Five-body structure of $sssc\bar{c}$

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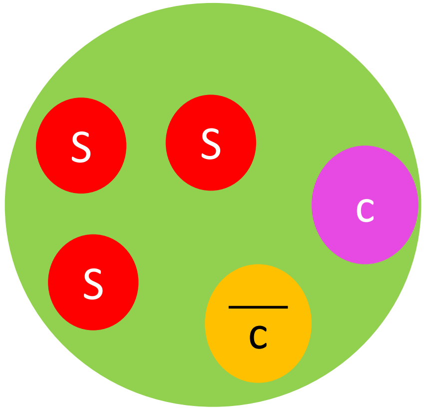
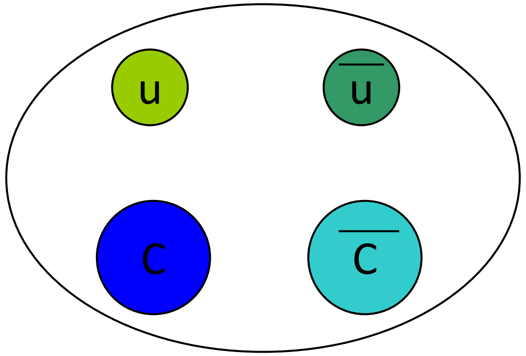


For this purpose, search for multi exotic quarks systems such as tetra quark systems, penta quark systems, and di-baryon systems have a long history.

Tetra quark systems:

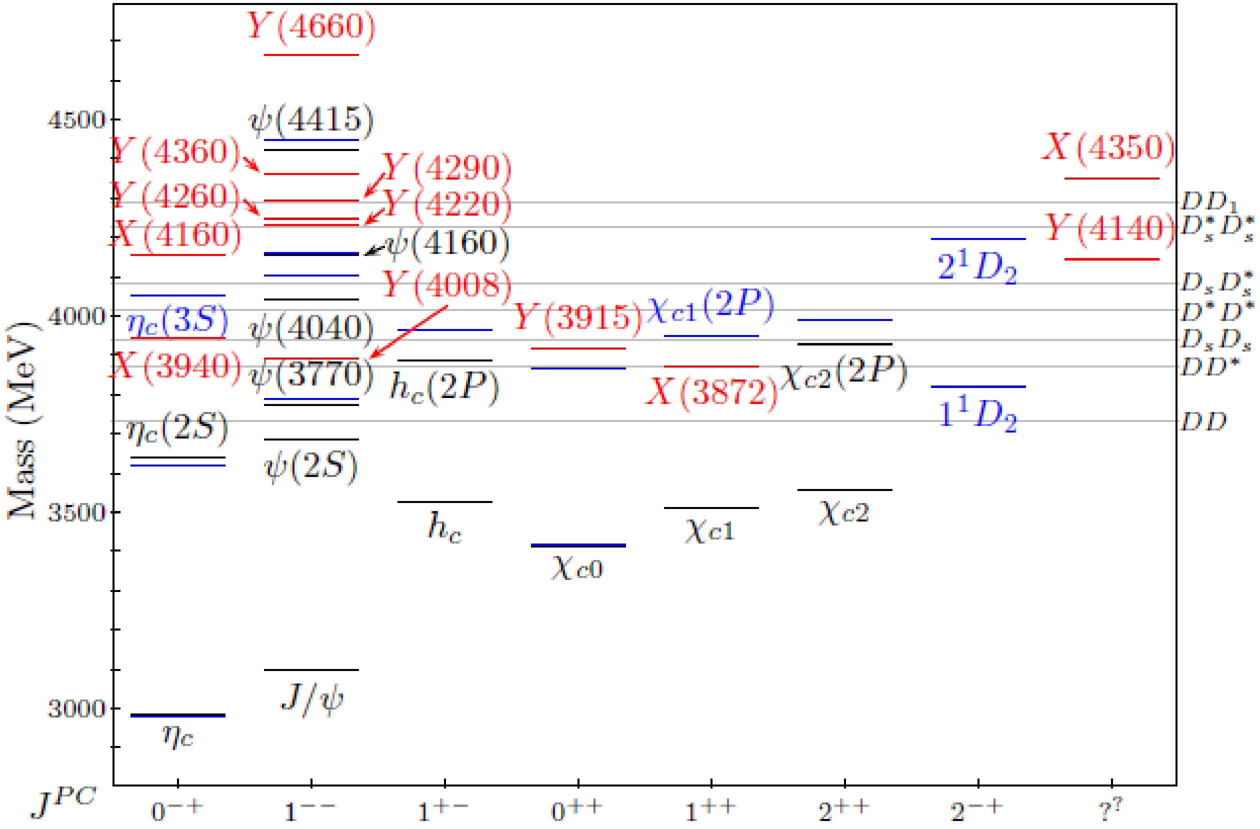
Phys. Rev. Lett. 91, 262001 (2003)
Belle Group

X(3872):3871.2±0.5 MeV
1^{++}
Γ<2.3MeV



After observation of X(3872), there are many observed exotic state candidates shown in red color. $Z(4430)^{\pm}$ have been observed , recently.

Black: Observed conventional *cc* states
Blue: Predicted conventional *cc* states
Red: Exotic state candidates with *cc* inside



• Observation of Θ⁺

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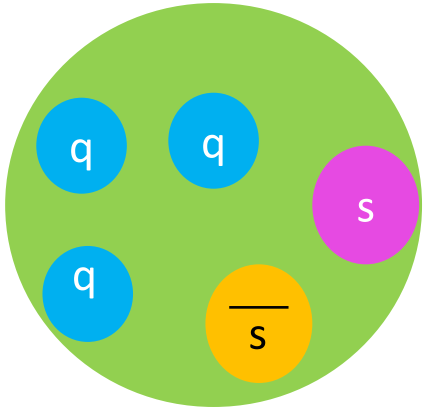

Five-body calculation of resonance and scattering states of pentaquark system

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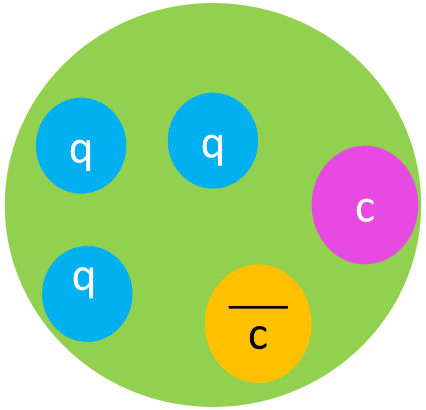
Available online 12 December 2005
Editor: J.-P. Blaizot

It was difficult to obtain the resonant states in the observed energy region.

On the other hand, we found sharp resonant state in the much higher energy region.



Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis of the three-body final state reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin $3/2$ and the other $5/2$.

State	Mass (MeV)	Width (MeV)	Fit fraction (%)	Significance
$P_c(4380)^+$	4380±8±29	205±18±86	8.4±0.7±4.2	9σ
$P_c(4450)^+$	4449.8±1.7±2.5	39± 5±19	4.1±0.5±1.1	12σ

- Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred

Quark model estimate of hidden-charm pentaquark resonances

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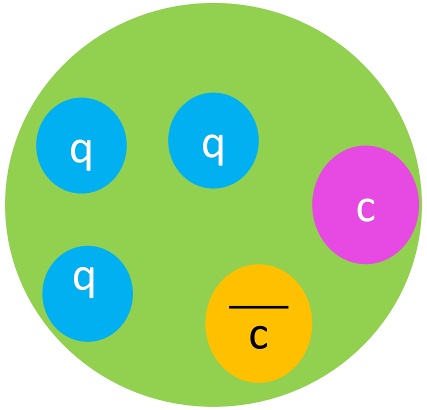
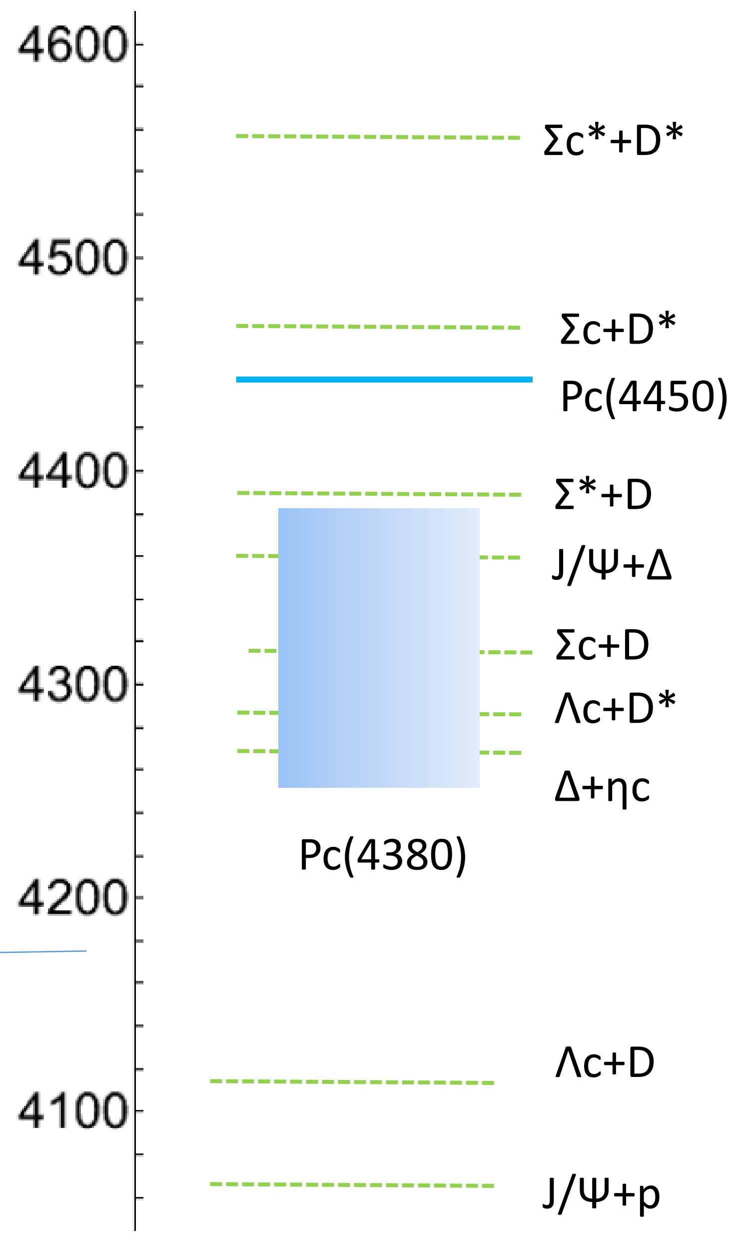
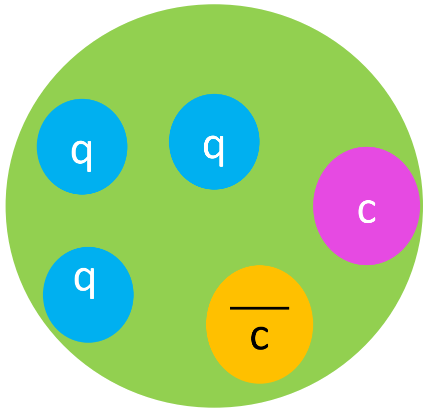
(Dated: March 23, 2018)



