1/2(0 ⁺)	$D_{s,J}(3040)^{\pm} 0(?^{f})$	$X(4050)^{\pm}$ 1 ⁻ (? ⁺)	$N(1860) = 5/2^+$	** \(\)	950) 7/2 ⁺ ****	$\Sigma(1000)$ $\Sigma(1730)$	3/2+ ;	* =(2500)	*	- <i>c</i> =0	1/2 ****
• $b_1(1235)$ 1+(1+-) • $\eta_2(1870)$ 0+(2-+)	$K_2(1450) = 1/2(2^{-1})$	BOTTOM	$X(4055)^{\pm}$ 1 ⁺ (?? ⁻)	$N(1875) 3/2^{-1}$	*** <u>\</u> \(2)	000) 5/2 ⁺ **	$\Sigma(1750)$	$1/2^{-3}$	***		-c = $-c'+$	1/2
• $a_1(1260)$ 1 ⁻ (1 ⁺⁺) • $\pi_2(1880)$ 1 ⁻ (2 ⁻⁺)	$K_2(1580)$ 1/2(2 ⁻)	(B = ±1)	$X(4100)^{\pm}$ 1 ⁻ (? [?])	N(1880) 1/2 ⁺	*** $\Delta(2$	150) 1/2 ⁻ *	$\Sigma(1770)$	1/2+ 3	* <u>Ω</u> -	3/2+ ****	$\frac{-c}{=0}$	1/2+ ***
• $f_2(1270)$ 0 ⁺ (2 ⁺⁺) $\rho(1900)$ 1 ⁺ (1)	K(1630) 1/2(?')	• B^{\pm} 1/2(0 ⁻)	• $\chi_{c1}(4140) 0^{+}(1^{+})$	N(1895) 1/2-	**** $\Delta(2$	200) 7/2 ⁻ ***	Σ(1775)	5/2 3	**** 12(2012)*	• • 7 • • • • *****	-c	3/2+***
$\bullet n(1295) 0^+(0^{-+}) a_2(1910) 0^-(2^{-+}) a_3(1950) 1^-(0^{++})$	$K_1(1650) = 1/2(1^+)$	• B° 1/2(0) • B^{\pm}/B^{0} ADMIXTURE	X(4160) = 0 (1)	N(1900) 3/2 ⁺	**** \Delta(2	300) 9/2 ⁺ **	Σ(1840)	3/2+ 3	* Ω(2250) ⁻	***	$\Xi_{c}(2790)$	1/2 ***
• $\pi(1300)$ 1 ⁻ (0 ⁻⁺) • $f_2(1950)$ 0 ⁺ (2 ⁺⁺)	• $K_2(1770)$ 1/2(1)	• $B^{\pm}/B^0/B_s^0/b$ -baryon	$Z_{c}(4200)$ 1 ⁺ (1 ⁺ -)	N(1990) 7/2 ⁺	** <i>Δ</i> (2	350) 5/2 *	Σ(1880)	1/2+ *	** Ω(2380) ⁻	**	$\Xi_{c}(2815)$	3/2 ***
• $a_2(1320)$ 1 ⁻ (2 ⁺⁺) • $a_4(1970)$ 1 ⁻ (4 ⁺⁺)	• K ₃ (1780) 1/2(3 ⁻)	ADMIXTURE	$\psi(4230) 0^{-}(1^{-})$	N(2000) 5/2 ⁺	** $\Delta(2$	390) 7/2+ *	Σ(1900)	1/2 *	* Ω(2470) ⁻	**	$\Xi_{c}(2930)$	**
• $\hbar_0(13/0)$ 0 ⁺ (0 ⁺ +) $\rho_3(1990)$ 1 ⁺ (3 ⁻)	• K ₂ (1820) 1/2(2 ⁻)	trix Elements	$R_{c0}(4240) = 1^{-}(0^{+})$	N(2040) 3/2 ⁺	* $\Delta(2$	400) 9/2 ⁻ **	$\Sigma(1915)$	5/2+ 3	****		$\Xi_{c}(2970)$	***
