Investigating excited Ω_c states from pentaquark perspective

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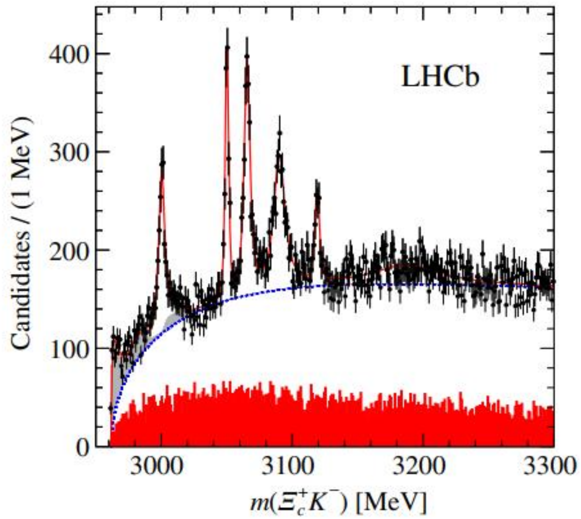
Collaborators：Hongxia Huang (黄虹霞), Jialun Ping (平加伦)

第七届强子谱和强子结构研讨会　2024.04.27　电子科技大学　成都

Outline

- Brief introduction of excited Ω_c states
- Quark delocalization color screening model
- Investigation of $ssc\bar{q}q$ system in QDCSM
- Summary

- **Experimental results**



LHCb collaboration
Phys. Rev. Lett. **118**, 182001 (2017)

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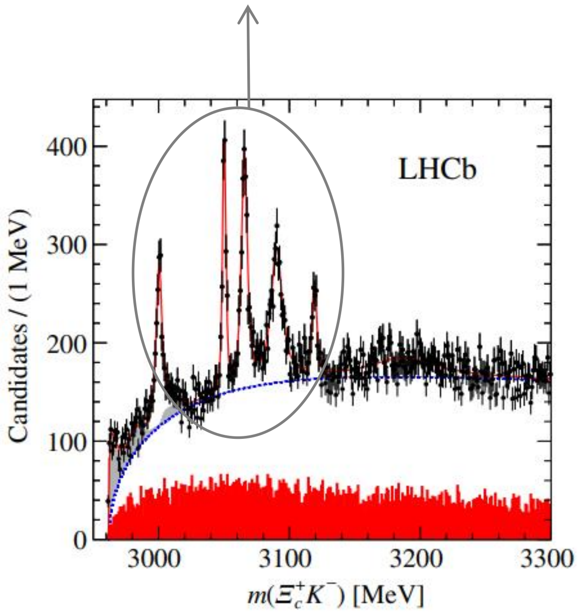
➢ Experimental results

Five narrow Ωc states:
Ωc(3000), Ωc(3050), Ωc(3066),
Ωc(3090), and Ωc(3119)



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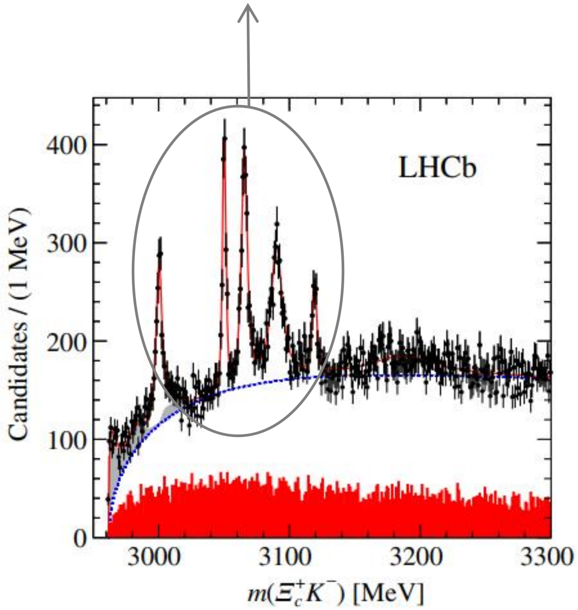

