Exotica production from heavy ion collisions

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1. Few words on Compact Multiquark configurations
2. Where are the compact multiquark states?
3. Exotica production from heavy ion collisions
4. Summary

1. Multiquark configuration in quark model: Aaron Park,* Woosung Park,† and Su Houng Lee‡
PRD92.014037, PRD93.074007, PRD94.054027, PRD95.054027, PRD96.034029,

2. Exotics and Heavy ion: PRL 106(2011)212001, PRC84(2011)06491, PPNP 95(2017)279
Sungtae Cho,[1] Takenori Furumoto,[2,3] Tetsuo Hyodo,[4] Daisuke Jido,[2] Che Ming Ko,[5] Su Houng Lee,[1] Marina Nielsen,[6] Akira Ohnishi,[2] Takayasu Sekihara,[2,7] Shigehiro Yasui,[8] and Koichi Yazaki[2,9]
(ExHIC Collaboration) +T. Song, K. Morita, Maeda

I: Few words on “Multiquark states”

X(3872)

- 2003 -

$$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$$

$$M = 3872.0 \pm 0.6 \pm 0.5\ \text{MeV}$$

- 2013 -

X(3872) $I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 3871.69 \pm 0.17$ MeV
$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
$m_{X(3872)} - m_{\psi(2S)}$
Full width $\Gamma < 1.2$ MeV, CL = 90%

Z(4430)

- 2007 -

$$B \to K\pi^{\pm}\psi'$$

$$M = 4433 \pm 4 \pm 2\ \text{MeV}$$

$$\Gamma = 45^{+18}_{-13}(\text{stat})^{+30}_{-13}(\text{syst})\ \text{MeV}$$

- 2014 -

Spin parity = 1+

Pentaquark - Pc

- 2015 -

$$\Lambda_b^0 \to J/\psi\ p K^-$$

$$S = 3/2 \begin{cases} M_1 = 4380 \pm 8 \pm 29 \text{ MeV} \\ \Gamma_1 = 205 \pm 18 \pm 86 \text{ MeV} \end{cases} \qquad S = 5/2 \begin{cases} M_2 = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV} \\ \Gamma_2 = 39 \pm 5 \pm 19 \text{ MeV} \end{cases}$$

Baryon with ccu

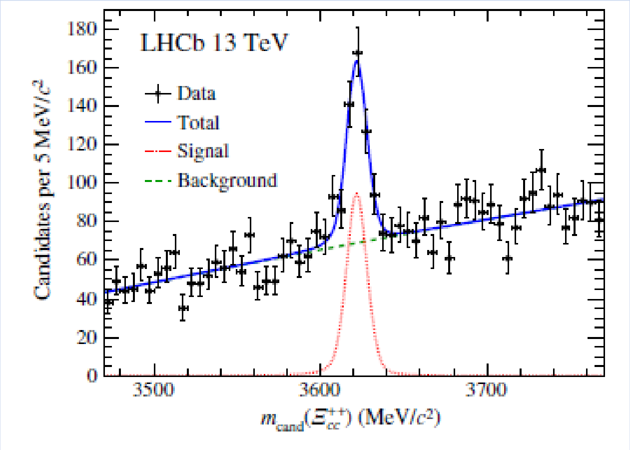
PRL119 (2017)112001

- 2017 -

$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$

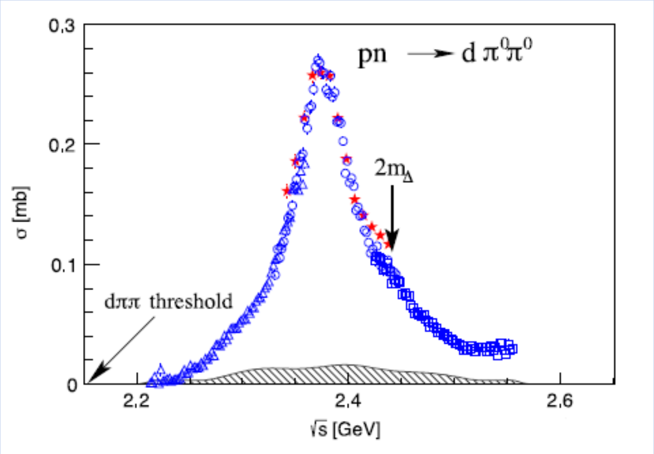
$$m_{\Xi_{cc}} - m_{\Lambda_c} = 1334.94 \pm 0.72 \pm 0.27 \text{ MeV}$$

$$m_{\Xi_{cc}} = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14 (\Lambda_c^+) \text{MeV}$$

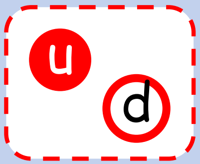
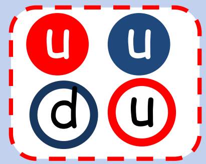
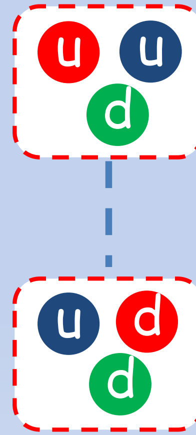
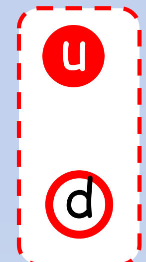


d*(2380) $I\left(J^{P}\right)=0\left(3^{+}\right)$

- WASA-at-COSY- Γ = 70 MeV



Normal meson, compact multiquark, molecules, resonances

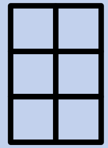
	Normal meson	Compact multiquark	Molecules	Resonance
Geometrical configuration				
Examples	Nucleon, pion, kaon	?	X(3872)	K*, rho meson