$\bullet \pi_1(1405) = 1^{-1}(1^{-1}) + \pi_2(2005) = 1^{-1}(2^{-1}) + \pi_2(2^{-1}) + \pi_2(2$	$K(1830) = 1/2(0^{-1})$ $K^{*}(1050) = 1/2(0^{+1})$	• B^* 1/2(1 ⁻)	• $\psi(4260)$ 0 ⁻ (1)	N(2060) = 5/2 $N(2100) = 1/2^{\pm}$	*** \(2	(420) 11/2 **** (750) 12/2 **	$\Sigma(1940)$	3/2 2	* ***		$\Xi_{c}(3055)$	***
• $h_1(141^2)$ = 0 - (1 + -) = (1 +	$K_0^{(1950)} = 1/2(0^{+})$ $K_0^{*}(1980) = 1/2(2^{+})$	• $B_1(5721)^{\circ}$ 1/2(1 ·) • $B_1(5721)^{\circ}$ 1/2(1 ·)	• $\chi_{c1}(4274) 0^+(1^{++})$	$N(2100) = 1/2^{-1}$	*** 4(2	050) 15/2 ***	$\Sigma(1940)$	1/2 3	*		$\Xi_{c}(3080)$	***
$a_1(1)$	• K ₄ [*] (2045) 1/2(4 ⁺)	$B_{j}^{*}(5732)$?(??)	$X(4350) 0^+(?^{!+})$	N(2120) = 3/2 $N(2190) = 7/2^{-1}$	****	.550) 15/2	$\Sigma(2000)$	7/2+ 3	****		$=_{c}(3123)$	*
$\bullet r_1($	K ₂ (2250) 1/2(2 ⁻)	• $B_2^*(5747)^+$ 1/2(2 ⁺)	$\psi(4300) = 0 (1)$	$N(2220) 9/2^+$	**** <i>1</i>	1/2+ ****	$\Sigma(2070)$	5/2+ 3	*		Ω_{c}^{2}	1/2' ***
$f_2(1)$ f	$K_3(2320) = 1/2(3^{-1})$	• $B_2^*(5747)^0$ 1/2(2 ⁺)	• $\psi(4415) 0^{-}(1^{-})$	N(2250) 9/2-	**** / <u>/(1</u> 4	405) 1/2 [—] ****	Σ(2080)	3/2+ 3	**		$O(3000)^{0}$	3/2 ***
• a_0 + (1)	$K_5(2500) = 1/2(5)$ $K_4(2500) = 1/2(4^{-1})$	$B_{I}(5840)^{0} 1/2(?^{2})$	• $Z_c(4430)$ 1 ⁺ (1 ⁺⁻)	N(2300) 1/2 ⁺	** /(15	520) 3/2 ⁻ ****	Σ(2100)	7/2 *	*		$\Omega_{c}(3050)^{0}$	***
$\rho(1)$ $-(1)$ $+(0++)$	K(3100) ??(???)	• B _J (5970) ⁺ 1/2(??)	$\chi_{c0}(4500) = 0^+(0^+)$	N(2570) 5/2-	** /(16	500) $1/2^+$ ***	Σ(2250)	;	***		$\Omega_{c}(3065)^{0}$	***
$\cdot f_{(1)}$	CHARMED	• <i>B</i> _J (5970) ⁰ 1/2(? [?])	$\chi_{c0}(4700) 0^+(0^{++})$	N(2600) 11/2	- *** //(16	(70) 1/2 ****	$\Sigma(2455)$,	**		$\Omega_{c}(3090)^{0}$	***
$f_1(1)$ or 4^{++}	$(C = \pm 1)$	BOTTOM, STRANGE		N(2700) 13/2	** /\(10	590) 3/2 **** 710) 1/2 ⁺ *	Σ(262 Σ(200				$\Omega_{c}(3120)^{0}$	***
$+ f_2'$ +(0 - +) +(2)	• D [±] 1/2(0 ⁻)	$(B = \pm 1, S = \mp 1)$	$DD = n_{+}(1S) = 0^{+}(0^{-}+)$		A(18	300) 1/2 ⁻ ***	$\Sigma(300)$					
