Molecular state interpretation of charmed baryons in the quark model

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[arXiv:2211.12129]

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Outline

Ⅰ Introduction

Experiments：

- Λ_c^+ first observed by Fermilab in 1976

  [B. Knapp, W. Y. Lee, P. Leung, S. D. Smith, A. Wijangco, J. Knauer, D. Yount, J. Bronstein, R. Coleman and G. Gladding, et al. Phys. Rev. Lett. 37, 882 (1976)]

- $\Lambda_c(2595)$ $\Lambda_c(2625)$ $\Lambda_c(2940)$ $\Sigma_c(2800)$ $\Xi_c(2645)$ $\Xi_c(3080)$ $\Omega_c(2770)$ ...

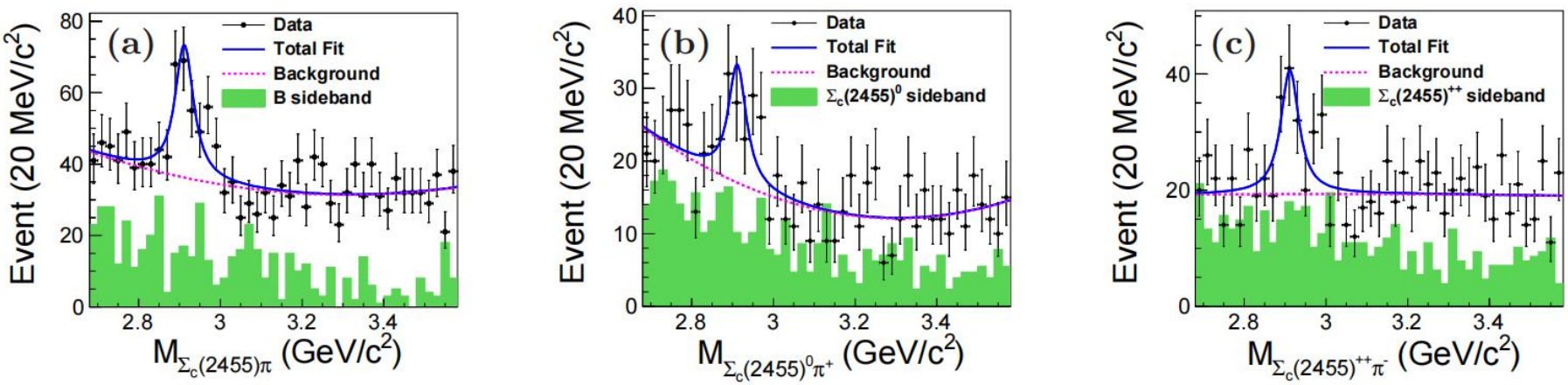
  keep being enriched step by step with the help of experimental collaborations

  [P. A. Zyla et al. [Particle Data Group], PTEP 2020, 083C01 (2020).]

- $\Lambda_c(2910)^+$:

A new structure was found in the $M_{\Sigma_c(2455)^{0,++}\pi^\pm}$ spectrum with a significance of 4.2σ including systematic uncertainty, which is tentatively named $\Lambda_c(2910)^+$. Its mass and width are measured to be $(2913.8 \pm 5.6 \pm 3.8)\mathrm{MeV}/c^2$ and $(51.8 \pm 20.0 \pm 18.8)\mathrm{MeV}$, respectively.

[Belle], [arXiv:2206.08822 [hep-ex]].



Motivation

- Various theoretical studies on the $\Lambda_c(2910)^+$:
  - light-cone QCD sum rule: $\mathrm{a}\ 2P\ \mathrm{state\ with}\ J^P = 1/2^-$
    [K. Azizi et al., Eur. Phys. J. C 82, 920 (2022)]
  - chiral quark model: $J^P = 5/2^-$ state $\Lambda_c \left| J^P = \frac{5}{2}^-, 2 \right\rangle_\rho$
    [W. J. Wang et al., Phys. Rev. D 106, 074020(2022)]
  - unquenched picture: contain a significant D^*N component, prefers $3/2^-$
    [Z. L. Zhang et al., [arXiv:2210.17188 [hep-ph]].]
  - ...