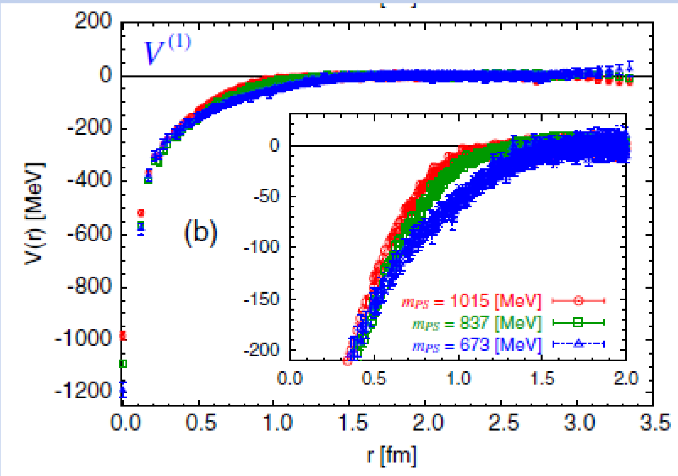
Pc, d*

II: Where are the compact “Multiquark states”

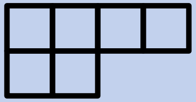
- Lattice Results : HAL QCD collaboration for H dibaryon in SU(3) symmetric limit

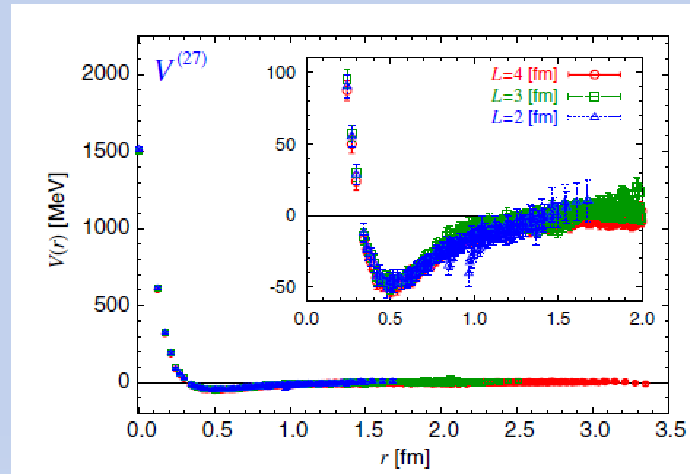
SU(3) flavor 1 state





SU(3) flavor 27 state





→ Flavor 1 channel could give compact configuration

Compact multiquark states could exists if there is a strong short range attraction

The r→0 behavior should be understood from quark model

Quark wave function for multiquark states (W.Park, A.Park, SHL)

- Some Previous works have limited Fock space: diquark picture …

- Hard to picture interplay between various contribution

- Hard to understand SU(3) breaking effects.

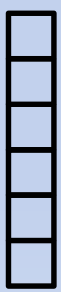
→ Work out the full (color) x (spin) x (flavor) wave function for all multiquark configurations at least for the ground state s-wave states

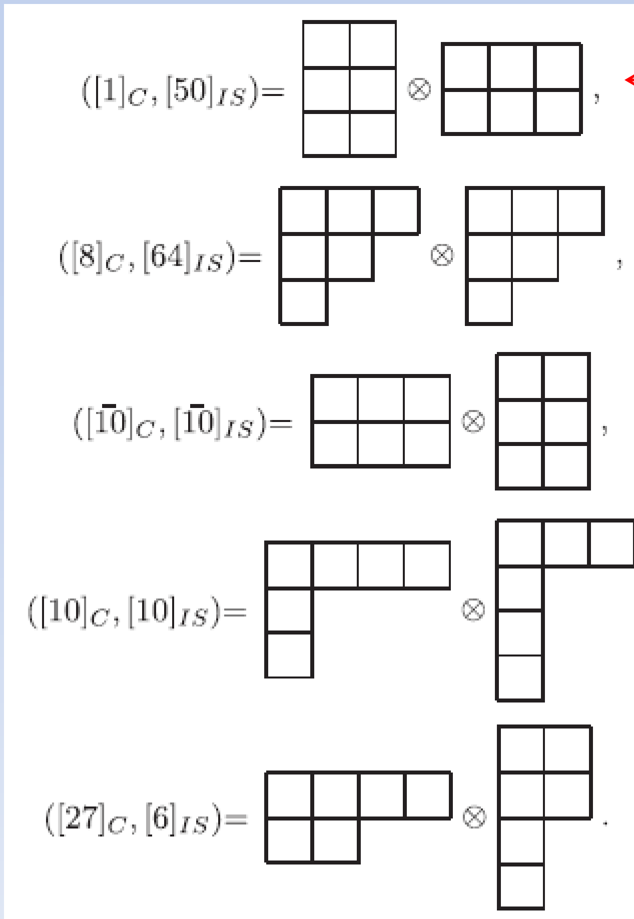
Quark wave function for light dibaryons *(W.Park, A.Park, SHL15.)*

- Choose the spatial part to be symmetric

- Choose the Color-Isospin-Spin part to be antisymmetric : SU(12)

$$[1^6]_{CIS} = ([1]_C,[50]_{IS}) \oplus ([8]_C,[64]_{IS}) \oplus ([10]_C,[10]_{IS}) \oplus ([10]_C,[10]_{IS}) \oplus ([27]_C,[6]_{IS})$$





Physical State

- Dibaryon: 5 Independent color singlet bases

$$\begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 & 4 \\ \hline 5 & 6 \\ \hline \end{array} \qquad \left|C_1\right\rangle = \left\{\left[(12)_6 3\right]_8 \left[4(56)_6\right]_8\right\}_1$$

$$\begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 & 4 \\ \hline 5 & 6 \\ \hline \end{array} \qquad \left|C_2\right\rangle = \left\{\left[(12)_{\bar{3}} 3\right]_8 \left[4(56)_6\right]_8\right\}_1$$

$$\begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 & 5 \\ \hline 4 & 6 \\ \hline \end{array} \qquad \left|C_3\right\rangle = \left\{\left[(12)_6 3\right]_8 \left[4(56)_{\bar{3}}\right]_8\right\}_1$$

$$\begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 & 5 \\ \hline 4 & 6 \\ \hline \end{array} \qquad \left|C_4\right\rangle = \left\{\left[(12)_{\bar{3}} 3\right]_8 \left[4(56)_{\bar{3}}\right]_8\right\}_1$$

$$\begin{array}{|c|c|}\hline 1 & 4 \\ \hline 2 & 5 \\ \hline 3 & 6 \\ \hline \end{array} \qquad \left|C_5\right\rangle = \left\{\left[(12)_{\bar{3}} 3\right]_1 \left[4(56)_{\bar{3}}\right]_1\right\}_1$$

