Few Quark Systems: Does quantum mechanics work in hadrons?

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Workshop on Few Body Systems in Hadron, Nuclear, Atomic and Molecular Physics
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- 量子少数多体系の厳密計算理論の確立とその応用研究

  for “Establishing Precision Computational Method in Quantum Few-body Systems and Developing its Applications”

- 「量子少数多体系」ってなに？

  What is “Quantum Few-body Systems”

  - なぜ難しいか Why are they difficult?
  - なぜ重要か Why are they important?
  - なぜ楽しいか Why do you (does she) enjoy this?

- どんな応用があるの？ What “Applications” are available?

ミクロの世界の個々と集団
～世界最強の量子 3体・4体問題計算理論～

仁科加速器研究センター

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背景

人間社会や自然界における集団の構成を考える時、構成員の間の相互作用が積み重なって集団としての性格や行動が作られていきます。このダイナミクスを明らかにすること、そのための適切な研究手法を構築することは、我々の社会における基本的な課題です。物理学においてのこのような研究手法の構築は大変重要な課題の一つとして、世界中で注目されています。

概要

本研究室では、陽子と中性子で構成されている原子核を３体問題～５体問題という観点からその性質を研究しています。このためには、３体問題～５体問題としてのシュレディンガー方程式を解く必要があります。スーパーコンピュータを駆使してこの基礎方程式を精密に解く手法を開発し、物理学の様々な分野に応用しています。

利点

- 応用範囲が広い（構成する粒子、相互作用は何でもよい）
- 使いやすい（マスターしやすい）
- 異なる粒子の５体問題まで解くことが可能

応用

- ハイパー核物理研究および中性子星内部構造の研究
- 冷却原子物理学への適用
- ミューオン触媒核融合

量子少数多体系計算

- ハイパー核からハドロンへ　あくなき前進

  “Five-body calculation of resonance and scattering states of pentaquark system”, E. Hiyama, M. Kamimura. A. Hosaka, H. Toki, M. Yahiro, Phys. Lett. B633 (2006) 237-244.

- 相互作用は何でもよい Any interaction is welcome! ?

- Goddess says,
  “Give me a Hamiltonian, then I will solve.”
  “Give me experimental data to fit.”

量子少数多体系計算

- Θ^+ の５体計算

  うまくいかない　unsuccessful

  低いエネルギー状態は出てこない

  高励起状態でシャープな共鳴が出るが、すでにいろいろ

  チャネルが開いているので、状態の特定が難しい

  ハミルトニアンがよくわからない

Five-body calculation of resonance and scattering states of pentaquark system
E. Hiyama, M. Kamimura, A. Hosaka, H. Toki and M. Yahiro

Physics Letters B 633 (2006) 237–244

Scattering problem of the $uudd\bar{s}$ system, in the standard non-relativistic quark model of Isgur-Karl, is solved for the first time, by treating the large five-body model space including the NK scattering channel accurately with the Gaussian expansion method and the Kohn-type coupled-channel variational method. The two-body interaction that reproduces observed properties of ordinary baryons and mesons is applied to the pentaquark system with no additional adjustable parameter. The five-body wave function calculated has the correct asymptotic form in its the scattering-channel component and describes qq and $q\bar{q}$ correlations properly. The N K scattering phase shift calculated shows no resonance in the energy region of the reported pentaquark $\Theta^+(1540)$, that is, at 0 − 500 MeV above the NK threshold (1.4 − 1.9 GeV in mass). The phase shift does show two resonances just above 500 MeV: a broad $1/2^+$ resonance with a width of $\Gamma \sim 110$ MeV located at ~ 520 MeV (~ 2.0 GeV in mass) and a sharp $1/2^-$ resonance with $\Gamma = 0.12$ MeV at 540 MeV. Properties of these states are discussed.