II Framework

Quark delocalization color screening model

$$H = \sum_{i=1}^{5}\left(m_i + \frac{\boldsymbol{p}_i^2}{2m_i}\right) - T_{CM} + \sum_{j>i=1}^{5} V(\boldsymbol{r}_{ij})$$

$$V(\boldsymbol{r}_{ij}) = \underbrace{V_{CON}(\boldsymbol{r}_{ij})}_{①} + \underbrace{V_{OGE}(\boldsymbol{r}_{ij})}_{②} + \underbrace{V_{\chi}(\boldsymbol{r}_{ij})}_{③}$$

The most relevant features of QCD at its low energy regime:

① color confinement (V_{CON}),

② perturbative one-gluon exchange interaction (V_{OGE}),

③ dynamical chiral symmetry breaking (V_{χ}) have been taken into consideration.

The quark delocalization effect:

$$\psi_\alpha(\mathbf{S}_i, \epsilon) = \left(\phi_\alpha(\mathbf{S}_i) + \epsilon\phi_\alpha(-\mathbf{S}_i)\right)/N(\epsilon),$$
$$\psi_\beta(-\mathbf{S}_i, \epsilon) = \left(\phi_\beta(-\mathbf{S}_i) + \epsilon\phi_\beta(\mathbf{S}_i)\right)/N(\epsilon),$$
$$N(\epsilon) = \sqrt{1 + \epsilon^2 + 2\epsilon e^{-S_i^2/4b^2}}.$$

Framework

① $V_{CON}(\boldsymbol{r}_{ij}) = -a_c \boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c \left[f(\boldsymbol{r}_{ij}) + V_0 \right]$

$$f(\boldsymbol{r}_{ij}) = \begin{cases} \boldsymbol{r}_{ij}^2 & i,j \text{ occur in the same cluster} \\ \frac{1-e^{-\mu_{q_i q_j} \boldsymbol{r}_{ij}^2}}{\mu_{q_i q_j}} & i,j \text{ occur in different cluster} \end{cases}$$

② $$V_{OGE}(\boldsymbol{r}_{ij}) = \frac{1}{4}\alpha_s \boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c \left[\frac{1}{r_{ij}} - \frac{\pi}{2}\delta(\mathbf{r}_{ij}) \left(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j}{3 m_i m_j} \right) \right]$$

③ $V_\chi(\boldsymbol{r}_{ij}) = V_\pi(\boldsymbol{r}_{ij}) + V_K(\boldsymbol{r}_{ij}) + V_\eta(\boldsymbol{r}_{ij})$

$$V_\pi(\boldsymbol{r}_{ij}) = \frac{g_{ch}^2}{4\pi} \frac{m_\pi^2}{12 m_i m_j} \frac{\Lambda_\pi^2 m_\pi}{\Lambda_\pi^2 - m_\pi^2} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \left[Y(m_\pi r_{ij}) - \frac{\Lambda_\pi^3}{m_\pi^3} Y(\Lambda_\pi r_{ij}) \right] \sum_{a=1}^{3} \lambda_i^a \lambda_j^a,$$

$$V_K(\boldsymbol{r}_{ij}) = \frac{g_{ch}^2}{4\pi} \frac{m_K^2}{12 m_i m_j} \frac{\Lambda_K^2 m_K}{\Lambda_K^2 - m_K^2} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \left[Y(m_K r_{ij}) - \frac{\Lambda_K^3}{m_K^3} Y(\Lambda_K r_{ij}) \right] \sum_{a=4}^{7} \lambda_i^a \lambda_j^a$$

$$V_\eta(\boldsymbol{r}_{ij}) = \frac{g_{ch}^2}{4\pi} \frac{m_\eta^2}{12 m_i m_j} \frac{\Lambda_\eta^2}{\Lambda_\eta^2 - m_\eta^2} m_\eta \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \left[Y(m_\eta r_{ij}) - \frac{\Lambda_\eta^3}{m_\eta^3} Y(\Lambda_\eta r_{ij}) \right] \times \left[\cos\theta_P (\lambda_i^8 \lambda_j^8) - \sin\theta_P (\lambda_i^0 \lambda_j^0) \right],$$

Methods:

① Resonance group method (RGM):

$$\Psi_{5q} = \mathcal{A}[[\phi_A(\boldsymbol{\rho}_A, \boldsymbol{\lambda}_A)\phi_B(\boldsymbol{\rho}_B]^{[\sigma]IS}\chi(\boldsymbol{R})Z(\boldsymbol{R}_{cm})]$$

$$\hat{\phi_A}(\boldsymbol{\rho}_A, \boldsymbol{\lambda}_A) = (\frac{2}{3\pi b^2})^{3/4}(\frac{1}{2\pi b^2})^{3/4}e^{-(\frac{\lambda_A^2}{3b^2}+\frac{\rho_A^2}{4b^2})}\eta_{I_A S_A}\chi_c(A),$$

$$\hat{\phi_B}(\boldsymbol{\rho}_B) = (\frac{1}{2\pi b^2})^{3/4}e^{-\frac{\rho_B^2}{4b^2}}\eta_{I_B S_B}\chi_c(B).$$

② Coordinate Generation Method:

$$\chi(\boldsymbol{R}) = \frac{1}{\sqrt{4\pi}}\left(\frac{6}{5\pi b^2}\right)^{3/4}\sum_{i,L,M} C_{i,L}\int \exp\left[-\frac{3}{5b^2}(\boldsymbol{R}-\boldsymbol{S}_i)^2\right] Y_{LM}\left(\hat{\boldsymbol{S}}_i\right) d\Omega_{\boldsymbol{S}_i}$$

③ Real-scaling Method:
(to check the resonance states)

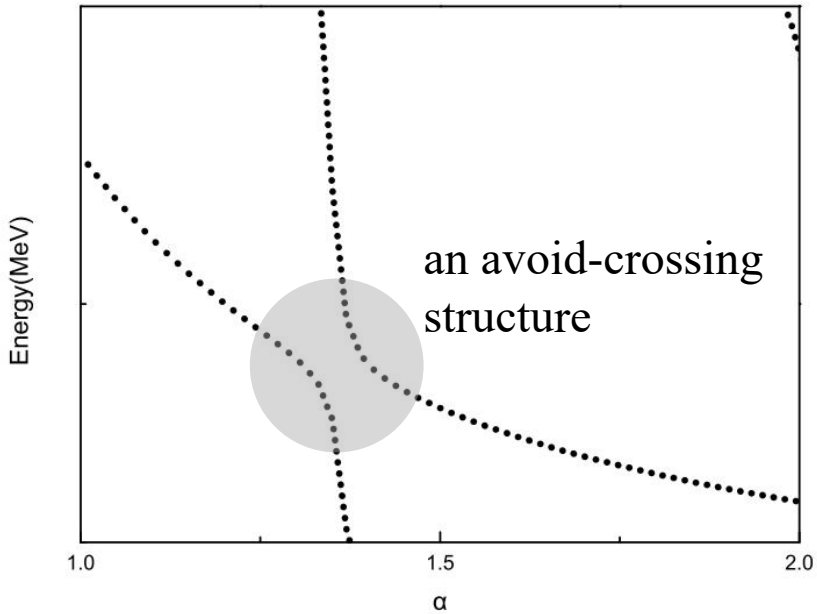


FIG. 1: The shape of the resonance in real-scaling method.

[H. S. Taylor, Adv. Chem. Phys. 18, 91 (1970)]

- spin degree of freedom:

$$\chi^{\sigma 1}_{\frac{1}{2},\frac{1}{2}}(5) = \chi^{\sigma}_{\frac{1}{2},\frac{1}{2}}(3)\chi^{\sigma}_{0,0}(2)$$

$$\chi^{\sigma 2}_{\frac{1}{2},\frac{1}{2}}(5) = -\sqrt{\frac{2}{3}}\chi^{\sigma}_{\frac{1}{2},-\frac{1}{2}}(3)\chi^{\sigma}_{1,1}(2) + \sqrt{\frac{1}{3}}\chi^{\sigma}_{\frac{1}{2},\frac{1}{2}}(3)\chi^{\sigma}_{1,0}(2)$$

$$\chi^{\sigma 3}_{\frac{1}{2},\frac{1}{2}}(5) = \sqrt{\frac{1}{6}}\chi^{\sigma}_{\frac{3}{2},-\frac{1}{2}}(3)\chi^{\sigma}_{1,1}(2) - \sqrt{\frac{1}{3}}\chi^{\sigma}_{\frac{3}{2},\frac{1}{2}}(3)\chi^{\sigma}_{1,0}(2) + \sqrt{\frac{1}{2}}\chi^{\sigma}_{\frac{3}{2},\frac{3}{2}}(3)\chi^{\sigma}_{1,-1}(2)$$