- Pentaquark: 3 Independent color singlet bases (W.Park, A. Park, S.Cho, SHL PRD95,054027)

$$\xcancel{\begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 & 4 \\ \hline 5 & 6 \\ \hline\end{array}} \qquad |C_1\rangle = \{[(12)_6 3]_8 [4(56)_6]_8\}_1$$

$$\xcancel{\begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 & 4 \\ \hline 5 & 6 \\ \hline\end{array}} \qquad |C_2\rangle = \{[(12)_{\bar{3}} 3]_8 [4(56)_6]_8\}_1$$

$$\begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 & 5 \\ \hline 4 & 6 \\ \hline\end{array} \qquad |C_3\rangle = \{[(12)_6 3]_8 [4(5)_{\bar{3}}]_8\}_1$$

$$\begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 & 5 \\ \hline 4 & 6 \\ \hline\end{array} \qquad |C_4\rangle = \{[(12)_{\bar{3}} 3]_8 [4(5)_{\bar{3}}]_8\}_1$$

$$\begin{array}{|c|c|}\hline 1 & 4 \\ \hline 2 & 5 \\ \hline 3 & 6 \\ \hline\end{array} \qquad |C_5\rangle = \{[(12)_{\bar{3}} 3]_1 [4(5)_{\bar{3}}]_1\}_1$$

- Heptaquark: 11 Independent color singlet bases (W.Park, A. Park, SHL PRD96,034029)

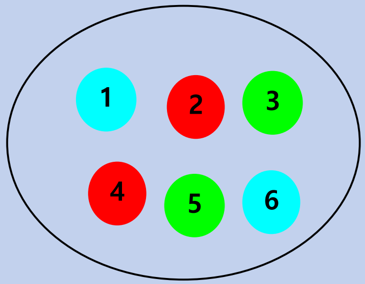
$$|C_1\rangle = \left(\begin{array}{|c|c|}\hline 1&2\\\hline 3&4\\\hline \multicolumn{1}{|c|}{5}\\\cline{1-1}\end{array}, \begin{array}{|c|}\hline \bar{6}\\\hline \bar{7}\\\hline\end{array}\right),\quad |C_2\rangle = \left(\begin{array}{|c|c|}\hline 1&3\\\hline 2&4\\\hline \multicolumn{1}{|c|}{5}\\\cline{1-1}\end{array}, \begin{array}{|c|}\hline \bar{6}\\\hline \bar{7}\\\hline\end{array}\right),\quad |C_3\rangle = \left(\begin{array}{|c|c|}\hline 1&2\\\hline 3&5\\\hline \multicolumn{1}{|c|}{4}\\\cline{1-1}\end{array}, \begin{array}{|c|}\hline \bar{6}\\\hline \bar{7}\\\hline\end{array}\right),\quad |C_4\rangle = \left(\begin{array}{|c|c|}\hline 1&3\\\hline 2&5\\\hline \multicolumn{1}{|c|}{4}\\\cline{1-1}\end{array}, \begin{array}{|c|}\hline \bar{6}\\\hline \bar{7}\\\hline\end{array}\right),\quad |C_5\rangle = \left(\begin{array}{|c|c|}\hline 1&4\\\hline 2&5\\\hline \multicolumn{1}{|c|}{3}\\\cline{1-1}\end{array}, \begin{array}{|c|}\hline \bar{6}\\\hline \bar{7}\\\hline\end{array}\right),$$

$$|C_6\rangle = \left(\begin{array}{|c|c|c|}\hline 1&2&3\\\hline \multicolumn{1}{|c|}{4}\\\cline{1-1} \multicolumn{1}{|c|}{5}\\\cline{1-1}\end{array}, \begin{array}{|c|c|}\hline \bar{6}&\bar{7}\\\hline\end{array}\right),\quad |C_7\rangle = \left(\begin{array}{|c|c|c|}\hline 1&2&4\\\hline \multicolumn{1}{|c|}{3}\\\cline{1-1} \multicolumn{1}{|c|}{5}\\\cline{1-1}\end{array}, \begin{array}{|c|c|}\hline \bar{6}&\bar{7}\\\hline\end{array}\right),\quad |C_8\rangle = \left(\begin{array}{|c|c|c|}\hline 1&3&4\\\hline \multicolumn{1}{|c|}{2}\\\cline{1-1} \multicolumn{1}{|c|}{5}\\\cline{1-1}\end{array}, \begin{array}{|c|c|}\hline \bar{6}&\bar{7}\\\hline\end{array}\right),\quad |C_9\rangle = \left(\begin{array}{|c|c|c|}\hline 1&2&5\\\hline \multicolumn{1}{|c|}{3}\\\cline{1-1} \multicolumn{1}{|c|}{4}\\\cline{1-1}\end{array}, \begin{array}{|c|c|}\hline \bar{6}&\bar{7}\\\hline\end{array}\right),$$

$$|C_{10}\rangle = \left(\begin{array}{|c|c|c|}\hline 1&3&5\\\hline \multicolumn{1}{|c|}{2}\\\cline{1-1} \multicolumn{1}{|c|}{4}\\\cline{1-1}\end{array}, \begin{array}{|c|c|}\hline \bar{6}&\bar{7}\\\hline\end{array}\right),\quad |C_{11}\rangle = \left(\begin{array}{|c|c|c|}\hline 1&4&5\\\hline \multicolumn{1}{|c|}{2}\\\cline{1-1} \multicolumn{1}{|c|}{3}\\\cline{1-1}\end{array}, \begin{array}{|c|c|}\hline \bar{6}&\bar{7}\\\hline\end{array}\right).$$

In quark model: wave function should follow Pauli Principle

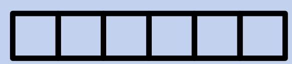
- Totally antisymmetric (color x spin x flavor) wave function (s-wave ground state)



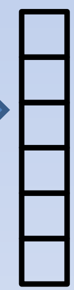
Example: $\Omega\Omega$ in the Spin=3 channel is highly repulsive because

→ Flavor is totally symmetric

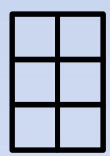
→ Spin is totally symmetric



→ Remaining part should be totally antisymmetric



→ But color singlet implies



→ Hence, assuming all quarks are in the S wave, Pauli principle forbids compact configuration.

