Charmonium and charmed tetraquarks

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• The past four years have witnessed the renaissance of hadron espectroscopy. Several new hadron states whose properties are hard to accommodate in the valence quark model have been discovered.

• The most important difficulties were found to describe the light scalar mesons. The same situation is appearing in the open charm and charmonium-like states.

Light scalar (isoscalar) mesons: Too many resonances observed

11 isoscalars I=0 : $f_0(600)$, $f_0(980)$, $f_0(1200\text{-}1600)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, $f_0(1790)$, $f_0(1810)$, $f_0(2020)$, $f_0(2100)$, $f_0(2200)$

Masses very difficult to accommodate as quark-antiquark states
Decays not compatible with a simple quark-antiquark structure

New open-charm and charmonium like states

Open charm

$D_{sJ}^*(2317)$	$D_{sJ}(2460)$	$D_0^*(2308)$	
- $J^P=0^+$	- $J^P=1^+$	- $J^P=0^+$	$D_{sJ}(2632)$ (Selex)
- P $c\bar{s}$ ~ 2.48 GeV	- P $c\bar{s}$ ~ 2.55 GeV	- P $c\bar{n}$ ~ 2.46 GeV	$D_{sJ}^*(2715)$ (Belle)
- $\Gamma < 4.6$ MeV	- $\Gamma < 5.5$ MeV	- Γ ~ 276 MeV	$D_{sJ}(2860)$ (Babar)
			....

Charmonium

X (3872)		
- $J^{PC}=1^{++}$ $(2^{++},2^{-+},...)$	Y(4260) : ??	X (3940)
- P $c\bar{c}$ ~ 3.9-4.0 GeV		Y (3940) : 2^3P_J
- $\Gamma < 2.3$ MeV	Y(4385) : 4^3S_1, 3^3D_1	Z (3940)

Overpopulation → Four-quark states

$$q\bar{q}\left[J^{PC}=0^{++}\right] \Rightarrow \quad S=1=L$$

- S=0

$$E(L=1)-E(L=0)=\begin{Bmatrix} h_1(1170)-\eta(550) \\ h_1(1595)-\eta'(958) \\ h_c(3526)-\eta_c(2980) \end{Bmatrix} \approx 0.5-0.6 \text{ GeV}$$

- S=1

$$[L=0] \begin{cases} \rho(770) \\ \omega(782) \end{cases} \Rightarrow [L=1] \quad X(J^{++}) \approx 1.3-1.4 \text{ GeV}$$

	$q\bar{q}$ ($\sim 2m_q$)	$q\bar{q}q\bar{q}$ ($\sim 4m_q$)
Negative parity	$0^-, 1^-$ (L=0)	$0^-, 1^-$ ($\ell_i \neq 0$)
Positive parity	$0^+, 1^+, 2^+$ (L=1)	$0^+, 1^+, 2^+$ ($\ell_i = 0$)

X(3872) → $c\bar{c}n\bar{n}$ To make physics clear → $c\bar{c}n\bar{n}$

HH: Solving the Schrödinger equation for $cc\bar{n}\bar{n}$

$$|\Psi\rangle = |\text{Color}\rangle|\text{Isospin}\rangle\left[|\text{Spin}\rangle\otimes|\text{R}\rangle\right]^{JM}$$

$$|\text{Color}\rangle = \left\{|\bar{3}_{12}3_{34}\rangle, |6_{12}\bar{6}_{34}\rangle\right\}$$

$$|\text{Spin}\rangle = |((s_1,s_2)S_{12},(s_3,s_4)S_{34})S\rangle = |(S_{12},S_{34})S\rangle$$

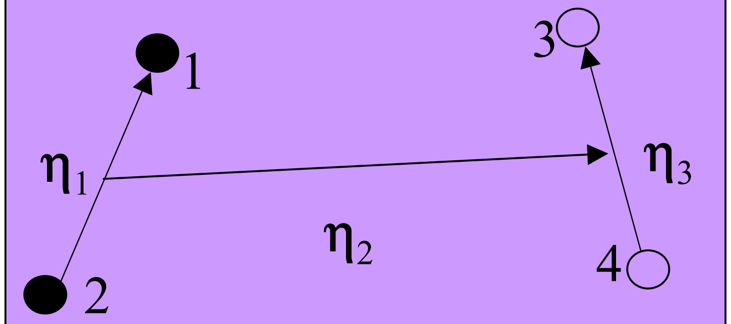
$$|\text{Isospin}\rangle = |(i_3,i_4)I_{34}\rangle$$

$$\langle\rho\Omega|R\rangle = U_n(\rho)\ \Omega Y_{[K]}(\Omega)$$

$$[\text{K}] \equiv \text{KK}_{12}\text{LM}_\text{L}\text{L}_{12}\ell_1\ell_2\ell_3$$