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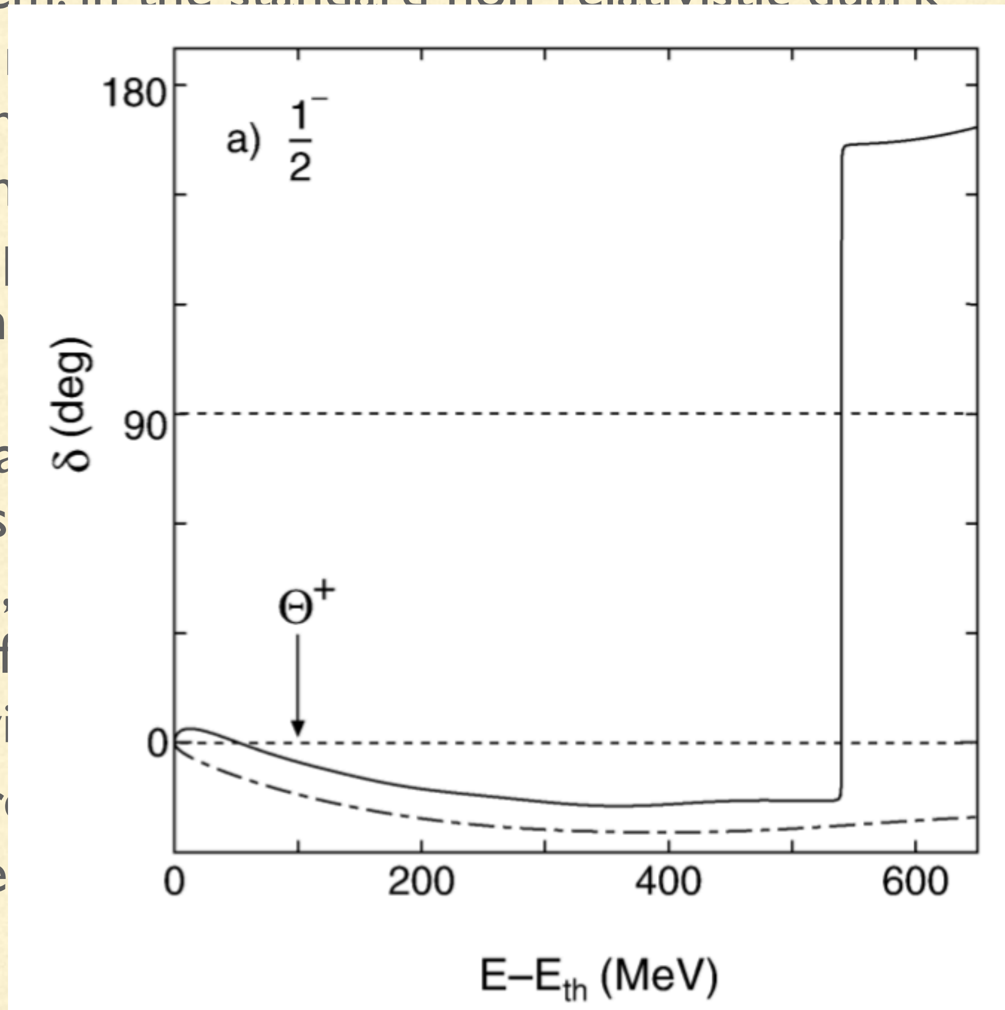


量子少数多体系計算

- ハイパー核の場合　For Hypernuclei
  相互作用がよくわからない
  ２体系の実験データがない（少ない）
  少数多体系に束縛状態が多数ある →少数系を解いて相互作用を決める

- ハドロン＝クォーク多体系の場合　For multi-quark system
  相互作用がよくわからない
  束縛状態がほとんどないので、共鳴状態を扱うしかない。
  何を解いて何と比べれば良いかはっきりしてない

量子少数多体系計算

- （そもそも）ハドロンはクォークの多体系の量子力学で記述できるか？粒子数が異なる状態の結合（Fock space）を取り入れないと共鳴状態や崩壊を扱えない。→QCDをそのまま解くしかない
- 束縛状態、基底状態だったら、粒子数を固定してもなんとかなる。チャーモニウムの低い励起状態ではうまくいった。でもΘ(1430)とかX(3872) みたいな状態がでてくると、結構つらい。
- それでも果敢に挑戦するのが肥山流。

Pentaquark P_c

- E. Hiyama, A. Hosaka, MO, J. M. Richard, "Quark model estimate of hidden-charm pentaquark resonances", *Phys. Rev. C98 (2018) 045208.*