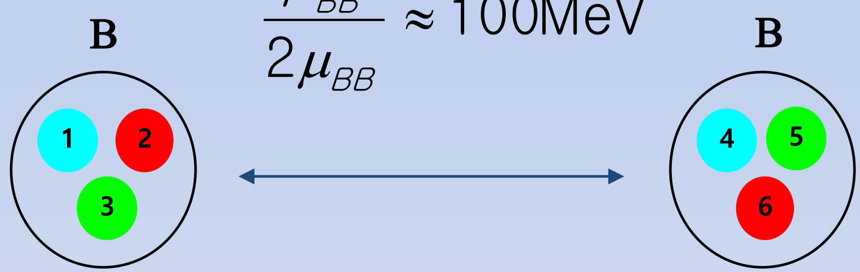
Such forbidden configuration are highly repulsive at r→0 (Oka et al quark cluster model)

- In Constituent quark model

$$H=\sum_{i=1}^{n}\left(m_i+\frac{p_i^2}{2m_i}\right)-\sum_{i<j}^{n}\left(\lambda_i^c\lambda_j^c\right)V_{ij}^C\left(r_{ij}\right)-\sum_{i<j}^{n}\frac{\left(\lambda_i^c\lambda_j^c\right)\left(\sigma_i\sigma_j\right)}{m_i m_j}V_{ij}^{SS}\left(r_{ij}\right)$$

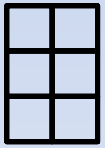
1) Additional Kinetic energy compared to separated hadrons

$$\frac{p_{BB}^2}{2\mu_{BB}}\approx 100\mathrm{MeV}$$



2) Color-color will not add much

$$\underbrace{\left(\lambda_1^c+\lambda_2^c+\lambda_3^c\right)}_{\text{If color singlet}}\lambda_j^c=0$$



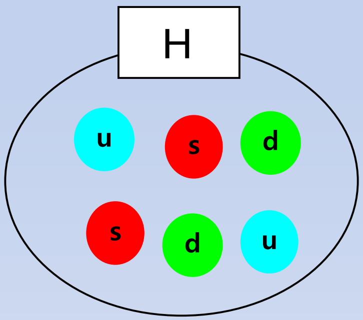
3) Color-spin interaction is important

- Color spin interaction

$$-\sum_{i<j}^{n}\frac{\overbrace{\left(\lambda_i^c\lambda_j^c\right)\left(\sigma_i\sigma_j\right)}^{K}}{m_i m_j}V_{ij}^{SS}\left(r_{ij}\right)$$

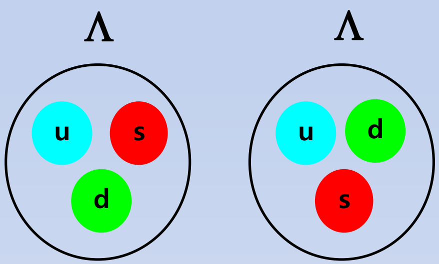
	qq				$\bar{q}q$			
Color	A	S	A	S	1	8	1	8
Flavor	A	A	S	S				
Spin	A(1)	S(3)	S(3)	A(1)	1	1	3	3
K	-8	-4/3	8/3	4	-16	2	16/3	-2/3

- Jaffe (77) : K for H and two Λ



$$K = -24$$

vs



$$K = (-8) + (-8) = -16$$

→ using Nucleon(K=-8) to Delta (K=+8) mass difference of 290 MeV

ΔK=-8 corresponds to about 145 MeV attraction > additional Kinetic energy of 100 MeV

- Dibaryons with 6 light quarks: W.Park, A. Park, SHL, PRD92(2015)014037

$$K = -\sum_{i<j}^{n} \left(\lambda_i^c \lambda_j^c\right)\left(\sigma_i \sigma_j\right)$$

$$K_{\text{dibaryon}} - \left(K_{\text{baryon 1}} - K_{\text{baryon 2}}\right)$$

Color spin interaction of 6 quark state and their decays

(I,S)	(3,0)	(2,1)	(1,2)	(1,0)	(0,3)	(0,1)
V_d	48	$\frac{80}{3}$	16	8	16	$\frac{8}{3}$
ΔV	32	$\frac{80}{3}$	16	24	0	$\frac{56}{3}$

→ The only non repulsive channel, but also no attraction

→ Strong indication that d*(2380) is a molecular configuration

(A. Gal, PLB769(2017)436) $s_\Delta = (1232 - B_{\Delta\Delta}/2)^2 - p^2_{\Delta\Delta}, \quad \bar{s}_\Delta = (1232 - B_{\Delta\Delta}/2)^2 - P^2_{\Delta\Delta},$

→ No compact dibaryon in flavor SU(2)

- Perhaps a heptaquark ?: W.Park, A. Park, SHL, PRD92(2015)014037

$-\sum_{i<j}^{n} \frac{K}{m_i m_j}$	**$q^2 s^3 \bar{s}^2$ heptaquark**	**$\Lambda + \phi + \phi$**	**$\Delta E_{hyperfine}$**
$m_{u,d} \approx \frac{3}{5} m_s$	$\left(-\frac{6}{m_u^2} - \frac{12.2}{m_u m_s} + \frac{9.3}{m_s^2}\right) \approx -\frac{7.23}{m_u^2}$	$-\frac{8}{m_u^2} + \frac{32}{3m_s^2}$	-56 MeV

- H dibaryon with realistic quark masses: W.Park, A. Park, SHL, PRD93(2016)074007

$$-\sum_{i<j}^{n} \frac{\left(\lambda_i^c \lambda_j^c\right)\left(\sigma_i \sigma_j\right)}{m_i m_j} V_{ij}^{SS}(r_{ij})$$

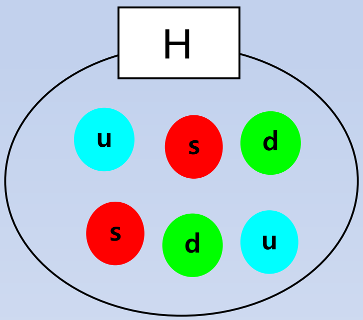
K

$m_{u,d} = 300$ MeV, $m_s = 500$ MeV

TABLE III. The matrix element of $-\langle \lambda_i^c \lambda_j^c \sigma_i \cdot \sigma_j \rangle$ for hyperfine potential of the dibaryon with respect to isospin and flavor.