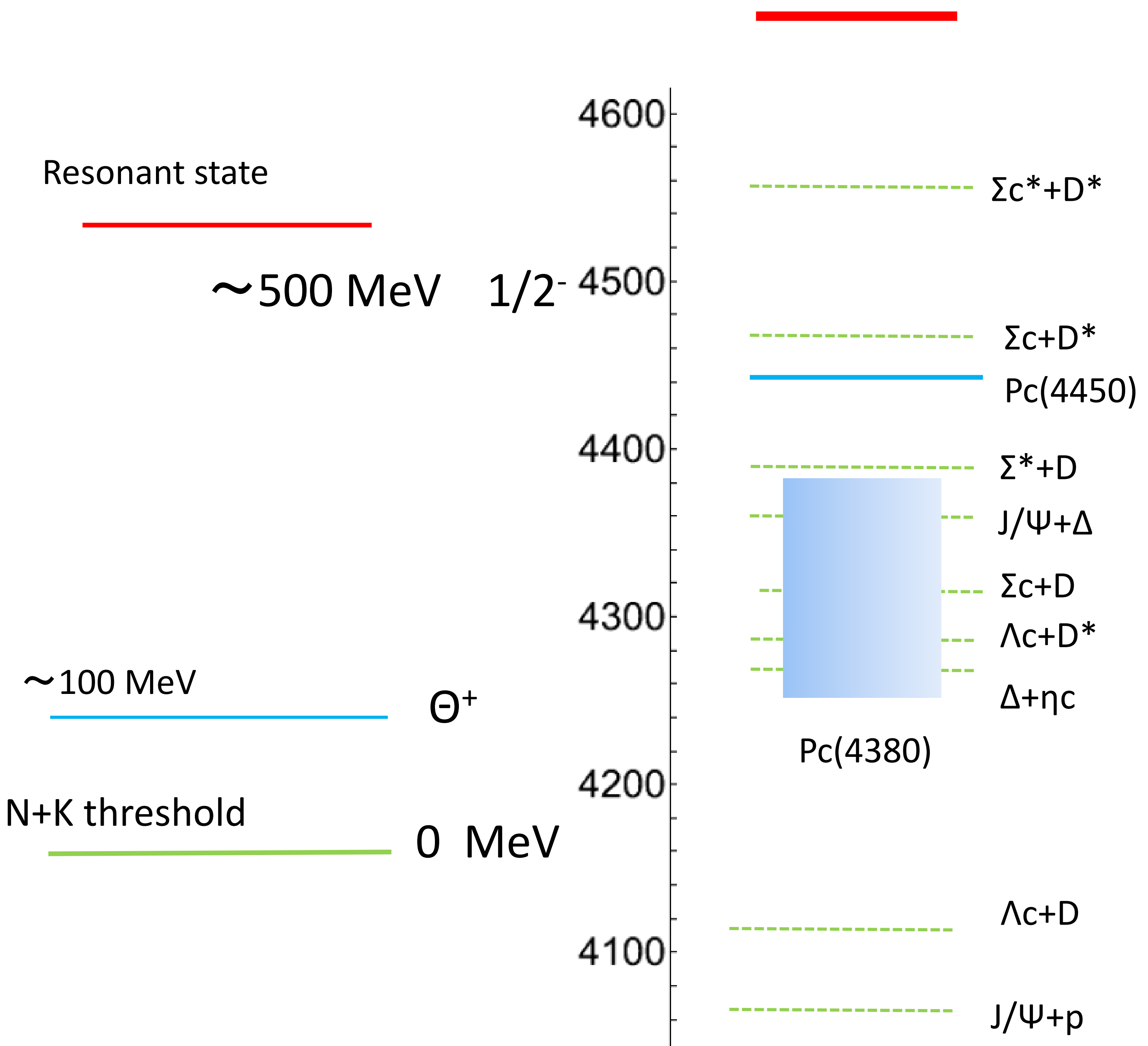
Phys. Rev. C 98, 045208 (2018)



It was difficult to obtain resonant state in the observed energy region.
On the other hand, we had sharp resonant state in the much higher energy region.



Summary of my work in the pentaquark

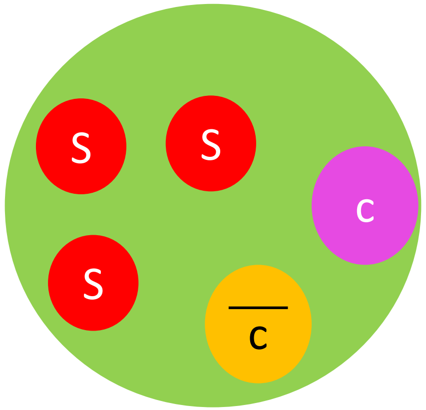


According to our calculation:
The observed data were indicated that meson-baryon resonant states.
Question:
The red color resonant states are reliable?

~140 MeV above N+K threshold, π+N+K channel is open.
In the case of Pc, there are several three-body decay channels below red states.
In our model, it is difficult to take account this three-body channels.

To check the reliability our model, it might be useful to compare the results by our model with the results using Lattice QCD.

One of the better pentaquark system for this purpose is ssscc-bar.



Ξc+Ds+K(4980)=> relative angular momentum is p-wave.

Then, it might be that this effect should be suppresed.

Ωc+Ds(4640)

First, we will calculate 5-body ssscc-bar system with quark model.

Hamiltonian

$$H = \sum_i \left(m_i + \frac{\mathbf{p}_i^2}{2m_i} \right) - T_G + V_{\text{Conf}} + V_{\text{CM}} - \Lambda/r$$

$\Lambda = 0.1653 \text{GeV}^2$

$$V_{\text{Conf}} = -\sum_{i<j} \sum_{\alpha=1}^{8} \frac{\lambda_i^\alpha}{2} \frac{\lambda_j^\alpha}{2} \left[\frac{k}{2} (\mathbf{x}_i - \mathbf{x}_j) \;\; + v_0 \right],$$

$K = 0.5069$

$$V_{\text{CM}} = \sum_{i<j} \sum_{\alpha=1}^{8} \frac{\lambda_i^\alpha}{2} \frac{\lambda_j^\alpha}{2} \frac{\xi_\sigma}{m_i m_j} e^{-(\mathbf{x}_i - \mathbf{x}_j)^2/\beta^2} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j .$$

$\xi_\alpha = (2\pi/3)kp$ $\beta = A((2m_i m_j)/(m_i + m_j))^{(-B)}$

$Kp = 1.8609$ $A = 1.6553$ $B = 0.2204$

$m_q = 315$ MeV, $m_c = 1836$ MeV

B. Silvestre-Brac and C. Semay,
Z. Phys. C 61 (1994) 271

Hadron	J^P	Exp.	AP1
η_c	0^-	2984	2984
J/ψ	1^-	3097	3104
D_s	0^-	1968	1955
D_s^*	1^-	2112	2107
Ω	$3/2^+$	1672	1673
Ω_c	$1/2^+$	2695	2685
Ω_c^*	$3/2^+$	2766	2759

In order to solve few-body problem accurately,

Gaussian Expansion Method (GEM) , since 1987,

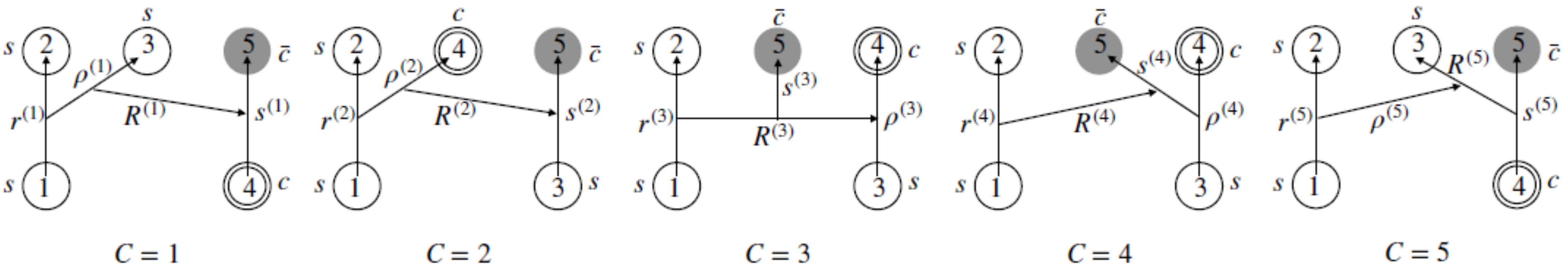
- A variational method using Gaussian basis functions
- Take all the sets of Jacobi coordinates

Developed by Kyushu Univ. Group,
Kamimura and his collaborators.

Review article :
E. Hiyama, M. Kamimura and Y. Kino,
Prog. Part. Nucl. Phys. 51 (2003), 223.