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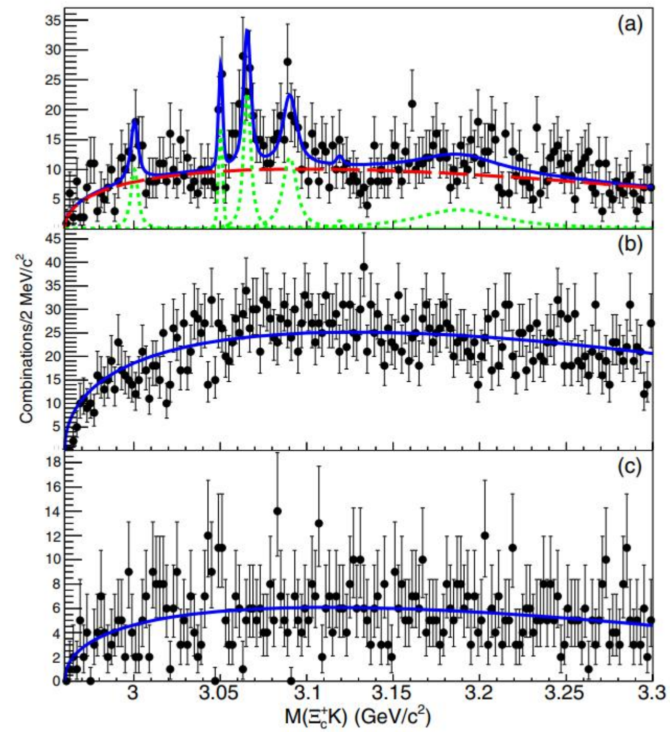

Belle collaboration
Phys. Rev. D **97**, 051102 (2018)

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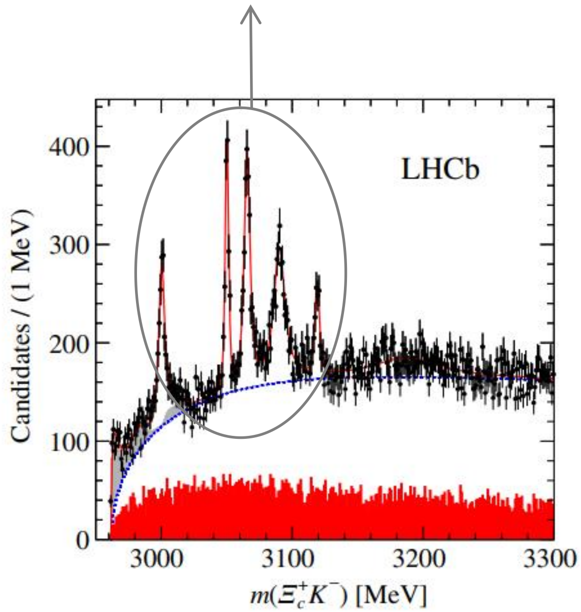
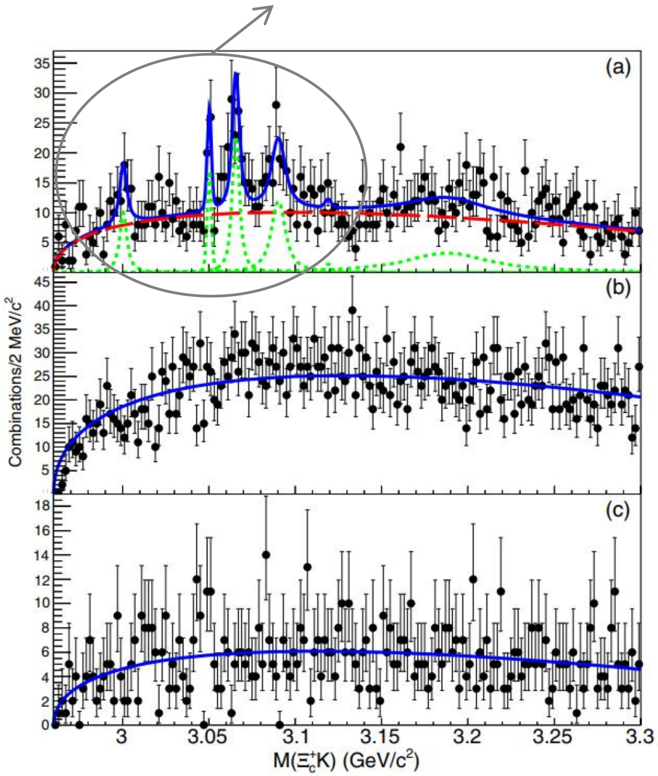