$Y_{[\text{K}]} \rightarrow$ HH functions

$U_n(\rho) \rightarrow$ Laguerre functions



$1,2 \rightarrow c \quad 3,4 \rightarrow n$

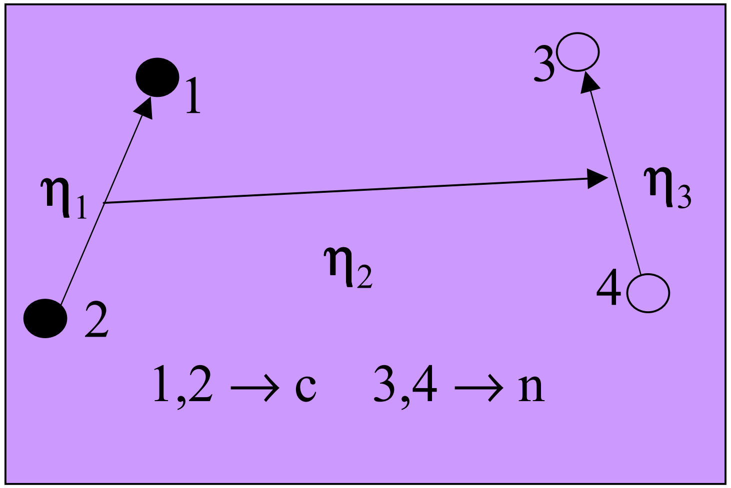
$$|\bar{3}_{12}3_{34}\rangle \rightarrow \begin{cases} (-1)^{S_{12}+\ell_1} = -1 \\ (-1)^{S_{34}+I+\ell_3} = +1 \end{cases}$$

$$|6_{12}\bar{6}_{34}\rangle \rightarrow \begin{cases} (-1)^{S_{12}+\ell_1} = +1 \\ (-1)^{S_{34}+I+\ell_3} = -1 \end{cases}$$

HH: Solving the Schrödinger equation for $cn\bar{c}\bar{n}$

$$|\Psi\rangle = |\text{Color}\rangle |\text{Isospin}\rangle \left[|\text{Spin}\rangle \otimes |R\rangle \right]^{JM}$$

$$|\text{Color}\rangle = \{ |1_{12} 1_{34}\rangle , |8_{12} 8_{34}\rangle \} \qquad \textbf{!}$$



C-parity is a good symmetry of the system

$$|C_{12}{}^{\Gamma_{12}}\rangle = \frac{1}{\sqrt{2}} \left(|C_{12}\rangle + \Gamma_{12} |C_{21}\rangle \right)$$

$|C_{12}\rangle = \{1_{12}, 8_{12}\}$ and Γ_{12}=+/- S/A

$$|(C_{34} I_{34})^{\Gamma 34}\rangle = \frac{1}{2} \left(|C_{34}\rangle \left(|u\bar{u}\rangle \pm |d\bar{d}\rangle \right) + \Gamma_{34} |C_{43}\rangle \left(|\bar{u}u\rangle \pm |\bar{d}d\rangle \right) \right)$$

$|C_{34}\rangle = \{1_{34}, 8_{34}\}$, Γ_{34}=+/- S/A , $|I_{34} = 1/0, I_{34}{}^{z} = 0\rangle$

$$|C_{12}{}^{\Gamma_{12}} (C_{34} I_{34})^{\Gamma_{34}}\rangle$$

Good symmetry states

C-parity=$\Gamma_{12}\Gamma_{34}$

$$\rightarrow \begin{cases} \Gamma_{12} (-1)^{S_{12}+\ell_1} = +1 \\ \Gamma_{34} (-1)^{S_{34}+\ell_3} = +1 \end{cases}$$

Interacting potentials

BCN

- -Confinement: Linear potential
- -One-gluon exchange: Standard Fermi-Breit potential

Parameters determined on meson espectroscopy

CQC

- -Confinement: Linear screened potential
- -One-gluon exchange: Standard Fermi-Breit potential
  Scale dependent α_s
- - Boson exchanges: Chiral symmetry breaking
  Not active for heavy quarks

Parameters determined on the NN interaction and meson/baryon espectroscopy

Capability of the HH method designed

L=0 $cc\bar{n}\bar{n}$ states (MeV)

(S,I)	VMCT*	HH (ℓ_i=0)	HH
(0,1)	4155	4154	3911
(1,0)	3927	3926	3860
(1,1)	4176	4175	3975
(2,1)	4195	4193	4031

VMCT*: Variational calculation using gaussian trial wave functions with only quadratic terms in the Jacobi coordinates (CQC).