High-precision calculations of various 3- and 4-body systems:

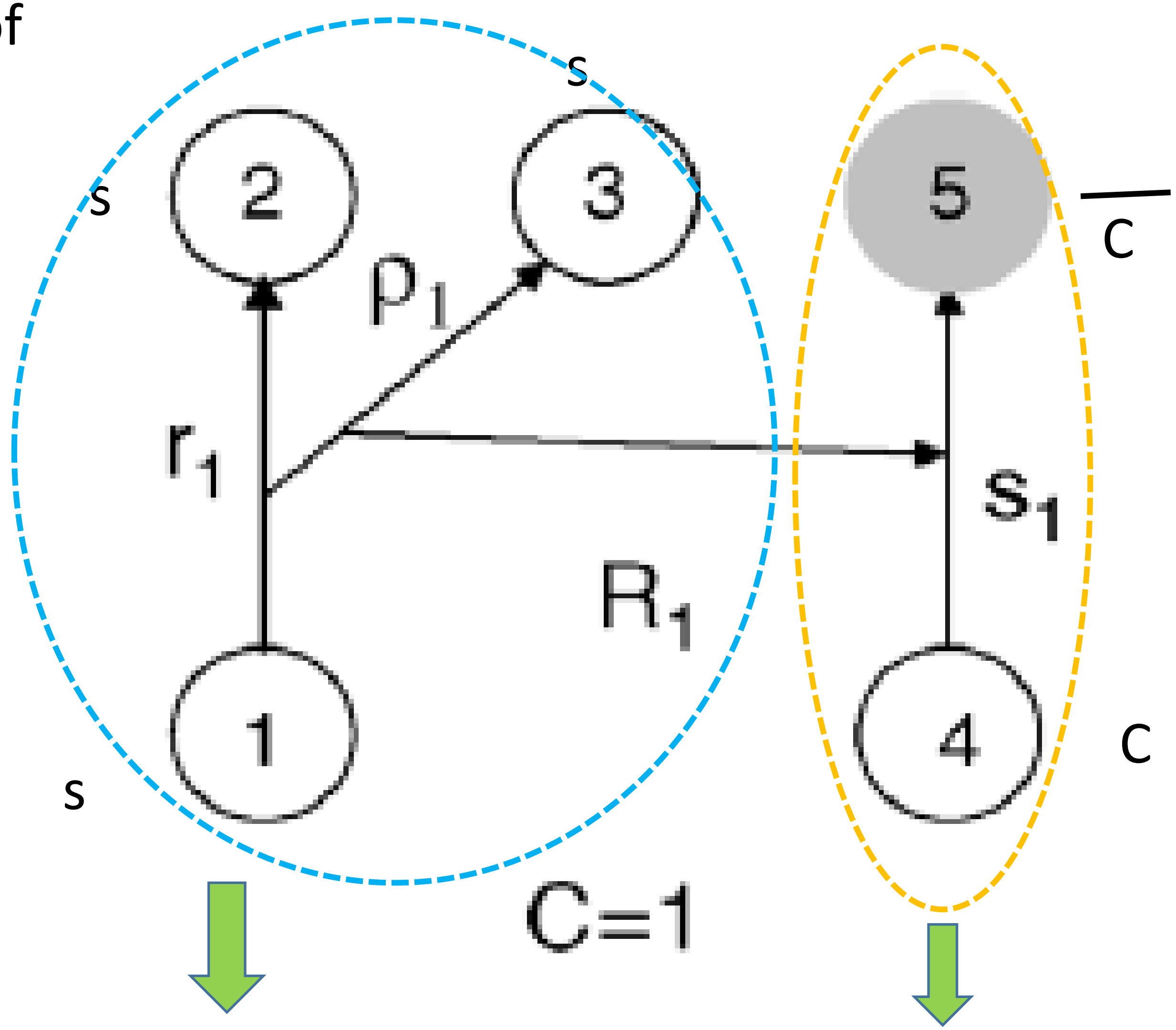
Exotic atoms / molecules ,
3- and 4-nucleon systems,
multi-cluster structure of light nuclei,
Light hypernuclei,
3-quark systems,
^{4}He-atom tetramer



$$\Psi_{JM}(qqqc\overline{c}) = \Phi_{JM}^{(C=1)} + \Phi_{JM}^{(C=2)} + \phi_{JM}^{(c=3)} + \Phi_{JM}^{(C=4)}$$

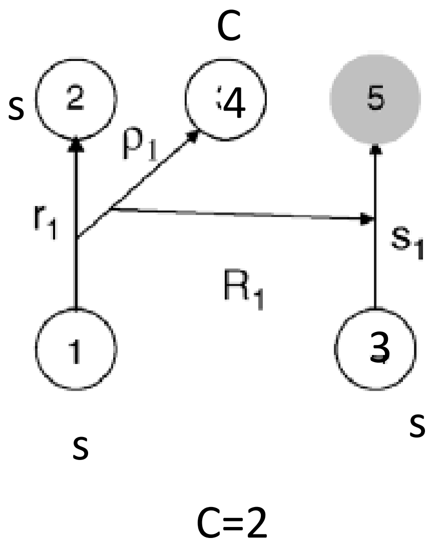
$$\Phi_{\alpha JM}(qqq\overline{cc}) = \mathcal{A}_{qqqq}\{[(\text{color})^{(c)}_{\alpha} \quad (\text{isospin})^{(c)}_{\alpha} \quad (\text{spin})^{(C)}_{\alpha} \quad (\text{spatial})^{(c)}_{\alpha}]_{JM}\}$$

Wavefunction of Color part

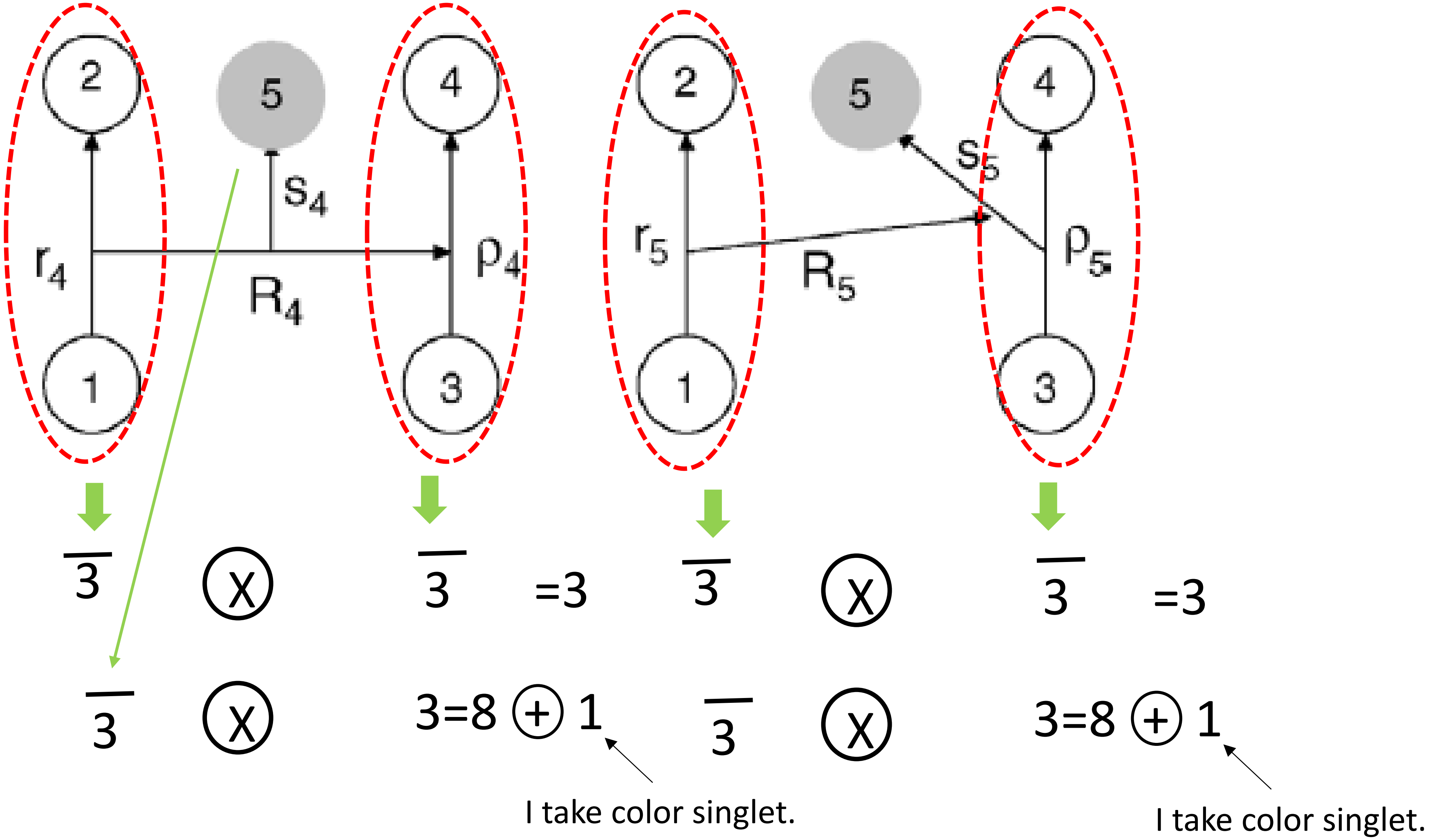


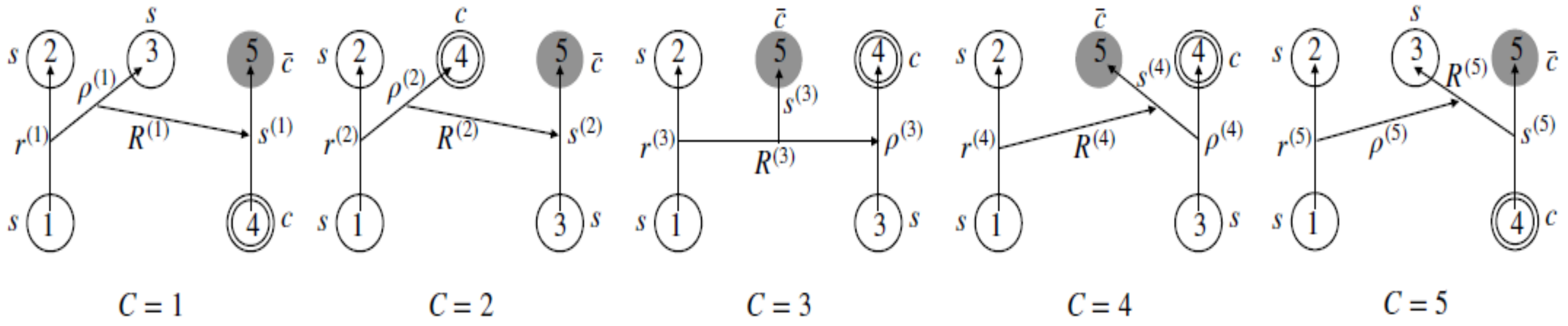
1 ⊗ 1 =1

Similar for C=2



Confining channels





$$\Psi_{JM}(qqqc\bar{c}) = \Phi_{JM}^{(C=1)} + \Phi_{JM}^{(C=2)} + \phi_{JM}^{(c=3)} + \Phi_{JM}^{(C=4)}$$

$$\Phi_{\alpha JM}(qqq\overline{cc}) = \mathcal{A}_{qqqq}\{[(\text{color})^{(c)}_{\alpha} \quad (\text{isospin})^{(c)}_{\alpha} \quad (\text{spin})^{(C)}_{\alpha} \quad (\text{spatial})^{(c)}_{\alpha}]_{JM}\}$$

$$(\text{spatial})^{(c)}_{\alpha} = \varphi_{nl}^{(c)}(r_c)\psi_{v\lambda}^{(c)}(\rho_c)\varphi^{(c)}_{kj}(s_c)\Phi_{n_R LM}^{(c)}(R_c)$$

$$\phi_{n_R L_c M}(\mathbf{R}) = R^{L_c} e^{-(R/\bar{R}_{n_R})^2} Y_{L_c M}(\hat{\mathbf{R}}) \qquad \bar{R}_{n_R} = \bar{R}_1 a^{n_R - 1} \quad \left(n_R = 1 - n_R^{\max}\right)$$