LHCb collaboration
Phys. Rev. Lett. **118**, 182001 (2017)

Four of them are confirmed



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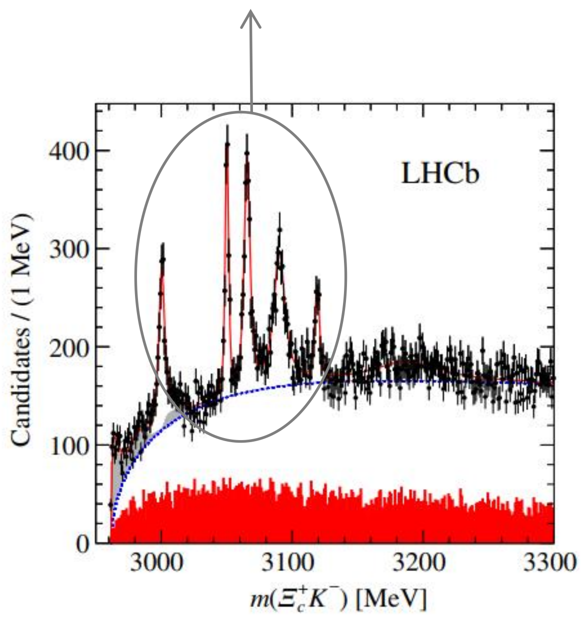

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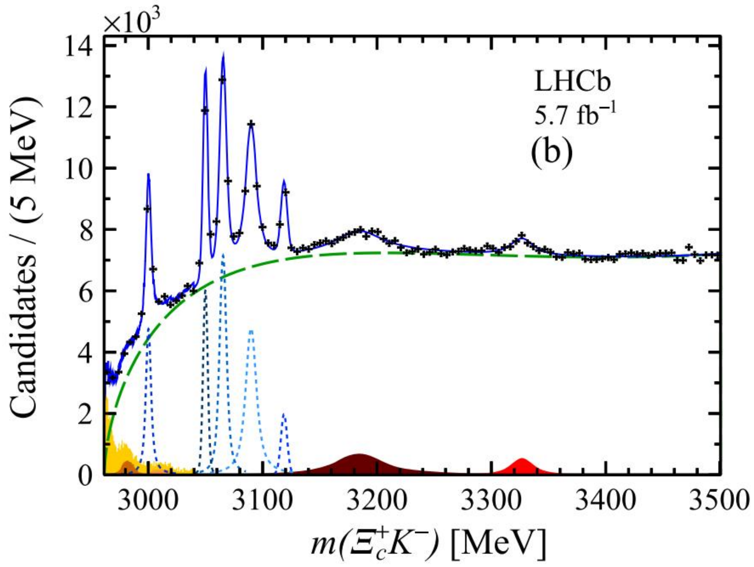


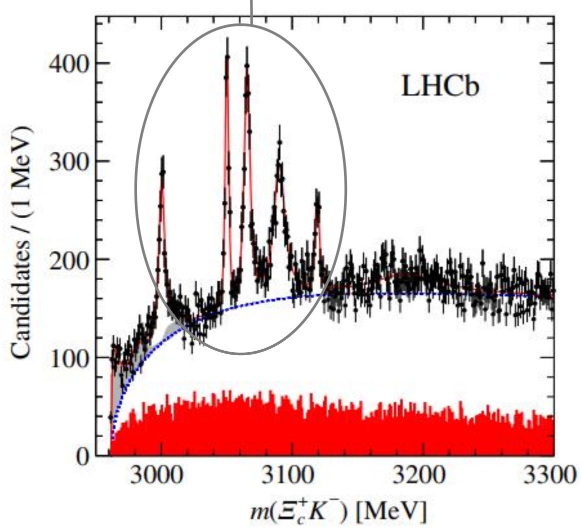
LHCb collaboration
Phys. Rev. Lett. **131**, 131902 (2023)