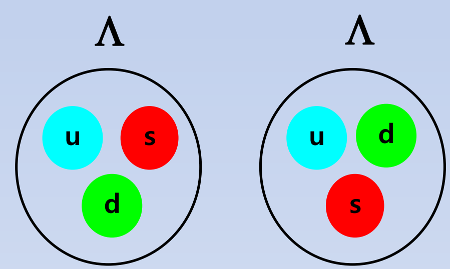
Isospin Flavor	$-\langle \lambda_i^c \lambda_j^c \sigma_i \cdot \sigma_j \rangle$ $i<j=1$–4	$-\langle \lambda_i^c \lambda_j^c \sigma_i \cdot \sigma_j \rangle$ $i=1$–4, $j=5, 6$	$-\langle \lambda_i^c \lambda_j^c \sigma_i \cdot \sigma_j \rangle$ $i=5$, $j=6$
$I=0$, F^1	$-5/6$	$-11/4$	3
$I=0$, F^{27}	$-13/18$	$13/12$	$11/3$
Cross terms	$1/(6\sqrt{3})$	$-1/(4\sqrt{3})$	$1/\sqrt{3}$
$I=1$, F^{27}	$4/9$	$1/3$	$8/3$
$I=2$, F^{28}	$16/5$	$16/5$	$16/5$
$I=2$, F^{27}	$146/45$	$-28/15$	$52/15$
Cross terms	$-2\sqrt{2}/(15\sqrt{3})$	$\sqrt{2}/(5\sqrt{3})$	$-4\sqrt{2}/(5\sqrt{3})$

→ If the SU(3) breaking is taken into account. Color spin with constituent quark mass



$\leftarrow \dfrac{p_{BB}^2}{2\mu_{BB}} \approx 100$ MeV

VS



$-\sum_{i<j}^{n} \frac{K}{m_i m_j}$	**H dibaryon**	**Λ + Λ**	**Δ E$_{hyperfine}$**	**Δ E$_{kinetic}$**
$m_{u,d} = m_s$	$-\dfrac{24}{m_u^2}$	$-\dfrac{8}{m_u^2} - \dfrac{8}{m_u^2}$	-145 MeV	+100MeV
$m_{u,d} \approx \frac{3}{5} m_s$	$\left(-\dfrac{5}{m_u^2} - \dfrac{22}{m_u m_s} + \dfrac{3}{m_s^2}\right) \approx -\dfrac{17.12}{m_u^2}$	$-\dfrac{8}{m_u^2} - \dfrac{8}{m_u^2}$	-20 MeV	+ 84 MeV

Where are the compact multiquark states? - What we need

1) Need Strong Color spin interaction

$$-\sum_{i<j}^{n} \frac{\left(\lambda_i^c \lambda_j^c\right)\left(\sigma_i \sigma_j\right)}{m_i m_j} V_{ij}^{SS}\left(r_{ij}\right)$$

→ that survive in the SU(3) breaking limit

2) Need heavy quarks to suppress additional kinetic term

$$\frac{p_{BB}^2}{2\mu_{BB}} \approx \frac{\left(1/size\right)^2}{2\mu_{BB}} \qquad \mu_{BB} \approx \frac{m_{baryon1} m_{baryon2}}{m_{baryon1} + m_{baryon2}}$$

→ both baryons should have heavy quarks

- Is Pentaquark (Pc) compact ? W.park, A. Park, S.Cho, SHL, PRD95(2017) 054027

1) Color spin interaction of Pc(4380) 3/2 $^-$ state $qqq\, c\bar{c}$

\- 2015 -

LHCb

$$\Lambda_b^0 \to J/\psi\ p K^-$$

$$S = 3/2 \begin{cases} M_1 = 4380 \pm 8 \pm 29\ \text{MeV} \\ \Gamma_1 = 205 \pm 18 \pm 86\ \text{MeV} \end{cases} \qquad S = 5/2 \begin{cases} M_2 = 4449.8 \pm 1.7 \pm 2.5\ \text{MeV} \\ \Gamma_2 = 39 \pm 5 \pm 19\ \text{MeV} \end{cases}$$

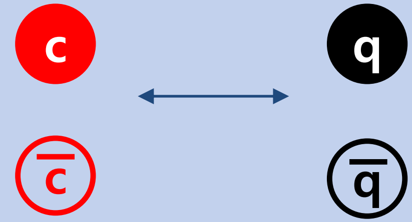
Pc(4380) can be reconstructed from $J/\psi + p$

$-\sum_{i<j}^{n} \frac{K}{m_i m_j}$ **Pc(4380)**	**J/ψ + π**	**Δ $E_{hyperfine}$**	**Δ $E_{kinetic}$**
$\left(-\frac{7.88}{m_u^2} + \frac{5.29}{m_c^2} - \frac{1.41}{m_u m_c}\right) \approx -\frac{7.95}{m_u^2}$	$\left(-\frac{8}{m_u^2} + \frac{16}{3m_c^2}\right) \approx -\frac{7.79}{m_u^2}$	-3 MeV	+ 70MeV

→ Most likely a molecular states

- Heavy Tetraquarks (Spin=1 case)

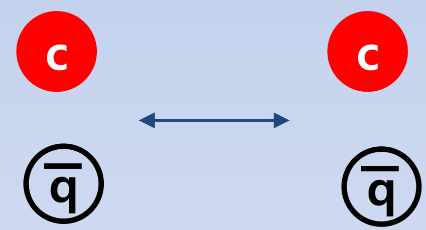
1) Heavy quark-antiquark: $c\bar{c}$



$$\mu_{BB} \approx \frac{m_{c\bar{c}} m_{q\bar{q}}}{m_{baryon1} + m_{baryon2}} \approx m_{q\bar{q}}$$