A quark model, which reproduces the ground-state mesons and baryons, i.e., the threshold energies, is applied to the $qqqc\bar{c}$ configurations, where q is a light quark and c the charmed quark. In the calculation, several open channels are explicitly included such as $J/\psi + N$, $\eta_c + N$, $\Lambda_c + \bar{D}$, etc. To distinguish genuine resonances and estimate their width, we employ the Gaussian expansion method supplemented by the real scaling method (stabilization). No resonance is found at the energies of the $P_c(4380)$ and $P_c(4450)$ pentaquarks. On the other hand, there is a sharp resonant state at 4690 MeV with a $J = 1/2^-$ state and another one at 4920 MeV with a $J = 3/2^-$ state which have a compact structure.

- Complete calculation of the Pentaquark $c\bar{c}uud$ (I=1/2, J^P= 1/2$^-$, 3/2$^-$) in the NR potential quark model with two-body confining potential. *B. Silvestre-Brac, Few Body Syst. 20 (1996) 1-25*

Pentaquark P_c

Hamiltonian

$$H = \sum_{i}^{5} \left(m_i + \frac{\boldsymbol{p}_i^{\,2}}{2m_i} \right) - T_G$$

$$- \frac{3}{16} \sum_{i<j=1}^{5} \sum_{a}^{8} \left((\lambda_i^a \cdot \lambda_j^a) V_{ij}(\boldsymbol{r}_{ij}) \right)$$

$$V_{ij}(\boldsymbol{r}) = - \frac{\kappa}{r} + \lambda r^p - \Lambda$$

$$+ \frac{2\pi\kappa'}{3m_i m_j} \frac{\exp(-r^2/r_0^2)}{\pi^{3/2} r_0^3} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$$

$$r_0(m_i, m_j) = A \left(\frac{2m_i m_j}{m_i + m_j} \right)^{-B}$$

	AP1	AL1
p	2/3	1
$m_{u,d}$(GeV)	0.277	0.315
m_s(GeV)	0.553	0.577
m_c(GeV)	1.819	1.836
κ	0.4242	0.5069
κ'	1.8025	1.8609
λ(GeV^{p+1})	0.3898	0.1653
Λ(GeV)	1.1313	0.8321
B	0.3263	0.2204
A(GeV^{B-1})	1.5296	1.6553

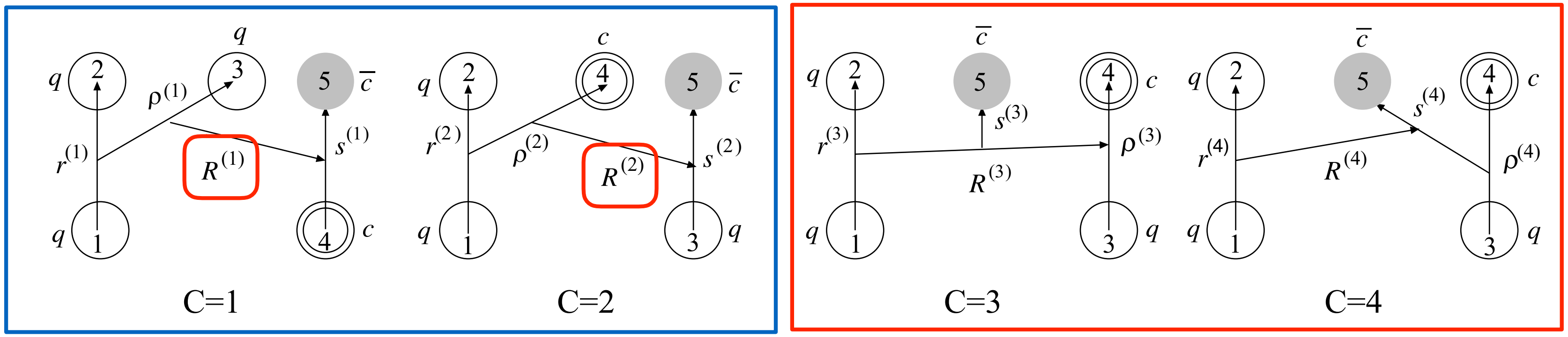
Pentaquark P_c

- Spectrum of two-body (meson) and three-body (baryon) systems

Hadron	J^P	Calc.	Expt.
η_c	0^-	2984	2983
J/ψ	1^-	3103	3096
$\bar{D}$	0^-	1882	1869
$\bar{D}^*$	1^-	2033	2007
N	$1/2^+$	937	938
Λ_c	$1/2^+$	2290	2286
Σ_c	$1/2^+$	2472	2455
Σ_c^*	$3/2^+$	2545	2520