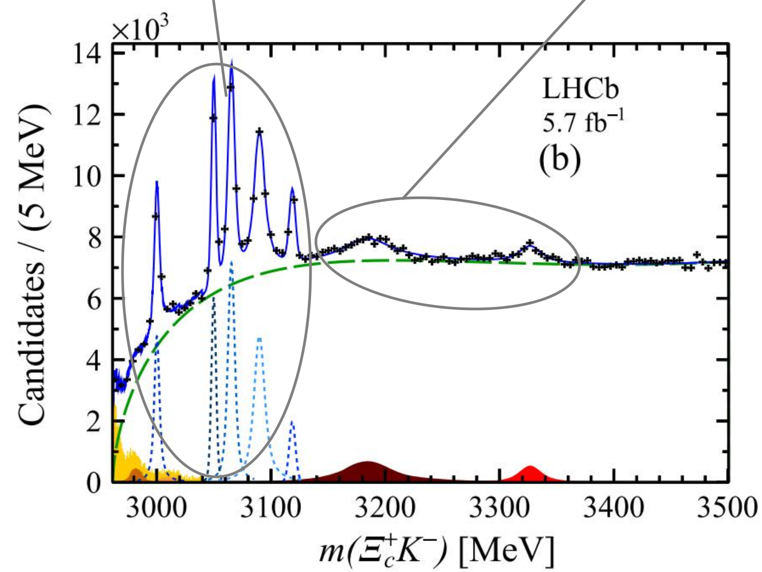
➢ Experimental results

Five narrow Ωc states:
Ωc(3000), Ωc(3050), Ωc(3066),
Ωc(3090), and Ωc(3119)

All five Ωc are confirmed

Two new excited states:
Ωc(3185) and Ω(3327)





LHCb collaboration
Phys. Rev. Lett. **118**, 182001 (2017)

LHCb collaboration
Phys. Rev. Lett. **131**, 131902 (2023)

- Theoretical work involving Ωc(3185) and Ωc(3327)

  - QCD sum rules:

    Z. G. Wang, F. Lu and Y. Liu, Eur. Phys. J. C **83**, 689 (2023)
    Q. Xin, X. S. Yang and Z. G. Wang, Int. J. Mod. Phys. A **38**, 2350123 (2023)
    U. Ozdem, Phys. Lett. B **849**, 138432 (2024)

  - Various quark models:

    S. Q. Luo and X. Liu, Phys. Rev. D **107**, 074041 (2023)
    P. Jakhad, J. Oudichhya, K. Gandhi and A. K. Rai, Phys. Rev. D **108**, 014011 (2023)
    E. Ortiz-Pacheco and R. Bijker, Phys. Rev. D **108**, 054014 (2023)
    G. L. Yu, Y. Meng, Z. Y. Li, Z. G. Wang and L. Jie, Int. J. Mod. Phys. A **38**, 2350082 (2023)
    J. H. Pan and J. Pan, Phys. Rev. D **109**, 076010 (2024)

  - Effective Lagrangian approach:

    J. Feng, C. Cheng, F. Yang and Y. Huang, arXiv:2303.17770

  - Contact range theory:

    M. J. Yan, F. Z. Peng and M. Pavon Valderrama, Phys. Rev. D **109**, 014023 (2024)

Theoretical work involving Ωc(3185) and Ωc(3327)

- Three-quark perspective:

  Z. G. Wang, F. Lu and Y. Liu, Eur. Phys. J. C **83**, 689 (2023)
  U. Ozdem, Phys. Lett. B **849**, 138432 (2024)
  S. Q. Luo and X. Liu, Phys. Rev. D **107**, 074041 (2023)
  P. Jakhad, J. Oudichhya, K. Gandhi and A. K. Rai, Phys. Rev. D **108**, 014011 (2023)
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  G. L. Yu, Y. Meng, Z. Y. Li, Z. G. Wang and L. Jie, Int. J. Mod. Phys. A **38**, 2350082 (2023)
  J. H. Pan and J. Pan, Phys. Rev. D **109**, 076010 (2024)

- Pentaquark perspective:

  Q. Xin, X. S. Yang and Z. G. Wang, Int. J. Mod. Phys. A **38**, 2350123 (2023)
  M. J. Yan, F. Z. Peng and M. Pavon Valderrama, Phys. Rev. D **109**, 014023 (2024)
  J. Feng, C. Cheng, F. Yang and Y. Huang, arXiv:2303.17770

- **Our work**

Phys. Rev. D **108**, 094045 (2023)

Based on **baryon-meson** configuration

- Bound state calculation
  single-channel
  coupled-channel

- Scattering process
  examine resonance state

Quark delocalization color screening model (QDCSM)

QDCSM was developed by Nanjing-Los Alamos collaboration in1990s aimed to multi-quark study. (Phys. Rev. Lett. 69, 2901 (1992))

- Two new ingredients (based on quark cluster model configuration)

  quark delocalization (orbital excitation)

$$\phi_\alpha(\mathbf{S}_i) = \left(\frac{1}{\pi b^2}\right)^{\frac{3}{4}} e^{-\frac{(\mathbf{r}-\mathbf{S}_i/2)^2}{2b^2}},$$
$$\phi_\beta(-\mathbf{S}_i) = \left(\frac{1}{\pi b^2}\right)^{\frac{3}{4}} e^{-\frac{(\mathbf{r}+\mathbf{S}_i/2)^2}{2b^2}}.$$

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

  color screening (color structure)

- Apply to the study of baryon-baryon interaction and dibaryons

  deuteron, d, NN, NΛ, NΩ, …*

- Apply to the study of baryon-meson interaction and pentaquarks

  NK, Nπ, Pc, …

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

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

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

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

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

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

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

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

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

single-channel

Structure	χ^{f_i}	χ^{σ_j}	Channel	E_{th}^{Theo}	E_{sc}	E_B	E_{th}^{Exp}	E'
$qss-\bar{q}c$	$i=2$	$j=1$	ΞD	3235	3238	ub	3187	3190
	$i=2$	$j=2$	ΞD^*	3319	3321	ub	3325	3327
	$i=2$	$j=3$	$\Xi^* D^*$	3441	3447	ub	3543	3549
$qsc-\bar{q}s$	$i=2$	$j=1$	$\Xi_c'\bar{K}$	3130	3137	ub	3072	3079
	$i=2$	$j=1$	$\Xi_c\bar{K}$	3060	3066	ub	2962	2968
	$i=2$	$j=2$	$\Xi_c'\bar{K}^*$	3449	3454	ub	3469	3574
	$i=2$	$j=2$	$\Xi_c\bar{K}^*$	3379	3386	ub	3359	3366
	$i=2$	$j=3$	$\Xi_c^*\bar{K}^*$	3466	3472	ub	3537	3543
$ssc-\bar{q}q$	$i=1$	$j=2$	$\Omega_c\omega$	3548	3545	-3	3477	3474
	$i=1$	$j=3$	$\Omega_c^*\omega$	3558	3554	-4	3548	3544

unbound

coupled-channel

Coupled-structure	E_{th}^{Theo} (Channel)	E_{cc}	E_B	E_{th}^{Exp}	E'
$qss-\bar{q}c$	3235 (ΞD)	3237	ub	3187	3190
$qsc-\bar{q}s$	3060 ($\Xi_c\bar{K}$)	3065	ub	2962	2967
$ssc-\bar{q}q$	3548 ($\Omega_c\omega$)	3545	-3	3477	3474
$qss-\bar{q}c,\ ssc-\bar{q}q$	3235 (ΞD)	3230	-5	3187	3192
$qss-\bar{q}c,\ qsc-\bar{q}s,\ ssc-\bar{q}q$	3060 ($\Xi_c\bar{K}$)	3064	ub	2962	2966