$$\chi^{\sigma 4}_{\frac{3}{2},\frac{3}{2}}(5) = \chi^{\sigma}_{\frac{1}{2},\frac{1}{2}}(3)\chi^{\sigma}_{1,1}(2)$$

$$\chi^{\sigma 5}_{\frac{3}{2},\frac{3}{2}}(5) = \chi^{\sigma}_{\frac{3}{2},\frac{3}{2}}(3)\chi^{\sigma}_{0,0}(2)$$

$$\chi^{\sigma 6}_{\frac{3}{2},\frac{3}{2}}(5) = \sqrt{\frac{3}{5}}\chi^{\sigma}_{\frac{3}{2},\frac{3}{2}}(3)\chi^{\sigma}_{1,0}(2) - \sqrt{\frac{2}{5}}\chi^{\sigma}_{\frac{3}{2},\frac{1}{2}}(3)\chi^{\sigma}_{1,1}(2)$$

$$\chi^{\sigma 7}_{\frac{5}{2},\frac{5}{2}}(5) = \chi^{\sigma}_{\frac{3}{2},\frac{3}{2}}(3)\chi^{\sigma}_{1,1}(2)$$

$\chi(5)$ stands for wave functions of five-quark system
$\chi(3)$ stands for wave functions of three-quark system
$\chi(2)$ stands for wave functions of two-quark system

Framework

- flavor degree of freedom:

$$\chi^{f1}_{0,0}(5) = \chi^{f}_{0,0}(3)\chi^{f}_{0,0}(2)$$

$$\chi^{f2}_{0,0}(5) = \sqrt{\frac{1}{2}}\chi^{f}_{\frac{1}{2},\frac{1}{2}}(3)\chi^{f}_{\frac{1}{2},-\frac{1}{2}}(2) - \sqrt{\frac{1}{2}}\chi^{f}_{\frac{1}{2},-\frac{1}{2}}(3)\chi^{f}_{\frac{1}{2},\frac{1}{2}}(2)$$

$$\chi^{f3}_{0,0}(5) = \sqrt{\frac{1}{3}}\chi^{f}_{1,1}(3)\chi^{f}_{1,-1}(2) - \sqrt{\frac{1}{3}}\chi^{f}_{1,0}(3)\chi^{f}_{1,0}(2) + \sqrt{\frac{1}{3}}\chi^{f}_{1,-1}(3)\chi^{f}_{1,1}(2) \quad (2$$

- color degree of freedom:

$$\chi^{c} = \frac{1}{\sqrt{6}}(rgb - rbg + gbr - grb + brg - bgr) \times \frac{1}{\sqrt{3}}(r\bar{r} + g\bar{g} + b\bar{b})$$

III Results

$J^P = \frac{1}{2}^-$ sector

TABLE III: The energies of the $qqq\bar{q}c$ pentaquark system with quantum numbers $J^P = \frac{1}{2}^-$ (unit: MeV).

structure	χ^{f_i}	χ^{σ_j}	χ^{c_k}	Channel	$E_{th}(Theo.)$	E_{sc}/E'_{sc}	E_B	E_{ccs}/E'_{ccs}	E_{cct}/E'_{cct}
$qqq-\bar{q}c$	$i=2$	$j=1$	$k=1$	ND	2778.3	2779.4/2809.1	0	2776.4/2801.0	2597.6/2574.4
	$i=2$	$j=2$	$k=1$	ND^*	2862.3	2864.4/2946.4	0		
$qqc-\bar{q}q$	$i=1$	$j=2$	$k=1$	$\Lambda_c\omega$	3027.0	3029.5/3069.2	0	2613.9/2583.1	
	$i=3$	$j=1$	$k=1$	$\Sigma_c\pi$	2623.0	2625.2/2593.6	0		
	$i=3$	$j=2$	$k=1$	$\Sigma_c\rho$	3254.0	3251.3/3226.6	-2.7		
	$i=3$	$j=3$	$k=1$	$\Sigma_c^*\rho$	3278.6	3266.1/3281.2	-12.5		

The proportion of each channel in $qqq-\bar{q}c$ channel coupling, ND : 84.0%; ND^* : 16.0%.
The proportion of each channel in $qqc-\bar{q}q$ channel coupling, $\Sigma_c\pi$: 87.3%; $\Lambda_c\omega$: 11.1%; rests: 1.6%.
The proportion of each channel in total channel coupling, $\Sigma_c\pi$: 90.0%; ND : 8.1%; rests: 1.9%.