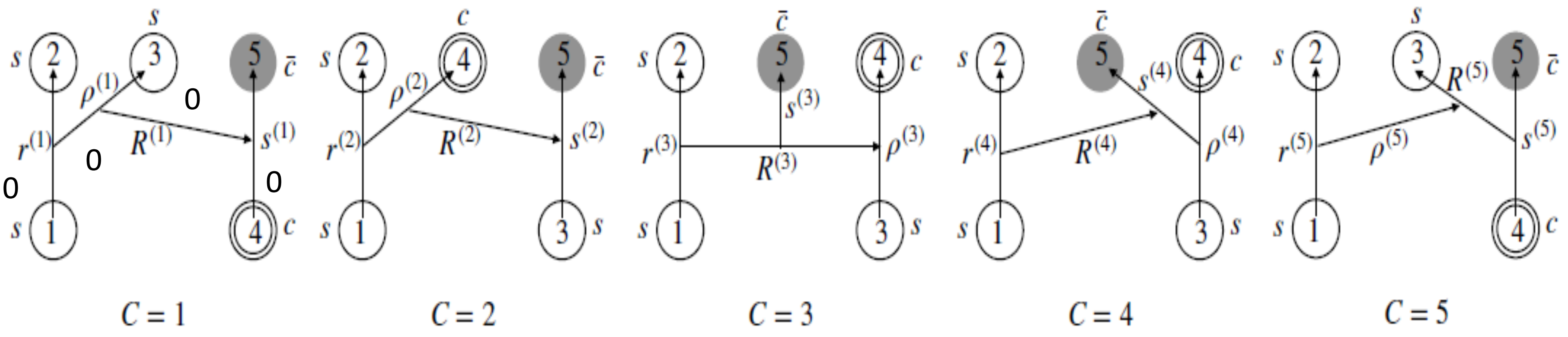
Same procedure is taken for r,ρ, and s.

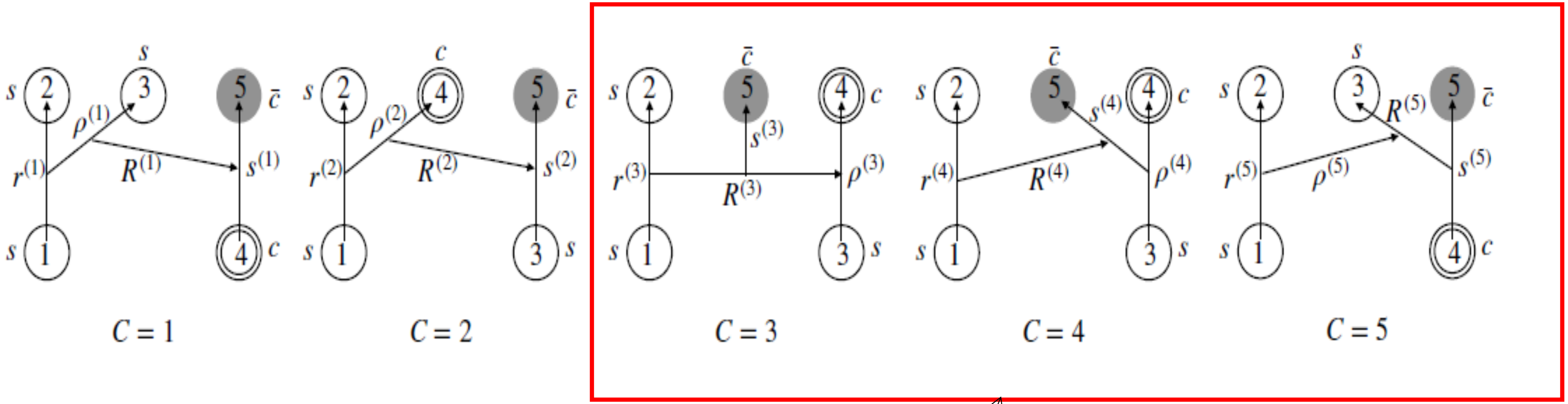
For the ssscc-bar, we consider the following 6 states,

Total orbital angular momentum: L=0, 1 For L=1, angular momentum of either coordinate , r, R,ρ, s =1. others are 0.

Total Spin : S=1/2, 3/2, 5/2

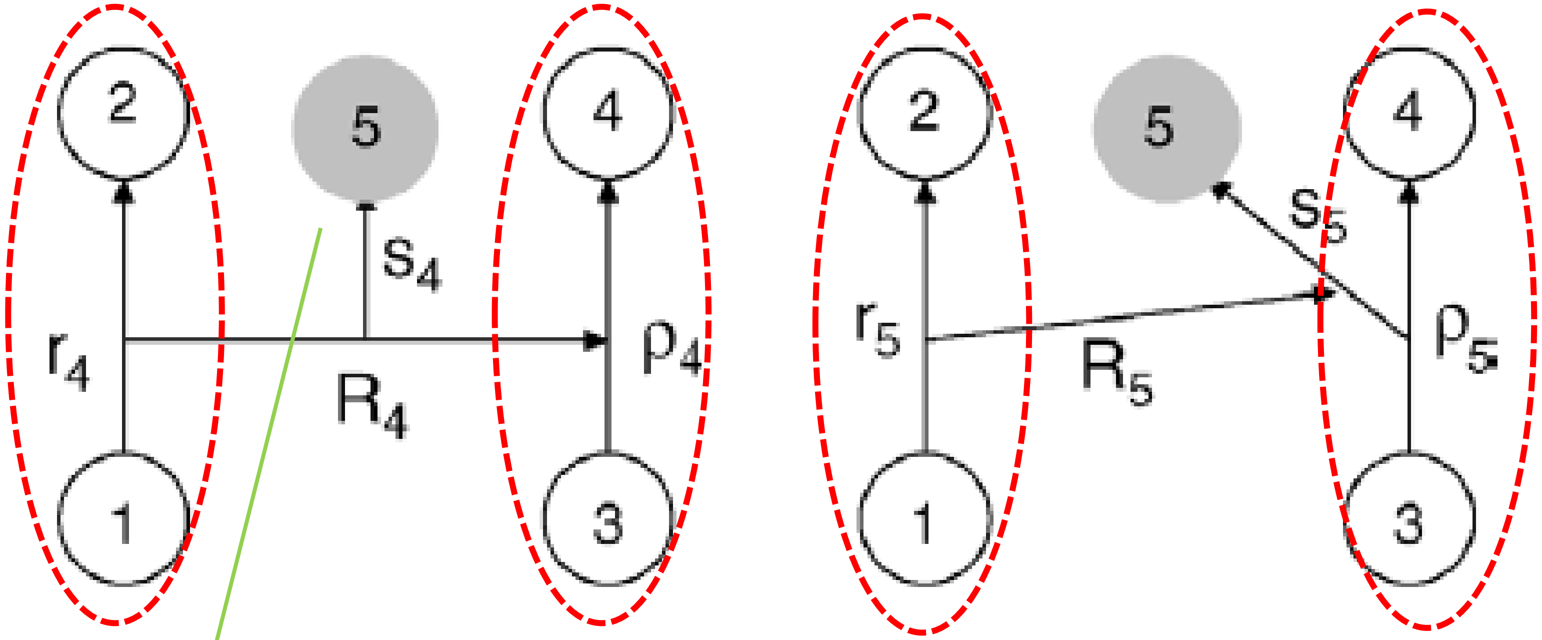
Total J^{π}= $1/2^-$, $3/2^-$, $5/2^-$, $1/2^+$, $3/2^+$, $5/2^+$





First, I take this configuration.