L=0 $cn\bar{c}\bar{n}$ states (MeV)

J^P	HOD* (N=8)	HH (K=8)	HH (K_{max})
0^+	3409	3380	3249 (26)
1^+	3468	3436	3319 (22)

HOD*: Diagonalization in a harmonic oscillator basis up to N=8 (BCN).

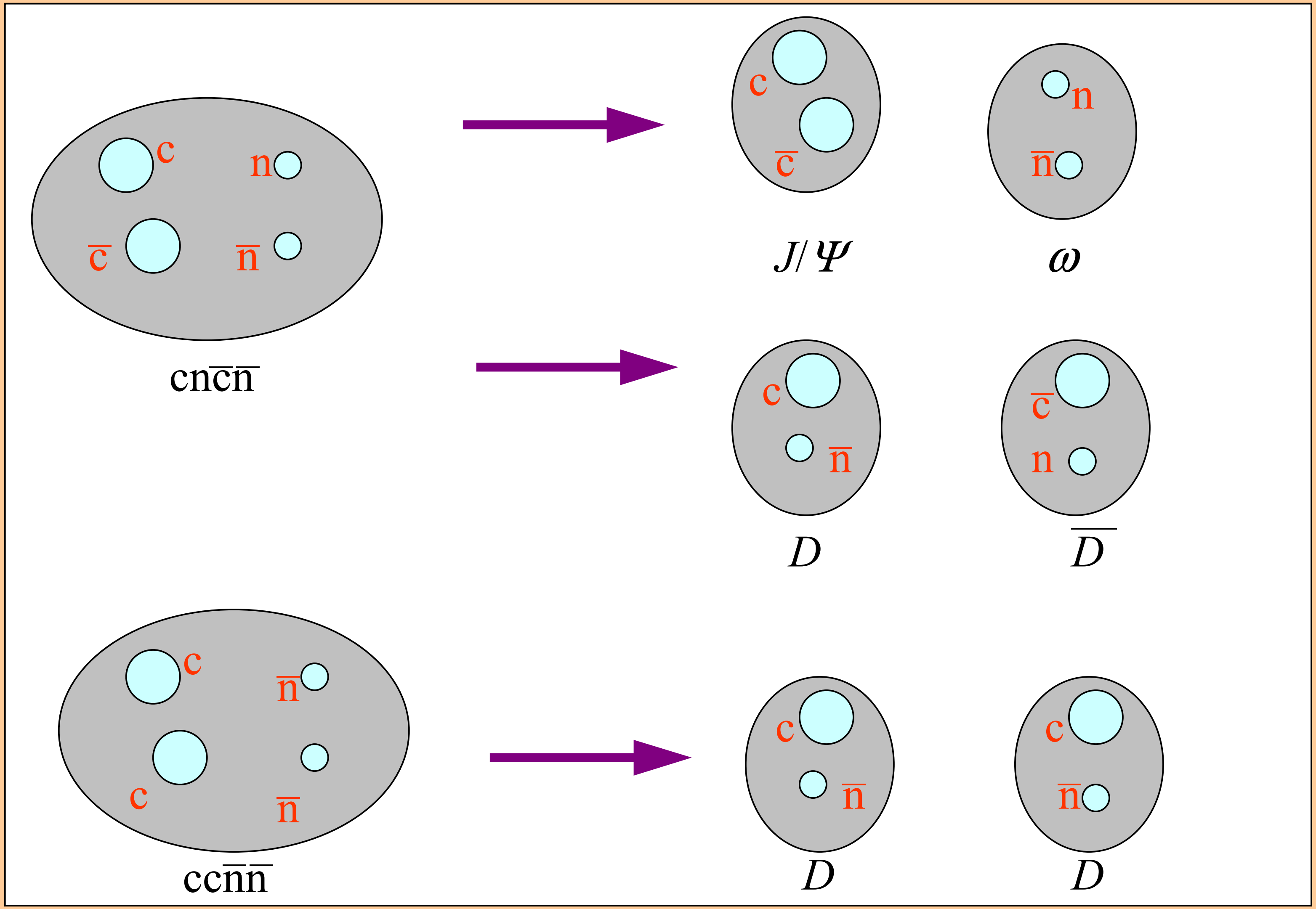
$cn\bar{c}\bar{n}$ (I=0)