$qqc-\bar{q}q$ structure formed a quasi-bound state(-3MeV), which is closed to the $\Sigma_c(2800)$.

similiar conclusion:

[Y. Dong et al., Phys. Rev. D **81**, 074011 (2010)]
[J. R. Zhang, Int. J. Mod. Phys. Conf. Ser. **29**, 1460220 (2014)]
[L. Zhao et al., Eur. Phys. J. A **53**, 28 (2017)]
[S. Sakai et al., Phys. Lett. B **808**, 135623 (2020)]
[Q. Zhang et al., Eur. Phys. J. C **81**, 224 (2021)]

Results

thresholds(red lines)

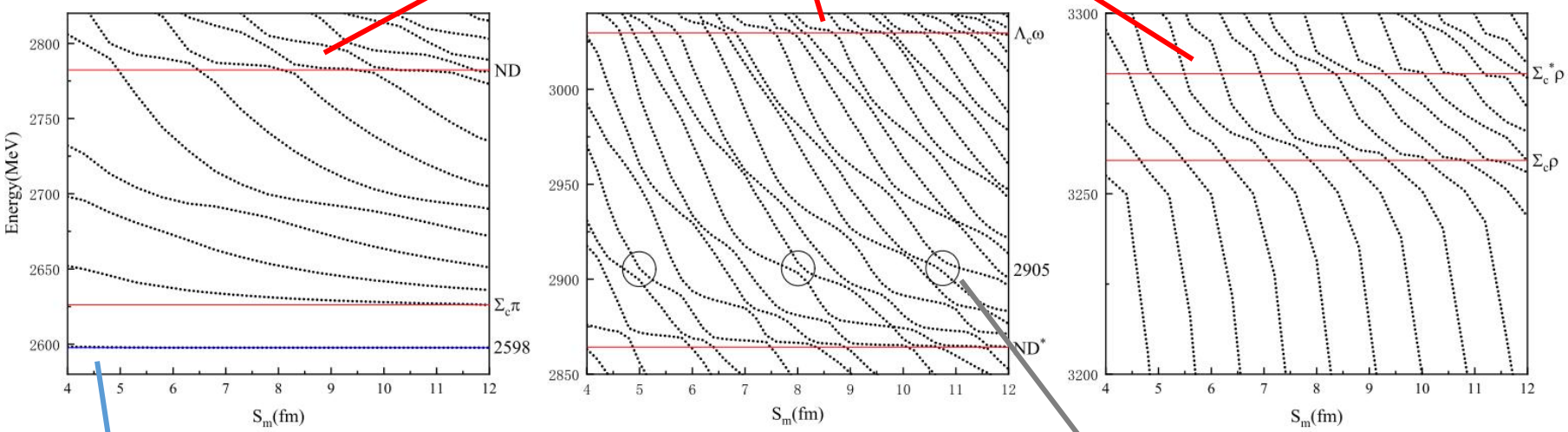


FIG. 2: Energy spectrum of $J^P = \frac{1}{2}^-$ system.

bound state(blue line)

possible resonance state for Λc(2910)
(avoid-crossing structure)

Results

TABLE IV: The RMS of the $qqq\bar{q}c$ pentaquark system with quantum numbers $J^P = \frac{1}{2}^-$ (unit: fm).

	Channel	R	nature
single channel	ND	2.85	scattering
	ND^*	3.73	scattering
	$\Lambda_c\omega$	3.99	scattering
	$\Sigma_c\pi$	3.39	scattering
	$\Sigma_c\rho$	1.87	bound
	$\Sigma_c^*\rho$	1.63	bound
channel-coupling	$E_{cct}(2598)$	1.35	bound
	$E_{ccs}(2776)$	3.45	scattering
	$E(2905)$	4.33	scattering

The proportion of each channel in $E_{cct}(2598)$,
$\Sigma_c\pi$: 90.0%; ND : 8.1%; rests: 1.9%.
The proportion of each channel in $E_{ccs}(2776)$,
ND : 84.0%; ND^* : 16.0%.
The proportion of each channel in E(2905),
ND^* : 86.6%; ND : 10.9%; rests: 2.5%.

the bound state
be 2574.4 MeV after mass correction
determined to be $\Lambda_c(2595)$