$-\sum_{i<j}^{n} \frac{K}{m_i m_j}$	**Tetraquark**	**J/ψ + π**	**Δ E$_{hyperfine}$**	**Δ E$_{kinetic}$**
$c\bar{c}$	$\left(-\frac{16}{m_u^2} + \frac{16}{3m_c^2}\right)$	$\left(-\frac{16}{m_u^2} + \frac{16}{3m_c^2}\right)$	0 MeV	+100MeV

2) Heavy quark-quark: cc



$$\mu_{MM} \approx \frac{m_{c\bar{q}} m_{c\bar{q}}}{m_{c\bar{q}} + m_{c\bar{q}}} \approx \frac{1}{2} m_{c\bar{q}}$$

$-\sum_{i<j}^{n} \frac{K}{m_i m_j}$	**Tetraquark**	**D + D***	**Δ E$_{hyperfine}$**	**Δ E$_{kinetic}$**
cc	$\left(-\frac{8}{m_u^2} + \frac{8}{3m_c^2}\right) \approx -\frac{7.47}{m_u^2}$	$\left(-\frac{8}{m_q m_c} + \frac{8}{3m_q m_c}\right)$	-97 MeV	+50MeV

- Heavy Tetraquarks

1) Previous works on Tcc

Z. Zouzou, B. Silverstre-Brac, C. Gilgnooux, J Richard (86), D. Janc, M. Rosina (04), Y. Cui, S. L. Zhu (07)

QCD sum rules: F Navarra, M. Nielsen, SHLee, PLB 649, 166 (2007)

simple diquark: SHL, S. Yasui, W.Liu, C Ko EPJ C54, 259 (2008), SHL, S. Yasui: EPJ C (09)

2) Promising final state signals

$$\mathrm{T}^{1}_{\mathrm{cc}}(\mathrm{ud}\bar{\mathrm{c}}\bar{\mathrm{c}}) \rightarrow (\bar{D}^{0} + D^{*-}) \rightarrow K^{+}\pi^{-} + K^{+}\pi^{-}\pi^{-}$$

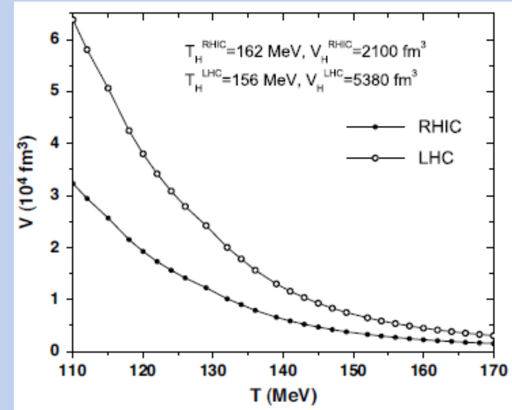
threshold	decay mode	lifetime
$M_{T_{cc}} > M_{D^*} + M_D$	$D^{*-}\bar{D}^0$	hadronic decay
$2M_D + M_\pi < M_{T_{cc}} < M_{D^*} + M_D$	$\bar{D}^0\bar{D}^0\pi^-$	hadronic decay
$M_{T_{cc}} < 2M_D + M_\pi$	$D^{*-}K^+\pi^-$, $D^{*-}K^+\pi^+\pi^-\pi^-$	0.41×10^{-12} sec.

→ Most likely a compact tetraquark states

III: Exotica production from Heavy Ion Collision

Details of coalescence model calculation (ExHIC PPNP 2017)

- Model central rapidity, central collision using Lattice EOS



- Heavy quark production (T Song)

Table 3.2
Estimates of heavy quark pairs dN/dy at midrapidity in 0%–10% central collision at RHIC and LHC.

	RHIC	LHC @2.76 TeV	LHC @5.02 TeV
Without shadowing			
$N_c = N_{\bar{c}}$	4.5	17	23
$N_b = N_{\bar{b}}$	0.034	0.68	1.2
With shadowing			
$N_c = N_{\bar{c}}$	4.1	11	14
$N_b = N_{\bar{b}}$	0.031	0.44	0.71

- Coalescence Parameters:

fit production of normal hadrons from statistical model

$$N_h^{\rm coal} = g_h \prod_{j=1}^{n} \frac{N_j}{g_j} \prod_{i=1}^{n-1} \frac{\int d^3y_i d^3k_i f_i(k_i) f^W(y_i, k_i)}{\int d^3y_i d^3k_i f_i(k_i)}$$

$$f_s^W(y_i, k_i) = 8\exp\left(-\frac{y_i^2}{\sigma_i^2} - k_i^2\sigma_i^2\right) \qquad \sigma_i = 1/\sqrt{\mu_i \omega}$$

$m_{u,d} = 300$ MeV

$m_s = 500$ MeV

$m_c = 1500$ MeV

$m_b = 4700$ MeV

	RHIC		LHC (2.76 TeV)		LHC (5.02 TeV)		RHIC	LHC (5 TeV)
	Sc. 1	Sc. 2	Sc. 1	Sc. 2	Sc. 1	Sc. 2	Refs [14,15]	
T_H (MeV)	162		156				175	
V_H (fm^3)	2100		5380				1908	5152
μ_B (MeV)	24		0				20	0
μ_s (MeV)	10		0				10	0
γ_c	22		39		50		6.40	15.8
γ_b	4.0×10^7		8.6×10^8		1.4×10^9		2.2×10^6	3.3×10^7
T_C (MeV)	162	166	156	166	156	166	175	
V_C (fm^3)	2100	1791	5380	3533	5380	3533	1000	2700
ω (MeV)	590	608	564	609	564	609	550	
ω_s (MeV)	431	462	426	502	426	502	519	
ω_c (MeV)	222	244	219	278	220	279	385	
ω_b (MeV)	183	202	181	232	182	234	338	
$N_u = N_d$	320	302	700	593	700	593	245	662
$N_s = N_{\bar{s}}$	183	176	386	347	386	347	150	405
$N_c = N_{\bar{c}}$	4.1		11		14		3	20
$N_b = N_{\bar{b}}$	0.03		0.44		0.71		0.02	0.8
T_F (MeV)	119		115				125	
V_F (fm^3)	20355		50646				11322	30569
N_K	67.5		134				142[a]	363[a]
$N_{\bar{K}}$	59.6		134				127[a]	363[a]
N_N	20		32				62[a]	150[a]
N_Δ	18		28				–	–
N_Λ	3.8		6.5				–	–
N_Ξ	2.6		4.4				4.7	13
N_Ω	0.37		0.62				0.81	2.3
$N_D = N_{\bar{D}}$	1.5		4.0		5.2		1.0	6.9
$N_{D^*} = N_{\bar{D}^*}$	2.0		5.4		6.9		1.5	10
$N_{D_1} = N_{\bar{D}_1}$	0.20		0.49		0.63		0.19	1.3
$N_B = N_{\bar{B}}$	8.1×10^{-3}		0.12		0.20		5.3×10^{-3}	0.21
$N_{B^*} = N_{\bar{B}^*}$	1.9×10^{-2}		0.27		0.45		1.2×10^{-2}	0.49
N_{Λ_c}	0.17		0.36		0.46		–	–
N_{Σ_c}	0.2		0.41		0.52		–	–
$N_{\Sigma_c^*}$	0.28		0.56		0.71		–	–
N_{Ξ_c}	0.11		0.25		0.32		0.10	0.65