$\int_{a(1)}^{b(1)} and more \int_{a(2+1)}^{b(3)} dt$	• D^0 1/2(0 ⁻¹) • $D^*(2007)^0$ 1/2(1 ⁻¹)	$\bullet B_s^0 = 0(0^-)$	• $\gamma(1S)$ 0 (0)		A(18	$1/2^+ ***$	2(317	•		-/	<i>= cc</i>	***
$h_1(15)$	• $D^*(2010)^{\pm}$ 1/2(1-2)	$\bullet D_{S} = 0(1)$ X(5568) [±] ?(??)	• $\chi_{b0}(1P) = 0^+(0^{++})$		A(18	320) 5/2 ⁺ ****					лo	1/2 ⁺ ***
• $\pi_1(1600)$ 1 ⁻ (1 ⁻ +) $f_0(2330)$ 0 ⁺ (0 ⁺ +)	• D*(2300) 1/2(0+)	• R-1(5830)0 0(1+)	• $\chi_{b1}(1P)$ 0 ⁺ (1 ⁺⁺)		A(18	330) 5/2- ****		\ /			$\Lambda_{b}(5912)^{0}$	1/2 ***
$\bullet a_1(1640) = 1 (1 + 1) \bullet f_2(2340) = 0 + (2 + 1) \bullet f_2(2350) = 1 + (5 - 1) \bullet f_2(2350) = 1 + $		01 1				****					$\Lambda_{b}(5920)^{0}$	3/2- ***
• $\eta_2(1645)$ 0 ⁺ (2 ⁻⁺) $f_6(2510)$ 0 ⁺ (6 ⁺)	Vlast c	nt hadr	ons are	reson	nana	Ces :					Σ_b	1/2+ ***
• $\omega(1650)$ 0 ⁻ (1 ⁻) OTHER LIGHT		/i iiuui			IUII			· /			Σ_b^*	3/2+ ***
• $\omega_3(16/0)$ 0 ⁻ (3) Further States	1	1 .1		•		****					$\Sigma_b(6097)^+$	***
	~ deca	v hv tl	ne stror	no tor	CP	***		onc	1 11 0 10		$\Sigma_b(6097)^-$	***
	ucca	y Uy u		ig ior		*		anc			$=_{b}^{*}, =_{b}^{*}$	1/2 ****
	D*(2640) [±] 1/2(? [:])	$\int \int G(J^{PC})$	r(2S) = 0 - (1)	1	/(2:	35U) 9/2 ***					$= \frac{1}{b}(5935)$	1/2 * *** 2/2 ***
	$D(2740)^0$ $1/2(??)$	• $\eta_c(1S) = 0^+(0^{-+})$	• $\chi_{b1}(3P)$ 0 ⁺ (1 ⁺⁺)		A(25	585) **					$=_{b}(5945)^{\circ}$ $=_{b}(5955)^{-}$	3/2 ⁺ ***
	$D_3(2750) = 1/2(3^{-})$	• $J/\psi(1S) = 0^{-}(1^{-})$	• $\chi_{b2}(3P)$ 0 ⁺ (2 ⁺⁺)								$\Xi_{b}(6227)$	***
	D(3000)- 1/2(?*)	• $\chi_{c0}(1P)$ 0 ⁺ (0 ⁺⁺)	• $\gamma(4S)$ 0 ⁻ (1 ⁻)								Ω_{b}^{-}	1/2+ ***
			• $Z_{b}(10650)$ 1 (1)									
		• $\chi_{C2}(1P)$ 0+(2++)	 <i>Υ</i>(10860) 0[−](1^{−−}) 								$P_{c}(4380)^{+}$	*
		• $\eta_c(25)$ 0 ⁺ (0 ⁻⁺)	• <i>T</i> (11020) 0 ⁻ (1)								$P_{c}(4450)^{+}$	*
		制	「字術クラスタ	'一研究会	May 2	8, 2020						2 /19