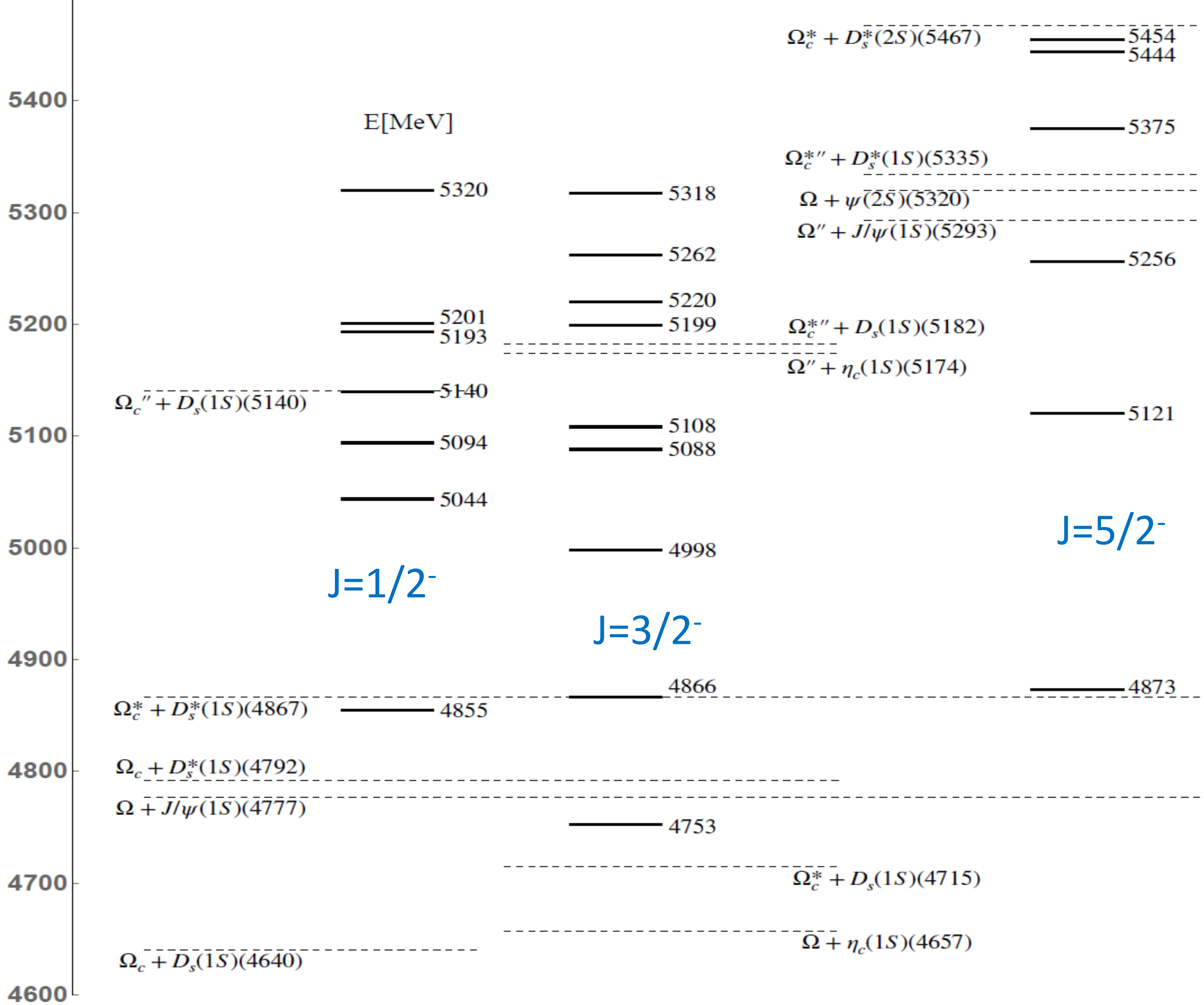
Confining channels

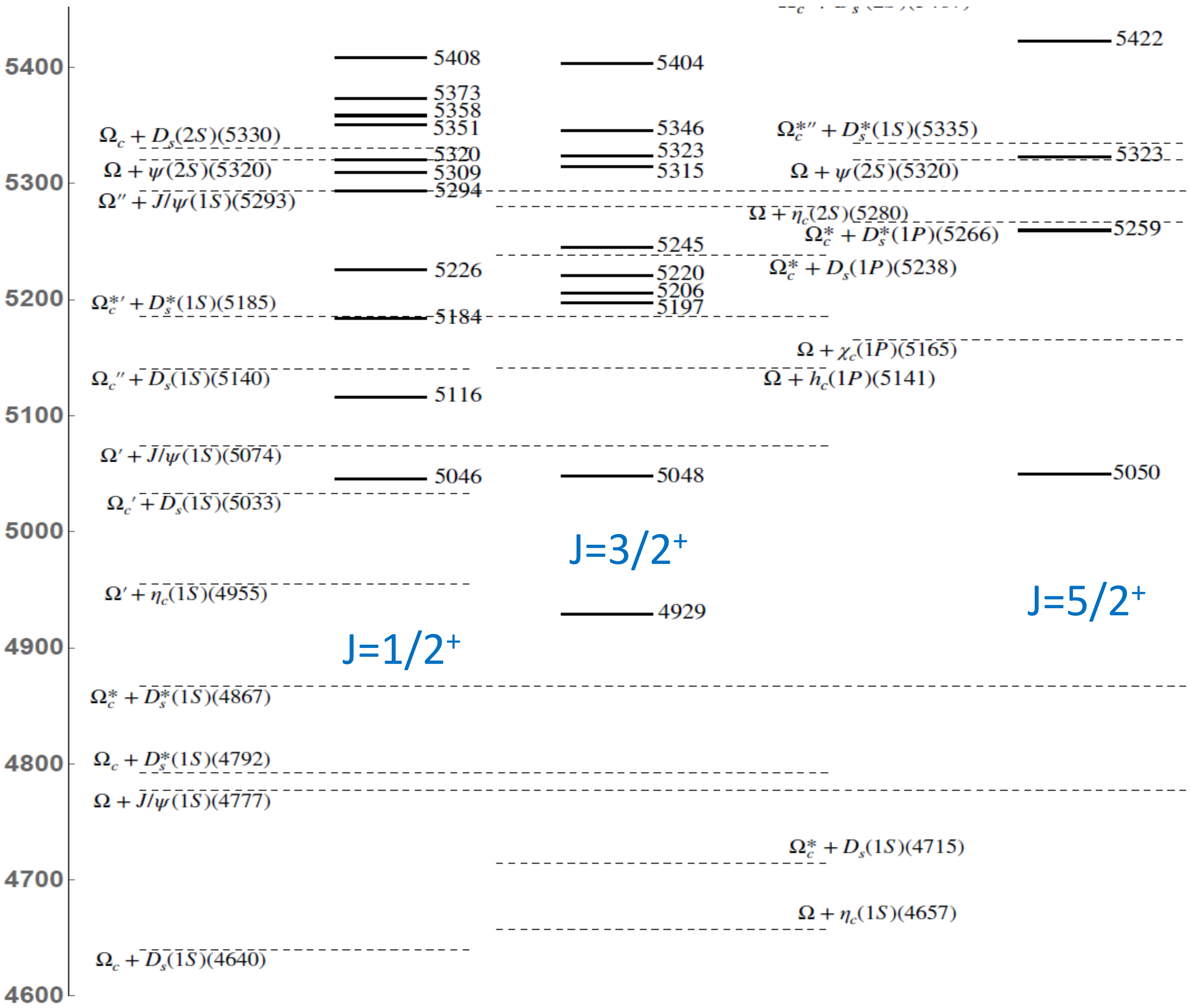


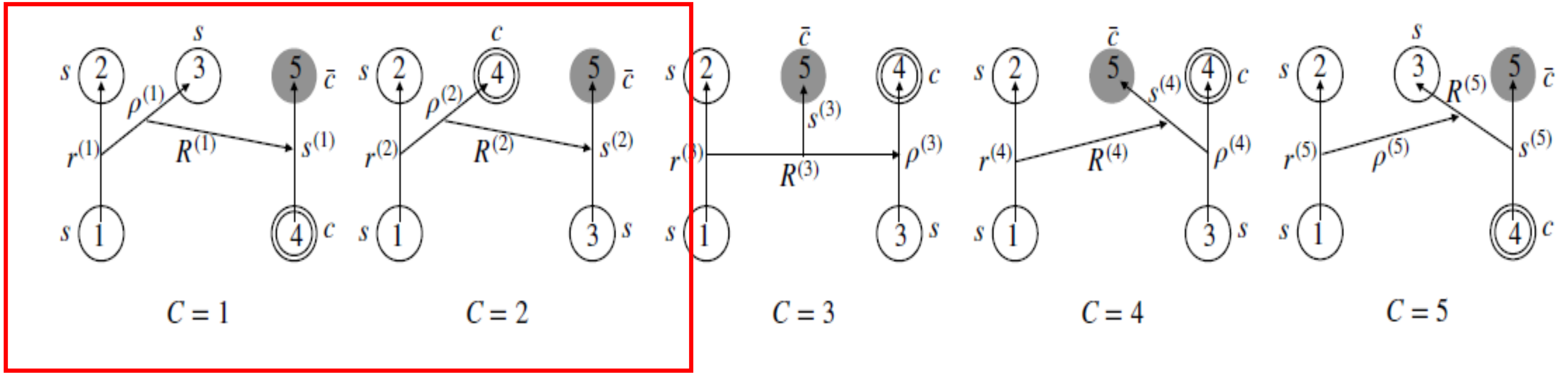
$\bar{3} \otimes \bar{3} = 3$ $\qquad$ $\bar{3} \otimes \bar{3} = 3$

$\bar{3} \otimes 3 = 8 \oplus 1$ $\qquad$ $\bar{3} \otimes 3 = 8 \oplus 1$

I take color singlet. $\qquad$ I take color singlet.


E[MeV]
5400
5300
5200
5100
5000
4900
4800
4700
4600
J=1/2-
J=3/2-
J=5/2-
5320
5201
5193
5140
5094
5044
4855
5318
5262
5220
5199
5108
5088
4998
4866
4753
5454
5444
5375
5256
5121
4873
$\Omega_c^* + D_s^*(2S)(5467)$
$\Omega_c^{*\prime\prime} + D_s^*(1S)(5335)$
$\Omega + \psi(2S)(5320)$
$\Omega'' + J/\psi(1S)(5293)$
$\Omega_c^{*\prime\prime} + D_s(1S)(5182)$
$\Omega'' + \eta_c(1S)(5174)$
$\Omega_c'' + D_s(1S)(5140)$
$\Omega_c^* + D_s^*(1S)(4867)$
$\Omega_c + D_s^*(1S)(4792)$
$\Omega + J/\psi(1S)(4777)$
$\Omega_c^* + D_s(1S)(4715)$
$\Omega + \eta_c(1S)(4657)$
$\Omega_c + D_s(1S)(4640)$


5400
5300
5200
5100
5000
4900
4800
4700
4600
$\Omega_c + D_s(2S)(5330)$
$\Omega + \psi(2S)(5320)$
$\Omega'' + J/\psi(1S)(5293)$
$\Omega_c^{*\prime} + D_s^*(1S)(5185)$
$\Omega_c'' + D_s(1S)(5140)$
$\Omega' + J/\psi(1S)(5074)$
$\Omega_c' + D_s(1S)(5033)$
$\Omega' + \eta_c(1S)(4955)$
$\Omega_c^* + D_s^*(1S)(4867)$
$\Omega_c + D_s^*(1S)(4792)$
$\Omega + J/\psi(1S)(4777)$
$\Omega_c + D_s(1S)(4640)$
5408
5373
5358
5351
5320
5309
5294
5226
5184
5116
5046
J=1/2⁺
5404
5346
5323
5315
5245
5220
5206
5197
5048
4929
J=3/2⁺
$\Omega_c^{*\prime\prime} + D_s^*(1S)(5335)$
$\Omega + \psi(2S)(5320)$
$\Omega + \eta_c(2S)(5280)$
$\Omega_c^* + D_s^*(1P)(5266)$
$\Omega_c^* + D_s(1P)(5238)$
$\Omega + \chi_c(1P)(5165)$
$\Omega + h_c(1P)(5141)$
$\Omega_c^* + D_s(1S)(4715)$
$\Omega + \eta_c(1S)(4657)$
5422
5323
5259
5050
J=5/2⁺

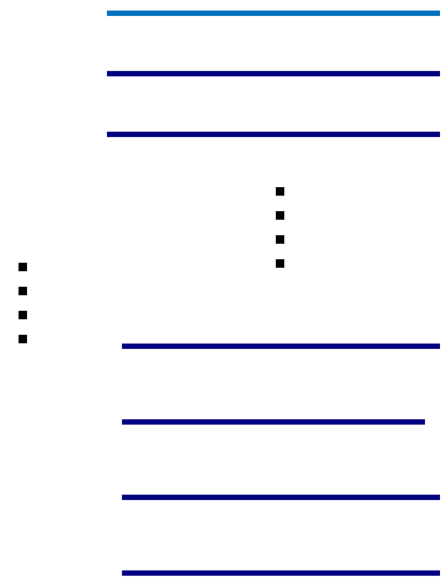


First, I include these configurations, scattering channels. Namely, we take all of configurations.

(H-E)Ψ=0

By the diagonalization of Hamiltonian, we obtain N eigenstates for each J^{π}.

Here, we use about 40,000 basis functions.
Then, we obtained 40,000 eigenfunction for each J^{π}.
First, we investigate J=1/2-, namely, L(total angular momentum)=0, S(total spin)=1/2.



These states are continuum states or resonant states. Then, it is necessary to distinguish resonant states or continuum states.