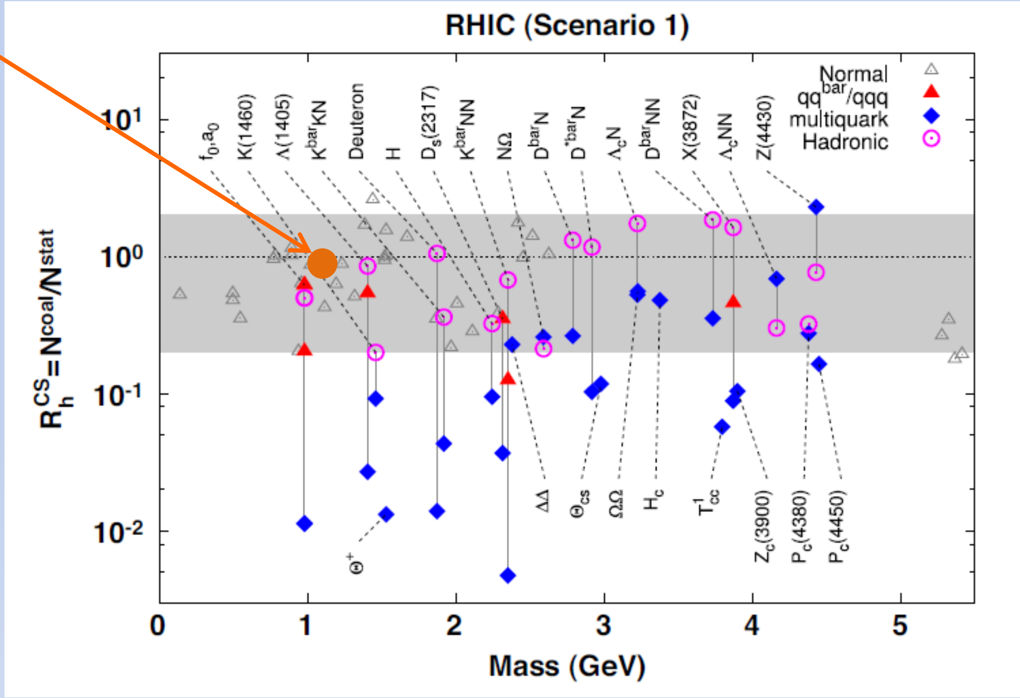
[a] Values contain feed down contributions.

- Hadron coalescence for molecules at kinetic freezeout point

$$\omega = \frac{3}{2\mu_R \langle r^2 \rangle} \quad \text{or} \quad B \approx \frac{\hbar^2}{2\mu_R a_0^2}, \quad \langle r^2 \rangle \approx \frac{a_0^2}{2}$$

Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.	$\omega_{\mathrm{Mol.}}$ (MeV)	Decay mode
Mesons									
$f_0(980)$	980	1	0	0^+	$q\bar{q}, s\bar{s}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\pi\pi$ (Strong decay)
$a_0(980)$	980	3	1	0^+	$q\bar{q}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\eta\pi$ (Strong decay)
$K(1460)$	1460	2	1/2	0^-	$q\bar{s}$	$q\bar{q}q\bar{s}$	$\bar{K}KK$	69.0(R)	$K\pi\pi$ (Strong decay)
$D_s(2317)$	2317	1	0	0^+	$c\bar{s}(L=1)$	$q\bar{q}c\bar{s}$	DK	273(B)	$D_s\pi$ (Strong decay)
T_{cc}^{1} [a]	3797	3	0	1^+	—	$qq\bar{c}\bar{c}$	$\bar{D}\bar{D}^*$	476(B)	$K^+\pi^- + K^+\pi^- + \pi^-$
$X(3872)$	3872	3	0	$1^+, 2^-$ [c]	$c\bar{c}(L=2)$	$q\bar{q}c\bar{c}$	$\bar{D}D^*$	3.6(B)	$J/\psi\pi\pi$ (Strong decay)
$Z^+(4430)$ [b]	4430	3	1	0^- [c]	—	$q\bar{q}c\bar{c}(L=1)$	$D_1\bar{D}^*$	13.5(B)	$J/\psi\pi$ (Strong decay)
T_{cb}^{0} [a]	7123	1	0	0^+	—	$qq\bar{c}\bar{b}$	$\bar{D}B$	128(B)	$K^+\pi^- + K^+\pi^-$
Baryons									
$\Lambda(1405)$	1405	2	0	$1/2^-$	$qqs(L=1)$	$qqqs\bar{q}$	$\bar{K}N$	20.5(R)–174(B)	$\pi\Sigma$ (Strong decay)
$\Theta^+(1530)$ [b]	1530	2	0	$1/2^+$ [c]	—	$qqqq\bar{s}(L=1)$	—	—	KN (Strong decay)
$\bar{K}KN$ [a]	1920	4	1/2	$1/2^+$	—	$qqqs\bar{s}(L=1)$	$\bar{K}KN$	42(R)	$K\pi\Sigma, \pi\eta N$ (Strong decay)
$\bar{D}N$ [a]	2790	2	0	$1/2^-$	—	$qqqq\bar{c}$	$\bar{D}N$	6.48(R)	$K^+\pi^-\pi^- + p$
$\bar{D}^*N$ [a]	2919	4	0	$3/2^-$	—	$qqqq\bar{c}(L=2)$	$\bar{D}^*N$	6.48(R)	$\bar{D} + N$ (Strong decay)
Θ_{cs} [a]	2980	4	1/2	$1/2^+$	—	$qqqs\bar{c}(L=1)$	—	—	$\Lambda + K^+\pi^-$
BN [a]	6200	2	0	$1/2^-$	—	$qqqq\bar{b}$	BN	25.4(R)	$K^+\pi^-\pi^- + \pi^+ + p$
B^*N [a]	6226	4	0	$3/2^-$	—	$qqqq\bar{b}(L=2)$	B^*N	25.4(R)	$B + N$ (Strong decay)
Dibaryons									
H [a]	2245	1	0	0^+	$qqqqss$	—	ΞN	73.2(B)	$\Lambda\Lambda$ (Strong decay)
$\bar{K}NN$ [b]	2352	2	1/2	0^- [c]	$qqqqqs(L=1)$	$qqqqqq\, s\bar{q}$	$\bar{K}NN$	20.5(T)–174(T)	ΛN (Strong decay)
$\Omega\Omega$ [a]	3228	1	0	0^+	$ssssss$	—	$\Omega\Omega$	98.8(R)	$\Lambda K^- + \Lambda K^-$
H_c^{++} [a]	3377	3	1	0^+	$qqqqsc$	—	$\Xi_c N$	187(B)	$\Lambda K^-\pi^+\pi^+ + p$
$\bar{D}NN$ [a]	3734	2	1/2	0^-	—	$qqqqqq\, q\bar{c}$	$\bar{D}NN$	6.48(T)	$K^+\pi^- + d, K^+\pi^-\pi^- + p + p$
BNN [a]	7147	2	1/2	0^-	—	$qqqqqq\, q\bar{b}$	BNN	25.4(T)	$K^+\pi^- + d, K^+\pi^- + p + p$