What we should do for (exotic) hadrons

We know QCD, but we can not answer the questions:

Do they exist? If they do, which ones? What is their internal structure? How best to look for them? Marek Karliner, QNP proceedings, 2018@Tsukuba https://journals.jps.jp/doi/book/10.7566/QNP2018

Studying heavy exotic hadrons is somewhat similar to investigating the social life of heavy quarks:

- (a) Who with whom?
- (b) For how long?
- (c) A short episode? or
- (d) "Till Death Us Do Part"?



2. Unsolved and new problems

- A. Roper and analogues: Light diquarks in heavy baryons
- B. Pc: Hadronic clusters for molecules
- C. Doubly heavy: Heavy diquarks in tetra and hexaquarks

Open clusters (colored subsystem) in hadrons



A. Roper and analogues: Light diquarks in heavy baryons

First excited state of 1/2+



Standard (naive) quark model

2ħω 1ħω 0ħω



 $E_{ground} < E_{negative parity} < E_{positive parity}$

Standard (naive) quark model

 $2\hbar\omega$ $1\hbar\omega$ $0\hbar\omega$ Ground state $1/2^+, 3/2^+$ 1st excited state $1/2^-, 3/2^-, 5/2^-$ 2nd excited state $1/2^+, 3/2^+, 5/2^+, ...$ Roper resonance



Radial excitation with meson cloud e.g. Burkart-Roberts, RevModPhys.91.011003

Suzuki, N., B. Julia-Diaz, H. Kamano, T. S. H. Lee, A. Matsuyama, and T. Sato, 2010, Phys. Rev. Lett. 104, 042302.

Large quark core mass \bigstar is reduced by coupling to meson clouds \bigstar



More states systematically



Possible senario

Transitions between diquark clusters



The transitions between **diquark** + **spectator heavy quark**

Decay pattern is computable in a model independent manner in the HQ limit

Evidence of diquarks (correlation)





Recent study

Arifi-Nagahiro-Tanida-Hosaka, Three-body decays of $\Lambda_c(2765)$: arXiv:2003.08202 [hep-ph], to appear in PRD $\Lambda_b(6072)$: arXiv:2004.07423 [hep-ph], just accepted by PRD TODAY!



B. Pc: Hadronic clusters for molecules PRL122 (2019) no.22, 222001



Narrow One peak at $\Sigma_c D => J = 1/2$ Two peaks at $\Sigma_c D^* => J = 1/2, 3/2$

Hadronic Molecule?

Quark model

Closed-pentaquark + Fallapart

Hiyama et.al. Phys.Rev.C 98 (2018) 4, 045208 Qi Meng et al, Phys.Lett.B 798 (2019) 135028

$$H = \sum_{i} (m_{i} + \frac{p_{i}^{2}}{2m_{i}}) - T_{G} - \frac{3}{16} \sum_{i < j} \lambda_{i} \cdot \lambda_{j} V_{ij}(r_{ij})$$
$$V_{ij}(r) = -\frac{\kappa}{r} + \lambda r^{p} - \Lambda + \frac{2\pi\kappa'}{3m_{i}m_{j}} \frac{\exp(-r^{2}/r_{0}^{2})}{\pi^{3/2} r_{0}^{3}} \sigma_{i} \cdot \sigma_{j}$$

- This cannot hold states near thresholds
- Allow compact states at some higher than thresholds

Model calculation

Yamaguchi et al, Phys.Rev. D96 (2017), 114031; Phys.Rev.D101 (2020) 9, 091502

Hadronic molecule of coupled channels with OPEP + 5q core





Predictions and data



- For systems of $Q\overline{Q}$, molecules are well developed (Next discussion)
- With one parameter *f*, tendency of masses are reproduced
- Width are explained by the OPEP tensor force



Strongly bound charmonia and bottomonia



T(bbud)

LETTER

Quark – level analogue of nuclear fusion with doubly heavy baryons

Marek Karliner¹ & Jonathan L. Rosner²



Summary

- Roper resonances: Arifi et al, $\Lambda_c(2765)$: arXiv:2003.08202 [hep-ph], to appear in PRD $\Lambda_b(6072)$: arXiv:2004.07423 [hep-ph], just accepted by PRD TODAY Flavor blind ~ Another evidence of light diquark clusters. Two pion decays explained by baryon sequential process Conventional quark model, too high mass, too small width
- Pc: Hiyama et.al. Phys.Rev.C 98 (2018) 4, 045208, Qi Meng et al, Phys.Lett.B 798 (2019) 135028 Yamaguchi et al, Phys.Rev. D96 (2017), 114031; Phys.Rev.D101 (2020) 9, 091502
 Likely to be molecules of hadronic clusters.
 OPEP alone does not seem provide enough attraction => other attractive source The origin of force is to be understood => Lattice simulations and models
- Doubly heavy stable states:

QQ Heavy diquarks strongly attractive => stable exotics Systematic theory calculation is on-going (Meng, Hiyama, Oka, ...)