[J. X. Lu et al., Phys. Rev. D 92, 014036 (2015)]
[J. Nieves etal., Phys. Rev. D 101, 014018 (2020)]
[Q. Zhang et al., Eur. Phys. J. C 81, 224 (2021)]

the ND & ND* quasi-bound state
determined to be scattering state

the avoid-crossing structure
(was possible to be Λc(2910))
determined to be scattering state

$J^P = \frac{3}{2}^-$ sector

TABLE V: The energies of the $qqq\bar{q}c$ pentaquark system with quantum numbers $J^P = \frac{3}{2}^-$ (unit: MeV).

structure	χ^{f_i}	χ^{σ_j}	χ^{c_k}	Channel	$E_{th}(Theo.)$	E_{sc}/E'_{sc}	E_B	E_{ccs}/E'_{ccs}	E_{cct}/E'_{cct}
$qqq-\bar{q}c$	$i=2$	$j=4$	$k=1$	ND^*	2862.3	2853.9/2937.9	-8.5	2853.9/2937.9	
$qqc-\bar{q}q$	$i=1$	$j=4$	$k=1$	$\Lambda_c\omega$	3027.0	3030.3/3069.2	0	2636.9/2646.9	2624.4/2634.7
	$i=3$	$j=4$	$k=1$	$\Sigma_c\rho$	3254.0	3177.4/3152.7	-76.6		
	$i=3$	$j=5$	$k=1$	$\Sigma_c^*\pi$	2647.6	2649.8/2658.0	0		
	$i=3$	$j=6$	$k=1$	$\Sigma_c^*\rho$	3278.6	3264.7/ 3279.8	-13.9		

The proportion of each channel in $qqc-\bar{q}q$ channel coupling, $\Sigma_c^*\pi$: 83.8%; $\Lambda_c\omega$: 8.5%; rests: 7.7%.
The proportion of each channel in channel coupling, $\Sigma_c^*\pi$: 95.6%; $\Lambda_c\omega$: 2.9%; rests: 1.5%.

the ND* bound state could result in a resonance state.

similiar conclusion:

[Y. Dong et al., Phys. Rev. D **82**, 034035 (2010)]
[J. He et al., Phys. Rev. D **82**, 114029 (2010)]
[P. G. Ortega et al., Phys. Lett. B **718**, 1381 (2013)]
[J. R. Zhang, Phys. Rev. D **89**, 096006 (2014)]
[X. Y. Wang et al., Phys. Rev. D **92**, 094032 (2015)]
[D. R. Entem etal., AIP Conf. Proc. **1701**, 050003 (2016)]
[L. Zhao et al., Eur. Phys. J. A **53**, 28 (2017)]
[X. G. He et al., Eur. Phys. J. C **51**, 883 (2007)]

Results

thresholds(red lines)