Pentaquark P_c

- **Variational method**



scattering channels **confined channels**

- **Real scaling method**

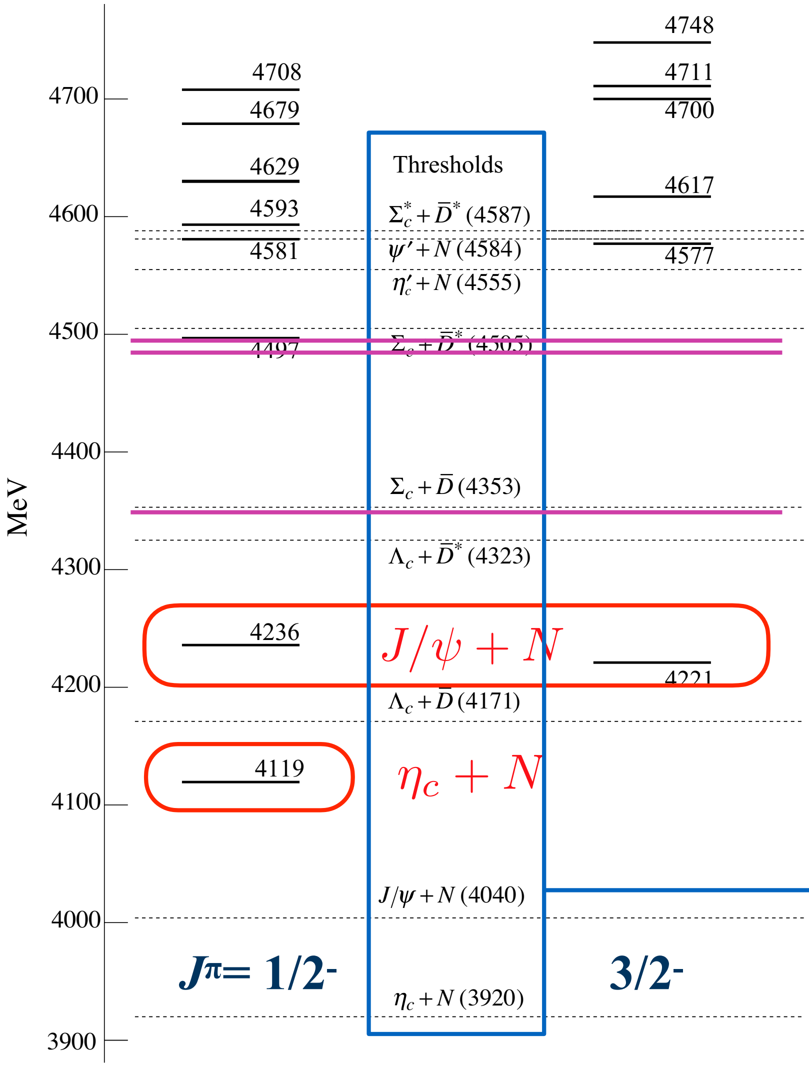
scale the relative coordinate in channels C=1, 2 by