	CQC			BCN		
J^{PC} (K_{max})	E_{4q} (MeV)	Δ_E^{The}	Δ_E^{Exp}	E_{4q} (MeV)	Δ_E^{The}	Δ_E^{Exp}
0^{++} (24)	3779	+ 34	+ 251	3249	+ 75	– 279
0^{+-} (22)	4224	+ 64	+ 438	3778	+ 140	+ 81
1^{++} (20)	3786	+ 41	+ 206	3808	+ 153	+ 228
1^{+-} (22)	3728	+ 45	+ 84	3319	+ 86	– 325
2^{++} (26)	3774	+ 29	– 106	3897	+ 23	+ 17
2^{+-} (28)	4214	+ 54	+ 517	4328	+ 32	+ 631
1^{-+} (19)	3829	+ 84	+ 301	3331	+ 157	– 197
1^{--} (19)	3969	+ 97	+ 272	3732	+ 94	+ 35
0^{-+} (17)	3839	+ 94	– 32	3760	+ 105	– 111
0^{--} (17)	3791	+ 108	+147	3405	+ 172	– 239
2^{-+} (21)	3820	+ 75	– 60	3929	+ 55	+ 49
2^{--} (21)	4054	+ 52	+ 357	4092	+ 52	+ 395
Total		0	3 !		0	5 !

$cc\bar{n}\bar{n}$

		CQC (BCN)			
	J^P (K_{max})	E_{4q} (MeV)	Δ_E^{The}	R_{4q}	$R_{4q}/(r^1_{2q}+r^2_{2q})$
I=0	0^+ (28)	4441	+ 15	0.624	> 1
	1^+ (24)	3861	– 76	0.367	0.808
	2^+ (30)	4526	+ 27	0.987	> 1
	0^- (21)	3996	+ 59	0.739	> 1
	1^- (21)	3938	+ 66	0.726	> 1
	2^- (21)	4052	+ 50	0.817	> 1
I=1	0^+ (28)	3905	+ 33	0.752	> 1
	1^+ (24)	3972	+ 35	0.779	> 1
	2^+ (30)	4025	+ 22	0.879	> 1
	0^- (21)	4004	+ 67	0.814	> 1
	1^- (21)	4427	+ 1	0.516	0.876
	2^- (21)	4461	– 38	0.465	0.766