L=0,S=1/2 for example

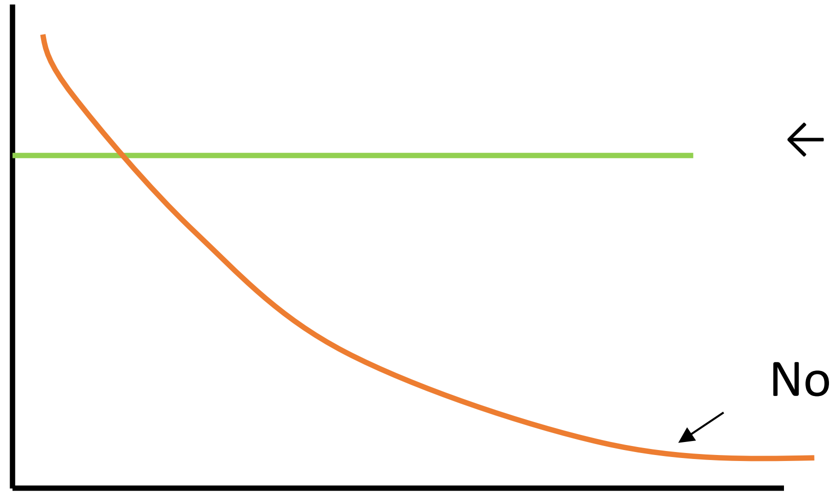
useful method: real scaling method

often used in atomic physics

In this method, we artificially scale the range parameters of our Gaussian basis functions by multiplying a factor α:

$r_n \rightarrow \alpha r_n$ in $r^l \exp^{(-r/r_n)^2}$ for exmple $0.8 < \alpha < 1.5$

and repeat the diagonalization of Hamiltonian for many value of α.



[schematic illustration of the real scaling]

What is the result in our pentaquark calculation?

of nonstoichiometric samples, because they have an

[5]R. F. Brebrick, J. Phys. Chem. Solids 32, 551 (1971).

Resonance state lifetimes from stabilization graphs

Jack Simons[a)]

Chemistry Department, University of Utah, Salt Lake City, Utah 84112
(Received 20 January 1981; accepted 18 May 1981)

The stabilization method (SM) pioneered by Taylor and co-workers[1] has proven to be a valuable tool for estimating the energies of long-lived metastable states of electron–atom, electron–molecule, and atom–diatom complexes. In implementing the SM one searches for eigenvalues arising from a matrix representation of the relevant Hamiltonian H which are "stable" as the basis set used to construct H is varied.

To obtain lifetimes of metastable states, one can choose from among a variety of techniques[2–7] (e.g., phase shift analysis, Feshbach projection "golden rule" formulas, Siegert methods, and complex coordinate scaling methods), many of which use the stabilized *eigenvector* as starting information. Here we demonstrate that one can obtain an *estimate* of the desired lifetime directly from the stabilization graph in a manner which makes a close connection with the complex coordinate rotation method (CRM) for which a satisfactory mathematical basis exists.

The starting point of our development is the observation that both the stable eigenvalue (E_r) and the eigenvalue(s) (E_c) which come from above and cross E_r (see Fig. 1 and Refs. 9–11 and 13) vary in a nearly linear manner (with α) near their avoided crossing points. This observation leads us to propose that the two eigenvalues arising in each such avoided crossing can be thought of as arising from two "uncoupled" states having energies $\epsilon_r(\alpha)=\epsilon+S_r(\alpha-\alpha_c)$ and $\epsilon_c(\alpha)=\epsilon+S_c(\alpha-\alpha_c)$, where S_r and S_c are the *slopes* of the linear parts of the stable and "continuum" eigenvalues, respectively. α_c is the value of α at which these two straight lines would intersect, and ϵ is their common value at $\alpha=\alpha_c$. This modeling of ϵ_r and ϵ_c is simply based upon the *observa-*

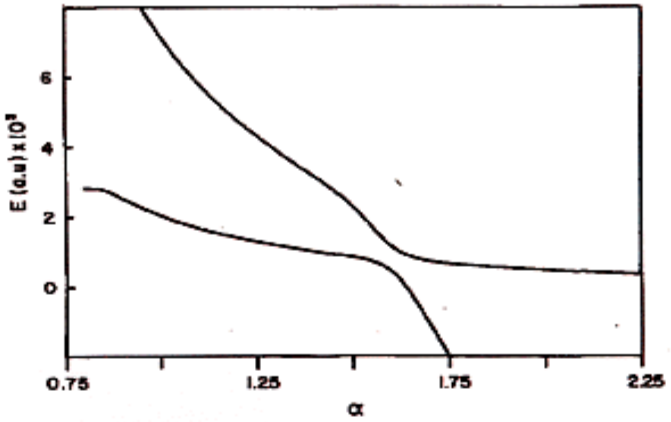
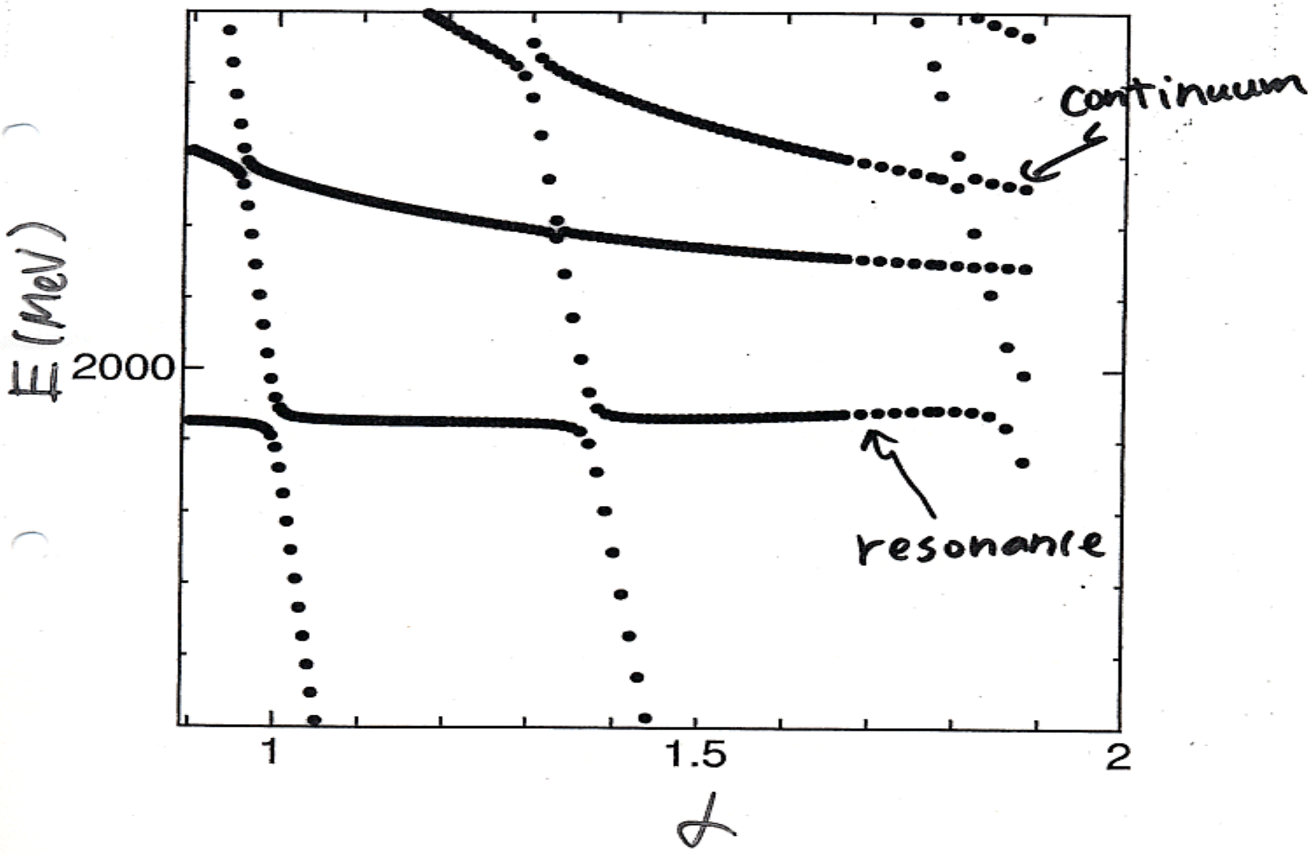


FIG. 1. Stabilization graph for the $^2\pi$ shape resonance state of LiH^- (Ref. 9).