$$R^{(1,2)} \rightarrow \alpha R^{(1,2)} \quad (\alpha \sim 1.0 - 1.5)$$

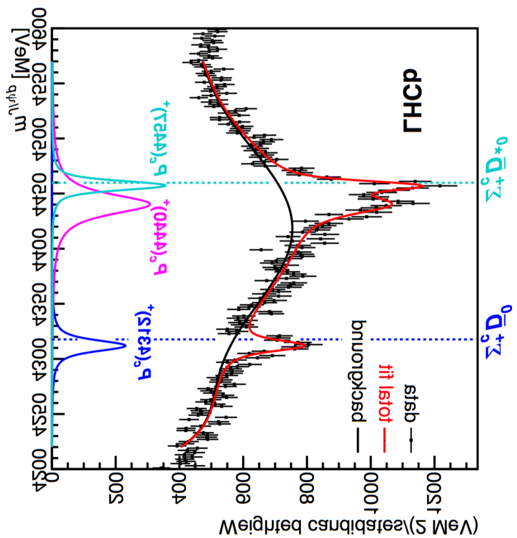
As the ranges of the variational basis functions are finite, all the eigenstates are discrete. Under the real scaling, the energy of the scattering states will change (decrease) towards the scattering threshold, but the compact state will stay.

Pentaquark P_c

- **Energy levels before coupling to the scattering channels (α=1)**



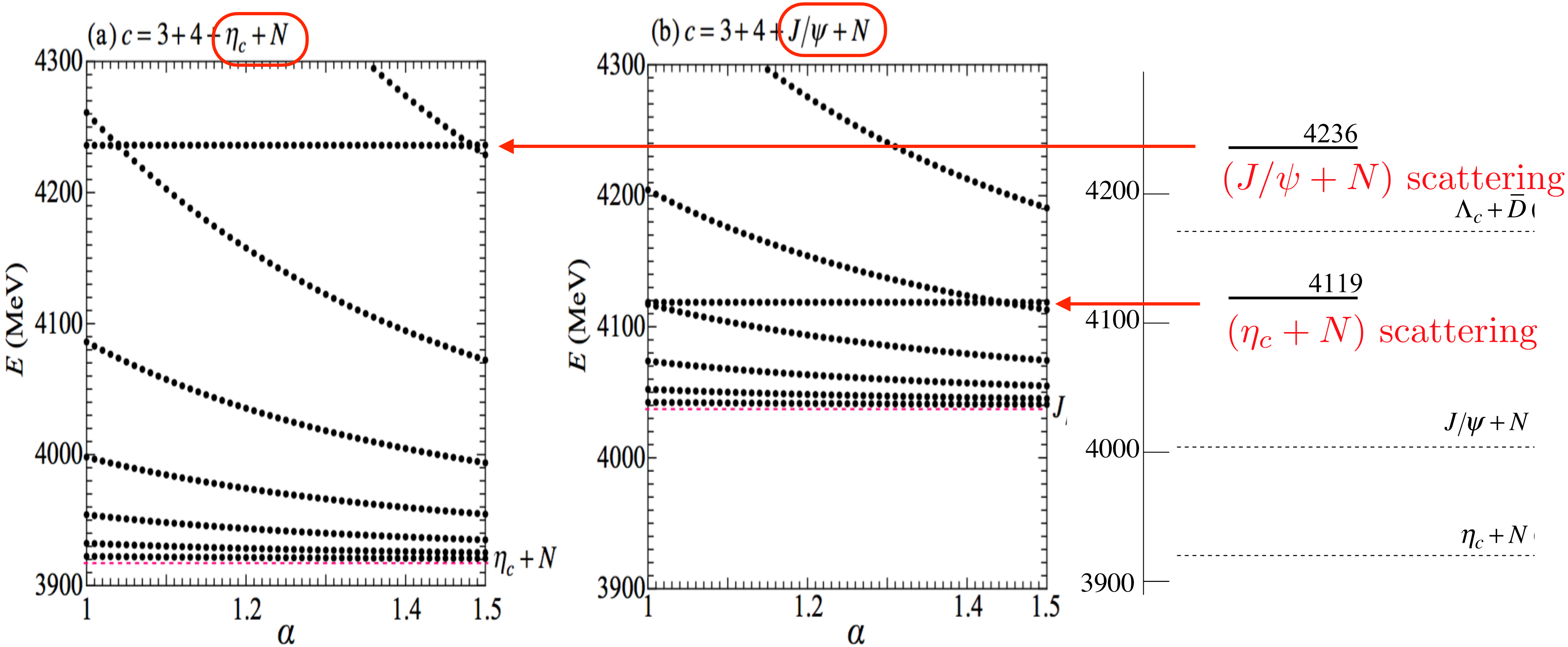
LHCb (*PRL 122 (2019) 222001*)