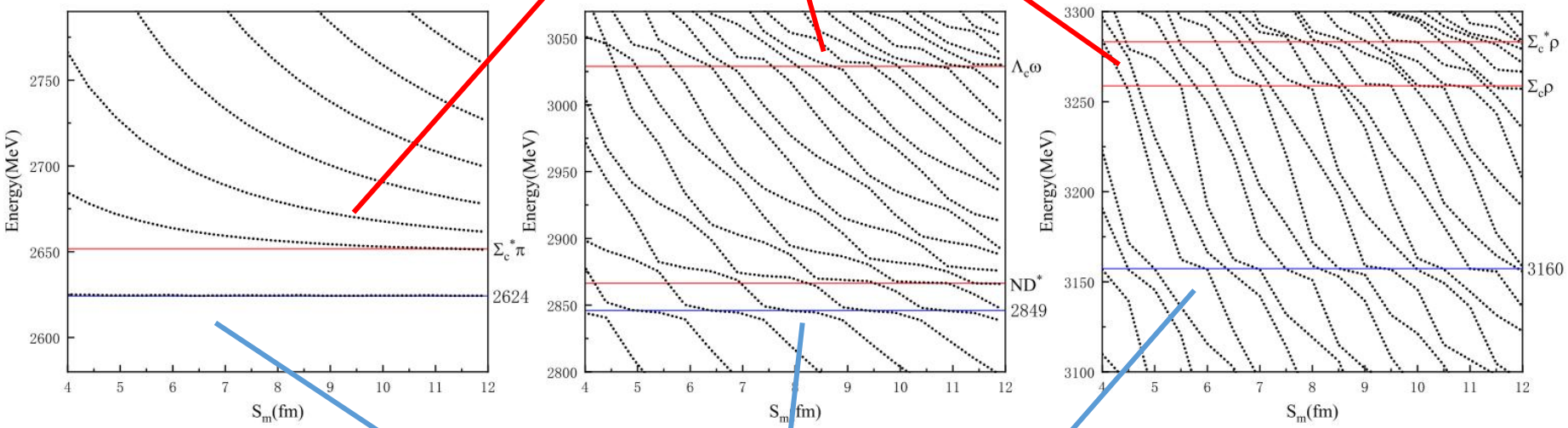


FIG. 4: Energy spectrum of $J^P = \frac{3}{2}^-$ system.

bound state & resonance states
(blue lines)

Results

TABLE VI: The RMS of the $qqq\bar{q}c$ pentaquark system with quantum numbers $J^P = \frac{3}{2}^-$ (unit: fm).

	Channel	R	nature
single channel	ND^*	1.91	bound
	$\Lambda_c\omega$	3.92	scattering
	$\Sigma_c\rho$	1.40	bound
	$\Sigma_c^*\pi$	3.56	scattering
	$\Sigma_c^*\rho$	1.74	bound
channel-coupling	$E_{cct}(2624)$	1.44	bound
	$E(2849)$	1.86	resonance
	$E(3160)$	1.38	resonance

The proportion of each channel in $E_{cct}(2624)$,
$\Sigma_c^*\pi$: 95.6%; $\Lambda_c\omega$: 2.9%; rests: 1.5%.
The proportion of each channel in E(2849),
ND^* : 66.5%; $\Sigma_c^*\pi$: 25.1%; rests: 8.4%.
The proportion of each channel in E(3160),
$\Sigma_c\rho$: 71.9%; $\Sigma_c^*\rho$: 25.2%; rests: 2.9%.

bound state
2634.7MeV after mass correction
determined to be $\Lambda_c(2625)$

[C. Garcia-Recio et al., Phys. Rev. D **79**, 054004 (2009)]
[O. Romanets et al., Phys. Rev. D **85**, 114032 (2012)]
[Q. Zhang et al., Eur. Phys. J. C **81**, 224 (2021)]

resonance state
2933.0MeV after mass correction
determined to be $\Lambda_c(2940)$

resonance state
3140MeV after mass correction
predicted to exist

$J^P = \frac{5}{2}^-$ sector

TABLE VII: The energies of the $qqq\bar{q}c$ pentaquark system with quantum numbers $J^P = \frac{5}{2}^-$ (unit: MeV).

structure	χ^{f_i}	χ^{σ_j}	χ^{c_k}	Channel	$E_{th}(Theo.)$	E_{sc}/E'_{sc}	E_B	E_{ccs}/E'_{ccs}	E_{cct}/E'_{cct}
$qqc-\bar{q}q$	$i=3$	$j=7$	$k=1$	$\Sigma_c^*\rho$	3278.6	3173.2/ 3188.3	-105.4	3173.2/3188.3	3173.2/3188.3

A deeply bound state is predicted to exist, with the binding energy of −105.4 MeV
the corrected mass of this state is 3188.3 MeV
The value of RMS of this state is 1.38 fm, which shows that it is a molecular state.

Ⅳ Summary

Summary

- Three bound states are obtained in present work, among which $\Lambda_c(2595)$ can be interpreted as the molecular state with $J^P = \frac{1}{2}^-$ and the main component is $\Sigma_c\pi$.
  $\Lambda_c(2625)$ can be interpreted as the molecular state with $J^P = \frac{3}{2}^-$ and the main component is $\Sigma_c^*\pi$.
  Besides, the $\Sigma_c^*\rho$ with $J^P = \frac{5}{2}^-$ is predicted to be a deeply bound state with the mass of 3188.3 MeV.

- In present work, $\Lambda_c(2910)$ cannot be interpreted as a molecular state, and $\Sigma_c(2800)$ cannot be explained as the ND molecular state with $J^P = \frac{1}{2}^-$

- Two resonancestates are obtained, in which the $\Lambda_c(2940)$ is likely to be interpreted as a molecular state with $J^P = \frac{3}{2}^-$, and the main component is ND*.
  Besides, a new molecular state $\Sigma_c\rho$ with $J^P = \frac{3}{2}^-$ is predicated, whose mass is about 3140 MeV.

Thanks for your attention!