Fachini [STAR]



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Summary I

1] Compact multiquark states can be understood from color spin flavor wave function:

- A strong attractive short range interaction is needed in the SU(3) broken limit
- Heavy quarks are needed to reduce extra Kinetic energy

→ Tcc could be strongly bound

$$\mathrm{T}^1_{\mathrm{cc}}(\mathrm{ud}\bar{\mathrm{c}}\bar{\mathrm{c}}) \rightarrow (\overline{D}^0 + D^{*-}) \rightarrow K^+\pi^- + K^+\pi^-\pi^-$$

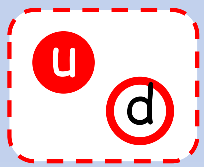
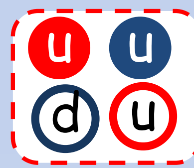
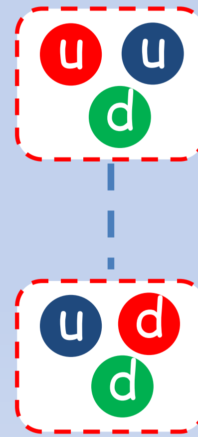
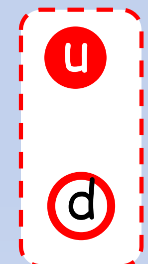
threshold	decay mode	lifetime
$M_{T_{cc}} > M_{D^*} + M_D$	$D^{*-}\bar{D}^0$	hadronic decay
$2M_D + M_\pi < M_{T_{cc}} < M_{D^*} + M_D$	$\bar{D}^0\bar{D}^0\pi^-$	hadronic decay
$M_{T_{cc}} < 2M_D + M_\pi$	$D^{*-}K^+\pi^-$, $D^{*-}K^+\pi^+\pi^-\pi^-$	0.41×10^{-12} sec.

→ Vertex detector: weakly decaying exotics : FAIR 10^4 D^0 /month,
LHC 10^5 D^0/month

→ T_{cc} production T_{cc}/D > 0.34×10^{-4} RHIC
> 0.8×10^{-4} LHC

Summary II

2] Measurements from Heavy Ion can discriminate the structures

	Normal meson	Compact multiquark	Molecules	Resonance
Geometrical configuration				
Examples	Nucleon, ..	Tcc , ...	Pc, d*, ..	K*, ρ meson
Production rate	= Statistical Model	<< Statistical Model	= Statistical Model	< Statistical Model

Back up slides

Suggestions

1. Lambda (1405): two poles?

$$\Lambda(1405) \rightarrow \pi^+ + \Sigma^- \rightarrow \pi^+ + n + \pi^-$$

$$\Lambda(1405) \rightarrow \pi^- + \Sigma^+ \xrightarrow{50\%} \pi^- + p + \pi^0$$

2. Dibayrons: d*(2323)→ $\Delta+\Delta$ H, N-Omega, Hc(uuudsc)

3. Light molecules or tetraquarks $f_0(980) \rightarrow \pi^+\pi^-$, $a_0(980) \rightarrow \eta\pi^\pm$

4. Heavy Tetraquarks $Z(3900) \rightarrow J/\psi + \pi^+$, $Z(4430) \rightarrow J/\psi + \pi^+$, or $\psi' + \pi^+$

$$X(5568) \rightarrow B_s^0 \pi^\pm \quad [bd][\bar{s}\bar{u}]$$

$$\boxed{\begin{array}{l} \mathrm{T}_{\mathrm{cb}}^{0}(\mathrm{ud}\bar{\mathrm{c}}\bar{\mathrm{b}}) \rightarrow (\bar{D}^0 + B^0) \rightarrow K^+\pi^- + K^+\pi^- \\ \mathrm{T}_{\mathrm{cc}}^{1}(\mathrm{ud}\bar{\mathrm{c}}\bar{\mathrm{c}}) \rightarrow (\bar{D}^0 + D^{*-}) \rightarrow K^+\pi^- + K^+\pi^-\pi^- \end{array}}$$

5. Heavy Pentaquarks $\boxed{\mathrm{P_c} \rightarrow J/\psi + p}$