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coupled-channel

quaqsibound

Coupled-structure	E_{th}^{Theo} (Channel)	E_{cc}	E_B	E_{th}^{Exp}	E'
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single-channel

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coupled-channel

unbound

quaqsibound

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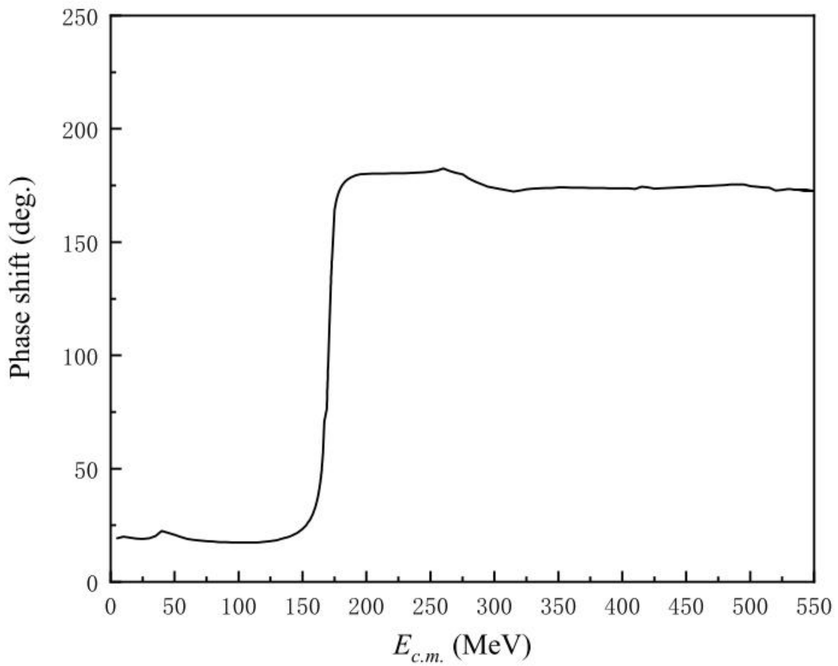
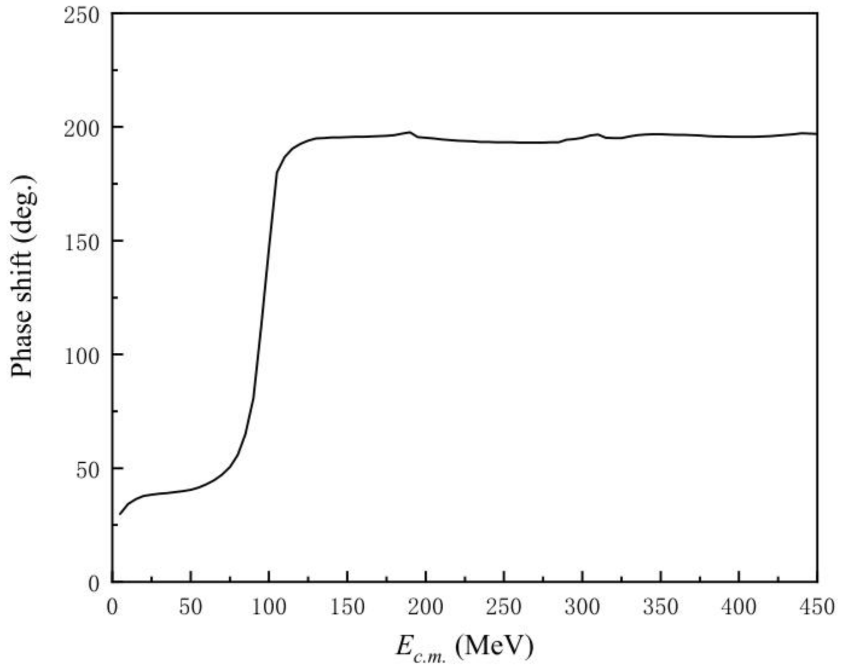
Scattering process