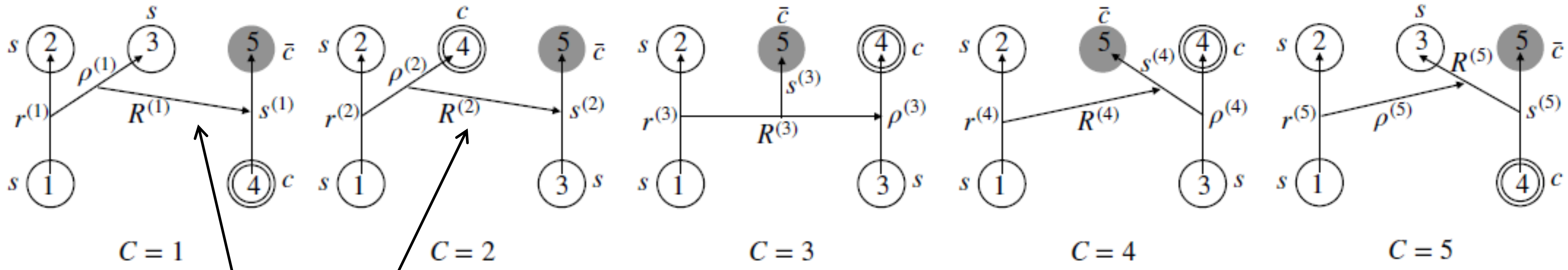
 0021-9606/81/172465-03$01.00

Example of real scaling

Not result of penta quark system



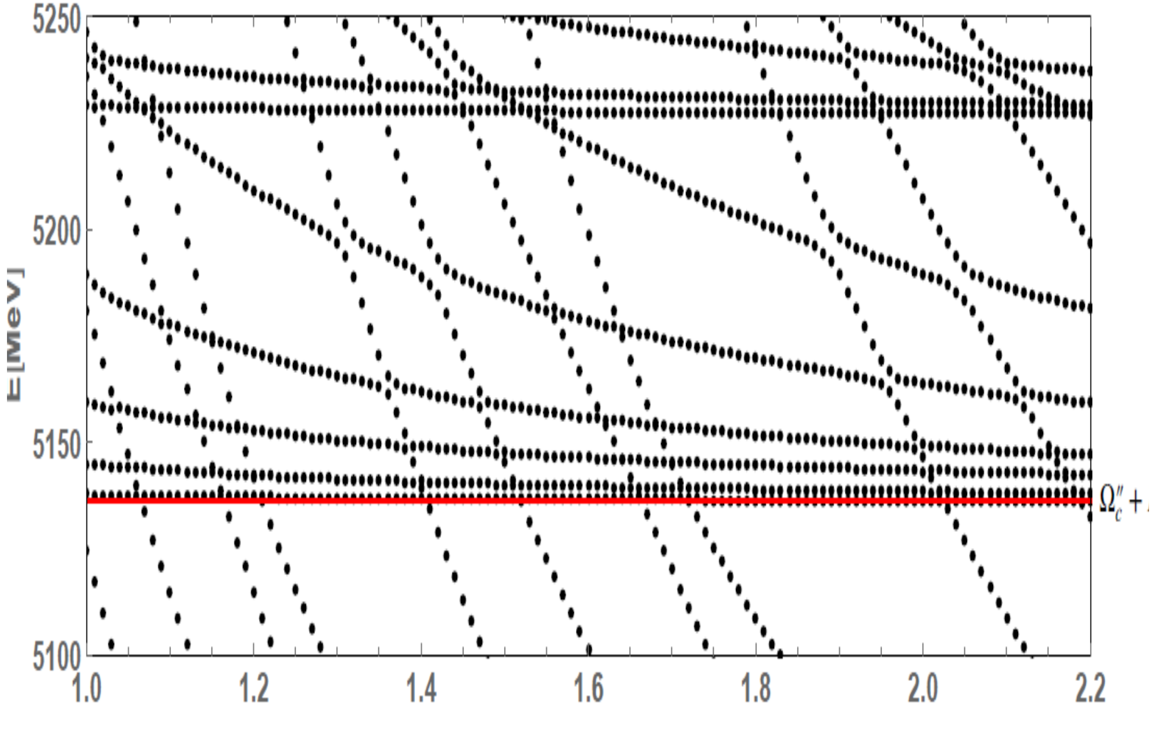
What is the result of our pentquark calculation?



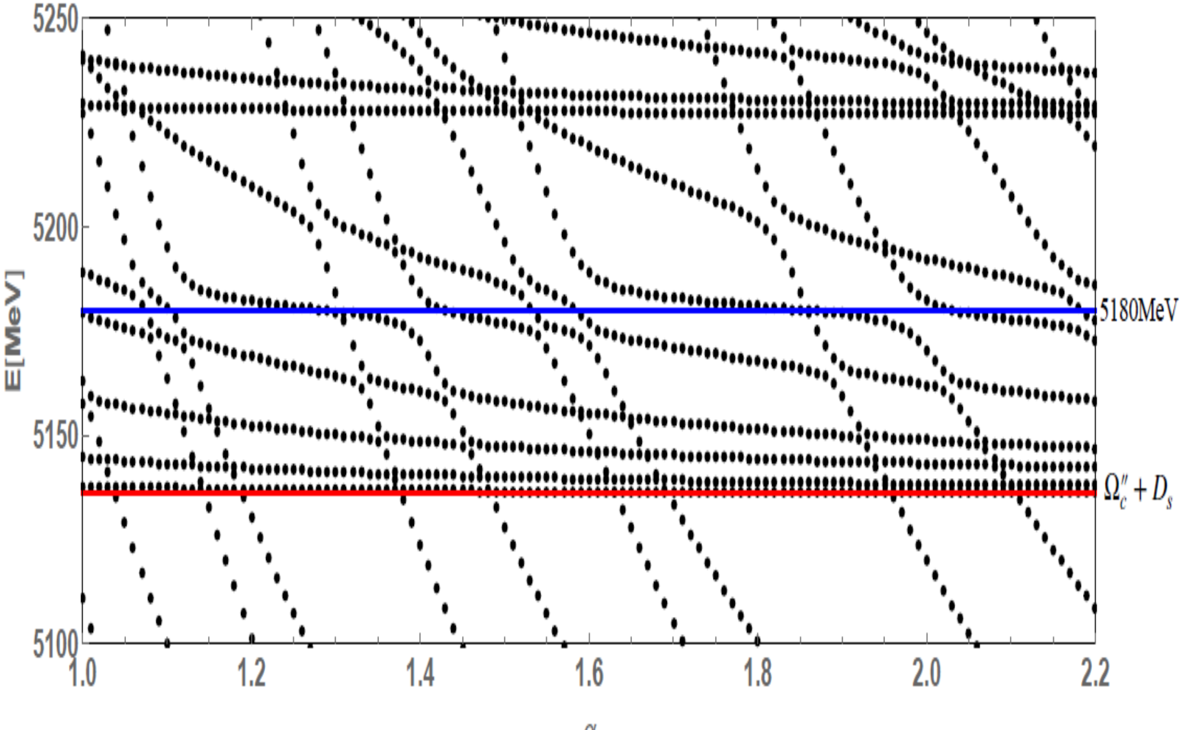
$$\phi_{n_R L_c M}(\mathbf{R}) = R^{L_c} e^{-(R/\bar{R}_{n_R})^2} Y_{L_c M}(\hat{\mathbf{R}})$$

R_{nR} => αR_{nR}

For example, we find a resonant state in J=1/2$^-$.

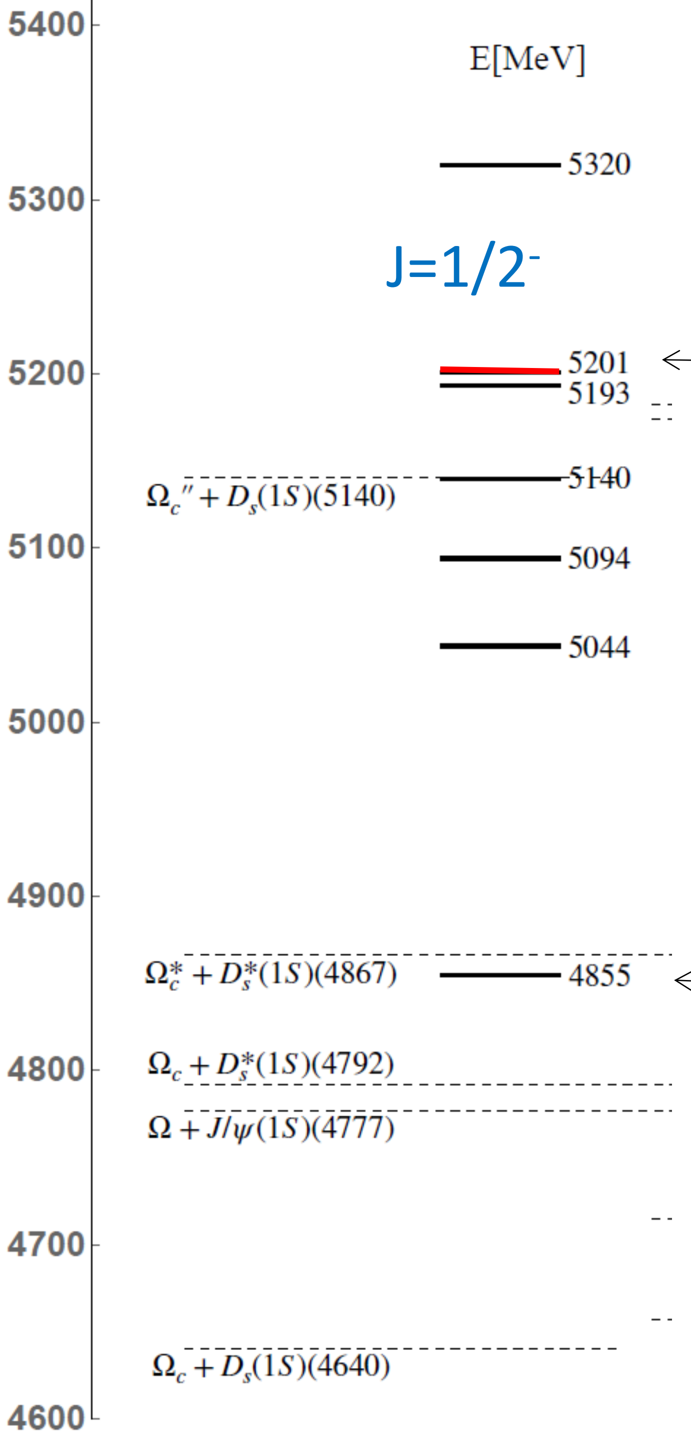


(a) $C = 1$ and 2



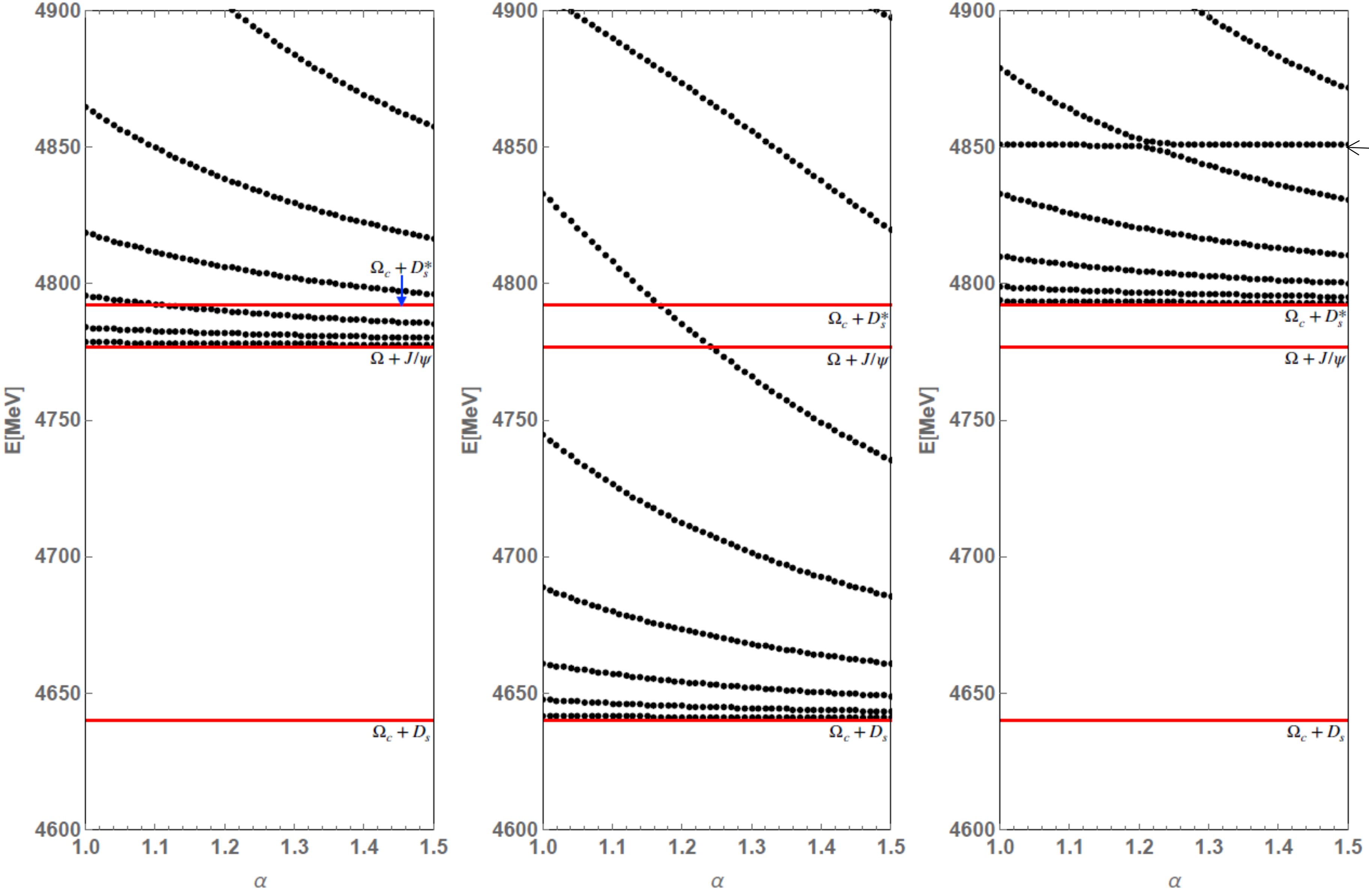
(b) $C = 1 - 5$

At 5.18 GeV, we have a narrow resonant state. Decay with is estimated to be 20 MeV.
Why we have a sharp resonant state at this energy?