many thresholds

Pentaquark P_c

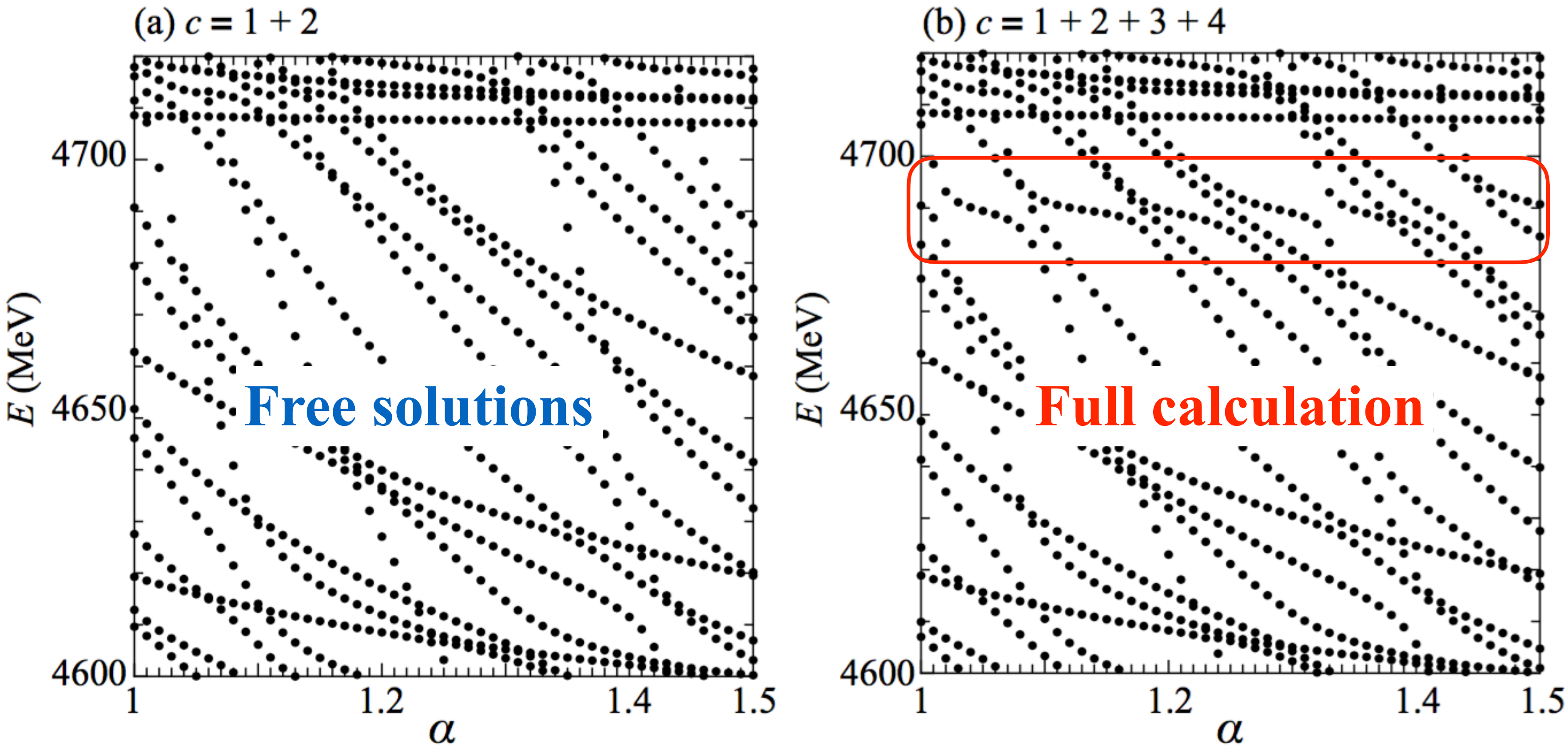
- Real scaling around 4100-4300 MeV for $1/2^-$



- Coupling of η_cN and J/ψN is weak because of the HQ spin symmetry

Pentaquark P_c

- At the end, most of the states are gone with the scattering channels and there remains a narrow $1/2^-$ state at E=4690 MeV.