Difference between the two physical systems



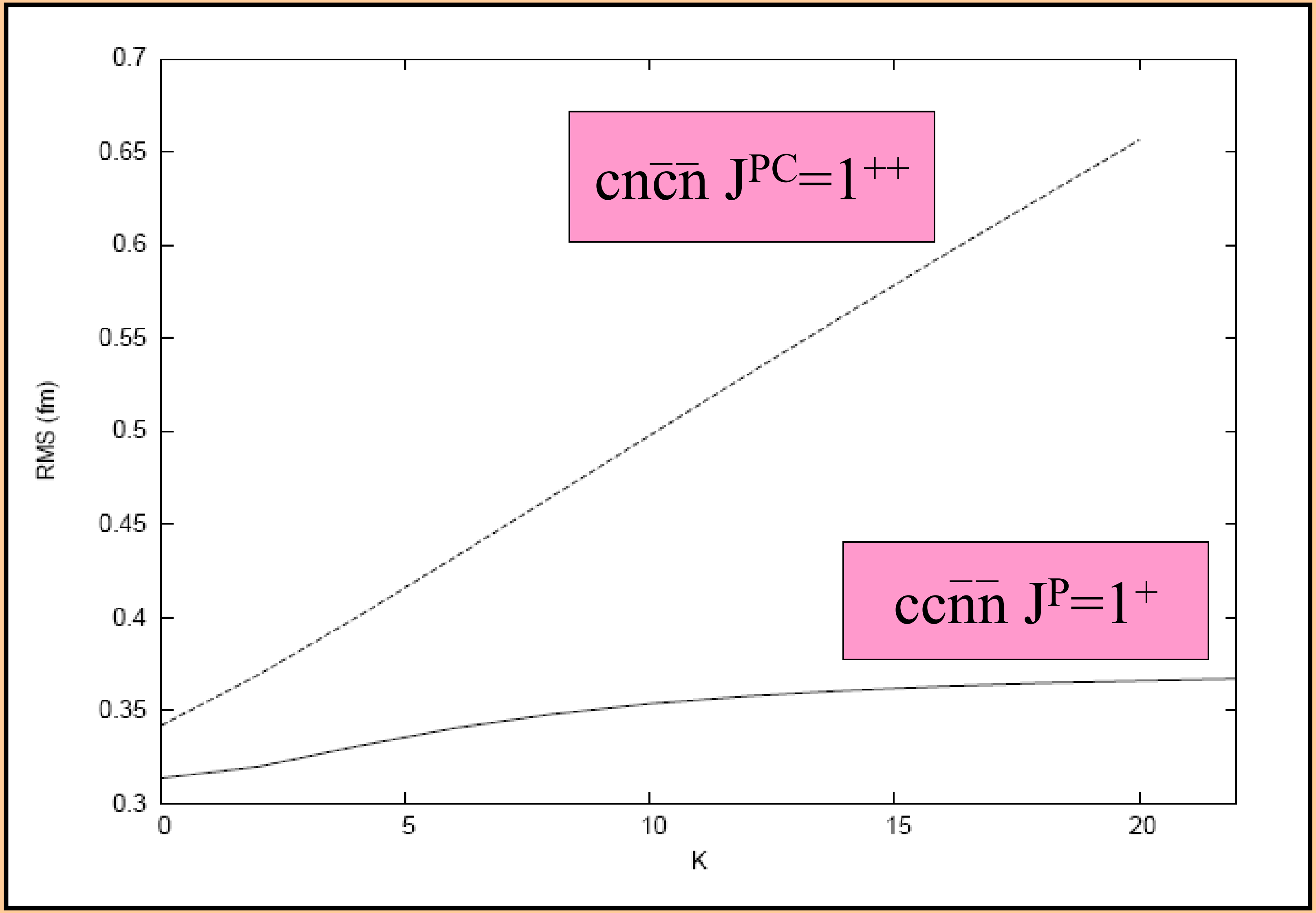
$c\bar{c}n\bar{n}$ $J^P=1^+$

	CQC			BCN		
K	E (MeV)	P_{11}	P_{88}	E (MeV)	P_{11}	P_{88}
0	4109	0.335	0.665	4100	0.345	0.655
2	3990	0.348	0.652	3999	0.374	0.626
4	3931	0.358	0.642	3954	0.398	0.602
6	3903	0.364	0.636	3933	0.417	0.583
8	3887	0.368	0.632	3921	0.430	0.570
10	3878	0.371	0.629	3914	0.440	0.560
12	3872	0.372	0.628	3910	0.448	0.552
14	3868	0.373	0.627	3907	0.454	0.546
16	3866	0.374	0.626	3904	0.458	0.542
18	3864	0.374	0.626	3903	0.462	0.538
20	3862	--	--	3901	0.465	0.535
24	3861	--	--	3900	--	--
$\propto$	$\sim$ 3860	--	--	$\sim$ 3899	--	--
$D D^*\|_S$	3937	1	0	3906	1	0

$cn\bar{c}\bar{n}$ $J^{PC}=1^{++}$

	CQC			BCN		
K	E (MeV)	P_{11}	P_{88}	E (MeV)	P_{11}	P_{88}
0	4141	1.000	0.000	4196	1.000	0.000
2	3985	0.982	0.018	4053	0.946	0.054
4	3911	0.979	0.021	3994	0.923	0.078
6	3870	0.983	0.017	3963	0.924	0.076
8	3845	0.987	0.013	3944	0.930	0.070
10	3827	0.991	0.009	3932	0.943	0.057
12	3814	0.993	0.007	3920	0.993	0.007
14	3805	0.994	0.006	3887	0.999	0.001
16	3797	0.995	0.005	3861	0.999	0.001
18	3791	0.996	0.004	3840	0.999	0.001
20	3786	0.997	0.003	3822	1.000	0.000
∞	$\sim$ 3745	--	--		--	--
$J/\Psi\,\omega\vert_S$	3745	1	0			
$\chi_{cJ}\,\eta\vert_P$				3655	1	0

Behavior of the radius (CQC)



Summary

• The study of four-quark bound states must definitively be based on exact solutions (approximate methods should be taken with care).

• The existence of four-quark bound states could only be drawn by comparing with the two-meson threshold calculated within the same model.

• It is hard to conclude four-quark structures in systems with two different physical thresholds ($c\bar{c}n\bar{n}$) but they should definitively exist on systems with a single asymptotic two-meson state ($cc\bar{n}\bar{n}$).

• The four-quark structure of the X(3872) could be explained in terms of quark correlations not considered by the valence quark model: diquark states, three-body forces, medium effects ...

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