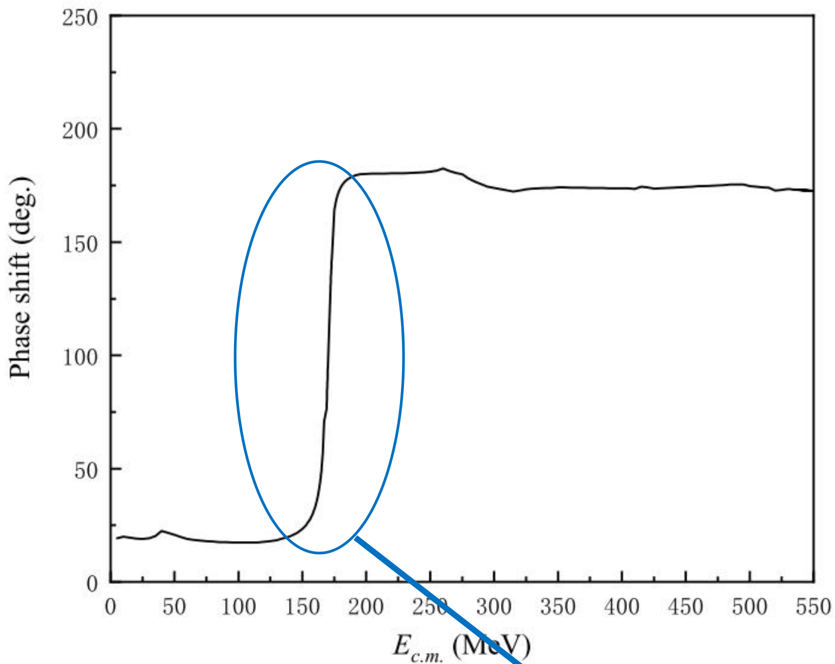


The phase shift of open channel $\Xi_c \bar{K}$

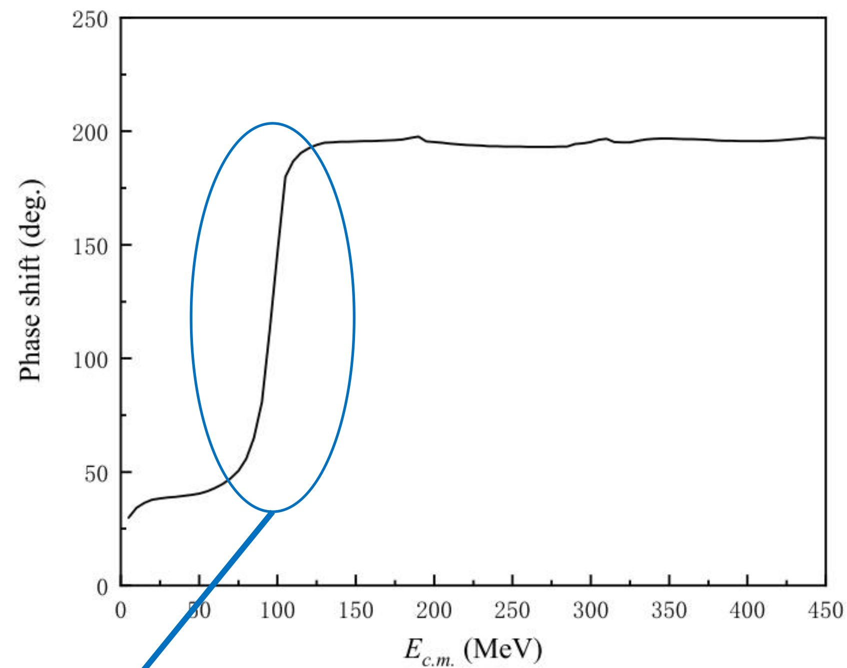


The phase shift of open channel $\Xi_c' \bar{K}$

Scattering process



The phase shift of open channel $\Xi_c \bar{K}$



The phase shift of open channel $\Xi_c' \bar{K}$

A resonance is identified, dominated by ΞD

Results

$$\begin{aligned} \text{In } \Xi_c\bar{K} \text{ channel}: \quad & M_{res}^{Theo} = 3230 \text{ MeV}, \\ & M'_{res} = 