Estimated decay width from the level crossing is about 40 MeV.

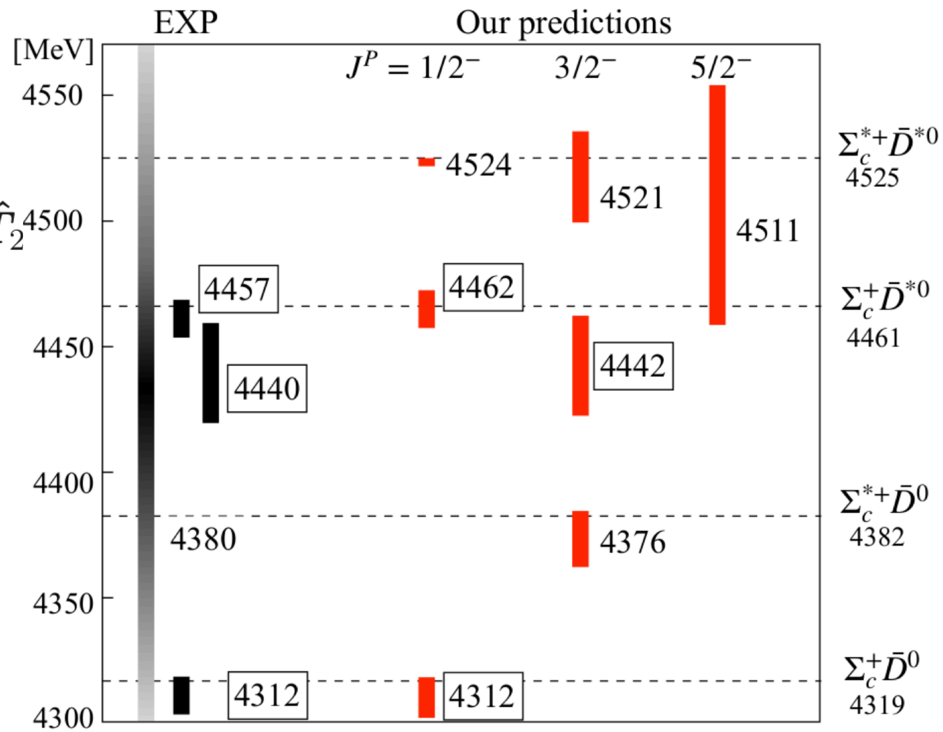
Pentaquark

- Another resonance structure at E=4920 MeV for $J^{\pi}=3/2^{-}$.
- No other (sharp) resonance is found for $1/2^{\pm}$, $3/2^{\pm}$, $5/2^{\pm}$ channels. Why?
- Choice 1: This model does not have a correct (confinement) potential, so that it cannot be applied to the pentaquark systems.
- Choice 2: This model does not predict loosely-bound hadronic molecules, because it does not induce any long-range interaction between color singlet hadrons, that is, no meson exchange force.

Pentaquark P_c

- Y. Yamaguchi, et al., Hidden-charm and bottom meson-baryon molecules coupled with five-quark states, PR D96 (2017) 114031.
- M. Z. Liu et al., Emergence of a Complete Heavy-Quark Spin Symmetry Multiplet, PRL 122 (2019) 242001.
- Y. Yamaguchi, et al., "Heavy quark spin symmetry with chiral tensor dynamics in the light of tl arXiv:1907.04684

$$V^{\pi}(\boldsymbol{q}) = -\left(\frac{g_A^M g_A^B}{4 f_\pi^2}\right) \frac{(\hat{\boldsymbol{S}}_1 \cdot \boldsymbol{q})(\hat{\boldsymbol{S}}_2 \cdot \boldsymbol{q})}{\boldsymbol{q}^2 + m_\pi^2} \hat{\boldsymbol{T}}_1 \cdot \hat{\boldsymbol{T}}_2$$