In this state, overlap between
open threshold is so small.
Overlap probability between open thresholds
and other states are so large. Then, others are melted
into some thresholds.

For example, let me explain
what kinds of threshold are this state
coupled into?

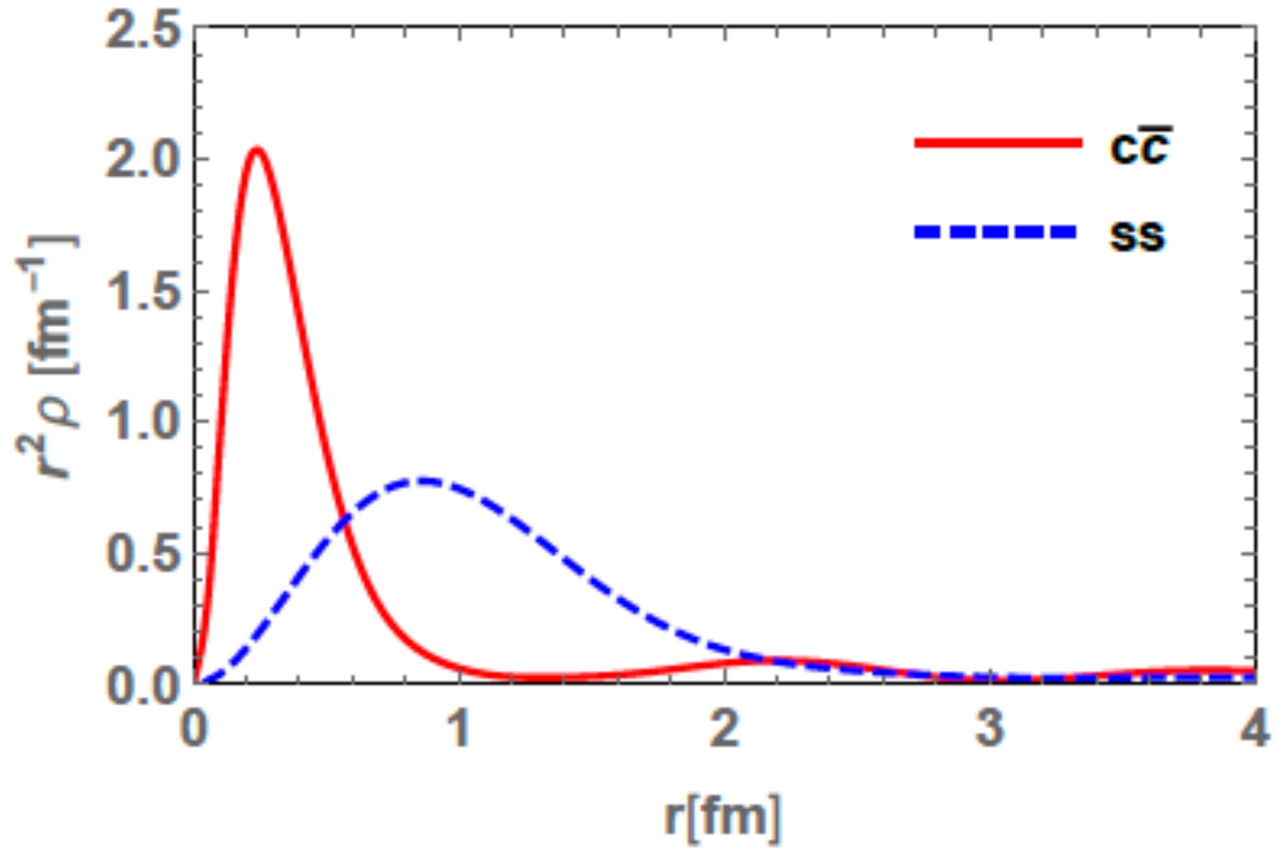


(a)$C = 3 + 4 + 5 + \Omega + J/\psi$ (b)$C = 3 + 4 + 5 + \Omega_c + D_s$ (c)$C = 3 + 4 + 5 + \Omega_c + D_s^*$

We have a state.
This means that overlap between Ωc+D*s is small.
However, overlap between Ωc+J/Ψ,Ωc+Ds is large.
Then, state at 4850 MeV is melted into some threshold.

Resonant states and decay widths

J^P	energy(MeV)	width(MeV)
$1/2^-$	5180	20
	5290	>100
$3/2^-$	5300	>100
$5/2^-$	5645	30
	5670	50
$1/2^+$	5360	80
$5/2^+$	5570	>100



At 0.2fm for cc-bar, we have a peak,
And at 0.8fm for ss, we have a peak.
We see that ss and cc-bar is compact.

Density distribution at 5180 MeV for J=1/2-

Summary

It was difficult to reproduce the data of Θ^+ and Pc with our quark model.
On the other hand, we found a sharp resonant state which has compact structure in the much higher energy region.

In order to check whether or not our model is reliable, in this work, we studied the structure of ssscc-bar which have never ever observed experimentally.

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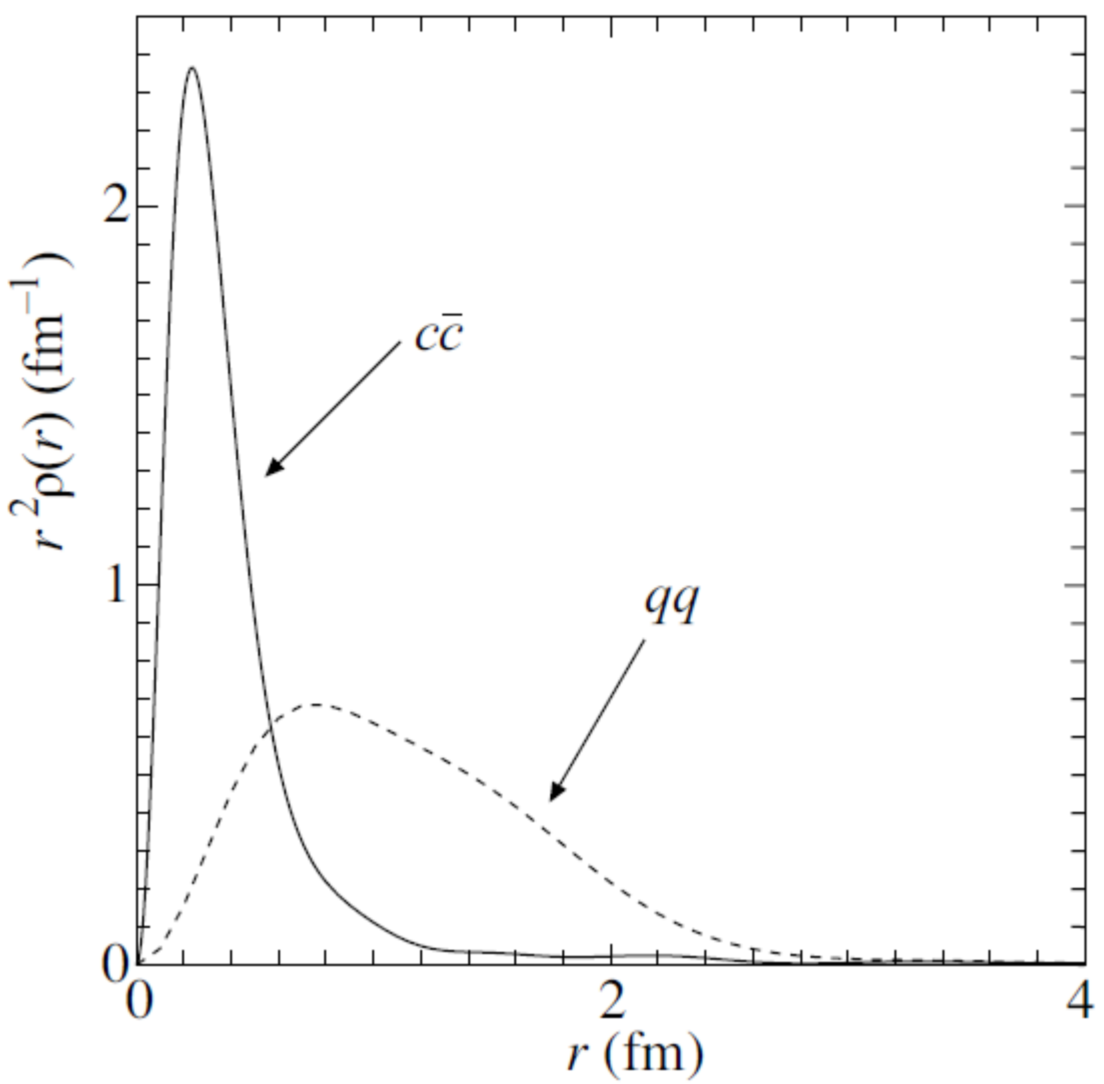
$5/2^+$	5570	>100

We predicted several resonant states for
1/2-, 3/2-, 5/2-, 1/2+ and 5/2+.
In the future, we should compare our results with those by Lattice QCD.
Then, we could conclude the reliability of our model.
The calculation with Lattice QCD is in progress by Philipp and Utku.

Thank you!



$r^2\rho(r)$ (fm^{-1})
r (fm)
$c\bar{c}$
qq
0
1
2
0
2
4