Conclusion

- **The quark model calculation suggests that the P_c pentaquarks found at LHCb are not compact 5-quark states, (possibly being molecular resonances of $\Sigma_c^{(*)}$+ $D^{(*)}$.)**
- **We predict a narrow $1/2^-$ state at E=4690 MeV (~200 MeV heavier than the LHCb pentaquarks).**
  Is it real? If such a state is confirmed, it is really a SUCCESS of the quark model. Note that several open three-body decay channels (Fock space) are not taken into account yet.
- **We have not understood why this state is sharp. It may come from "exotic" color configurations, where the properties of the interaction are not well understood.**
- **How can the lattice QCD help us to this problem? Heavy sector (including strangeness) may be the best place to compare.**

Pentaquark ssscc^{bar}

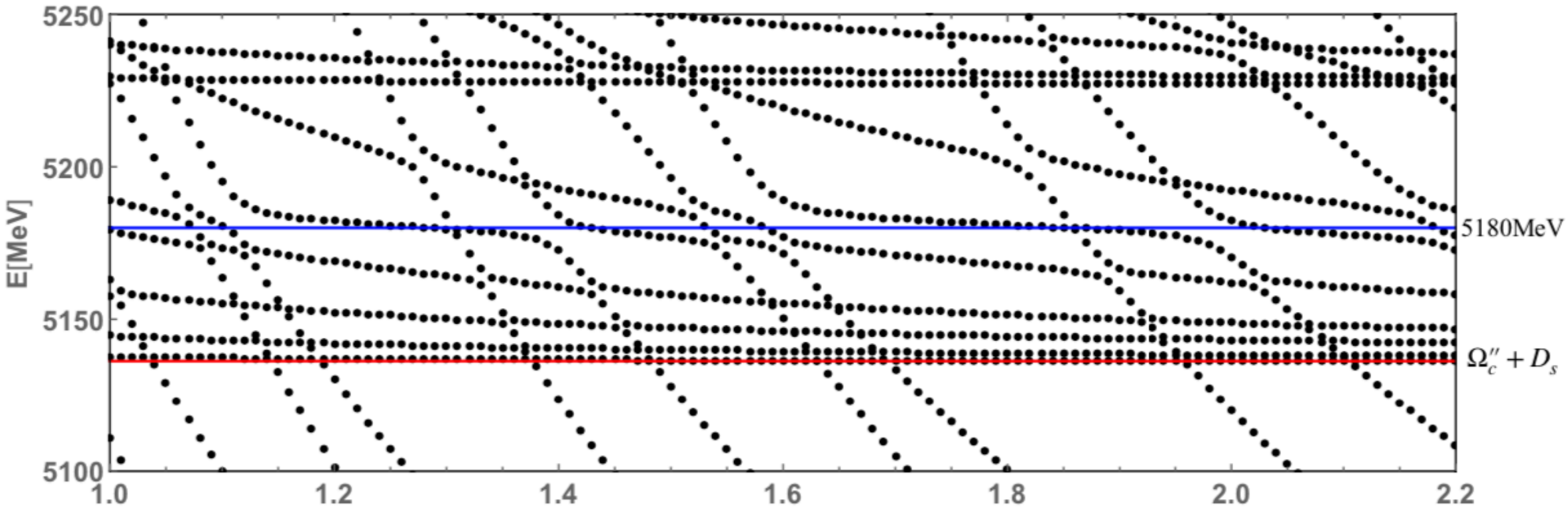
- **Compare the QM calculation with lattice QCD**

Compact $sssc\bar{c}$ pentaquark states predicted by a quark model

Qi Meng[a,*], Emiko Hiyama[b,c,d,e], Kadir Utku Can[c], Philipp Gubler[d], Makoto Oka[c,d], Atsushi Hosaka[c,d,e] and Hongshi Zong[a,f,g]

arXiv:1907.00144

***J*^{P}= 1/2$^-$ (sss color=8, 1/2, cc^{bar} color=8 0)**



Pentaquark ssscc^{bar}

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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

In future,

- **Few-Body Problems in Hadrons**
  We need to set a real (not realistic/feasible) goal.
  Few-body model with predictive power.
  My Dream is . . .

- **The Hiyama group(s) at RIKEN and Kyushu has been and will be a powerful source of young researchers (PD, Students, Foreigners). Keeping this activity is a must and needs supports from many people.**