3182 \text{ MeV}, \\ & \Gamma_{res} = 8.4 \text{ MeV}, \\ \text{In } \Xi'_c\bar{K} \text{ channel}: \quad & M_{res}^{Theo} = 3221 \text{ MeV}, \\ & M'_{res} = 3174 \text{ MeV}, \\ & \Gamma_{res} = 33.6 \text{ MeV}. \end{aligned}$$

ΞD: corrected mass: 3174--3182 MeV， width: 42 MeV

Ωc(3185): mass: $3185.1 \pm 1.7^{+7.4}_{-0.9} \pm 0.2$ MeV , width: $50 \pm 7^{+10}_{-20}$ MeV

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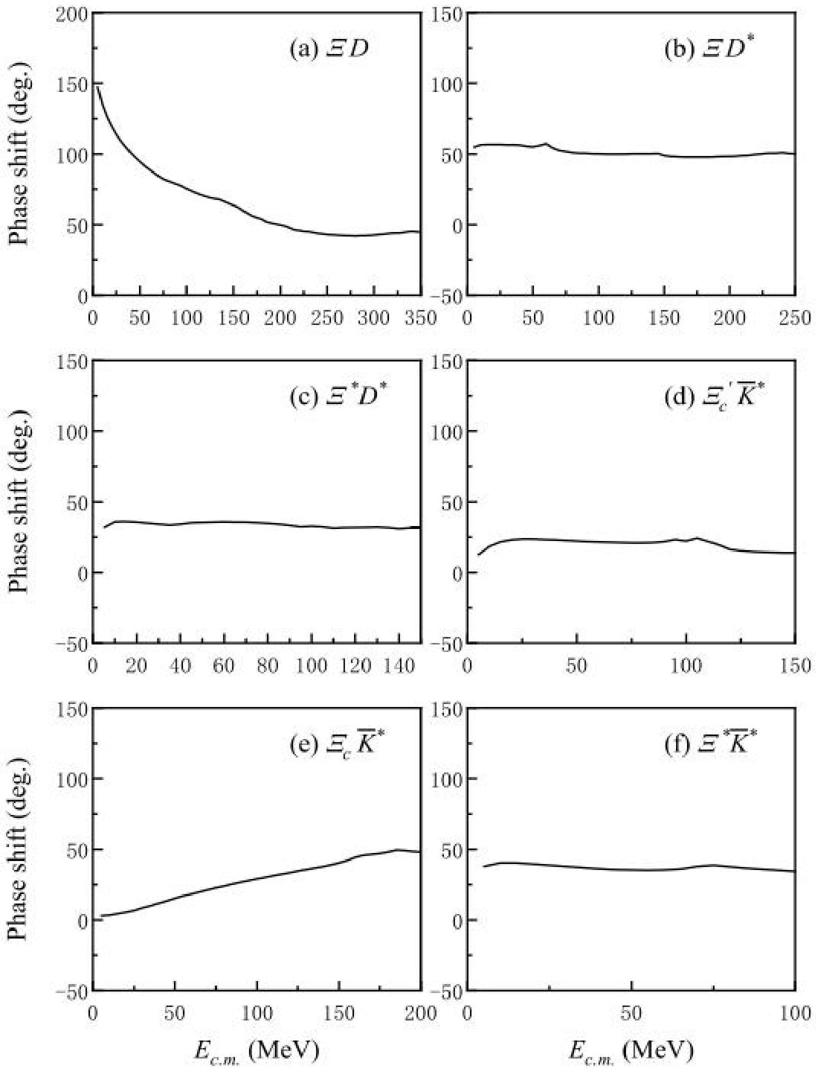
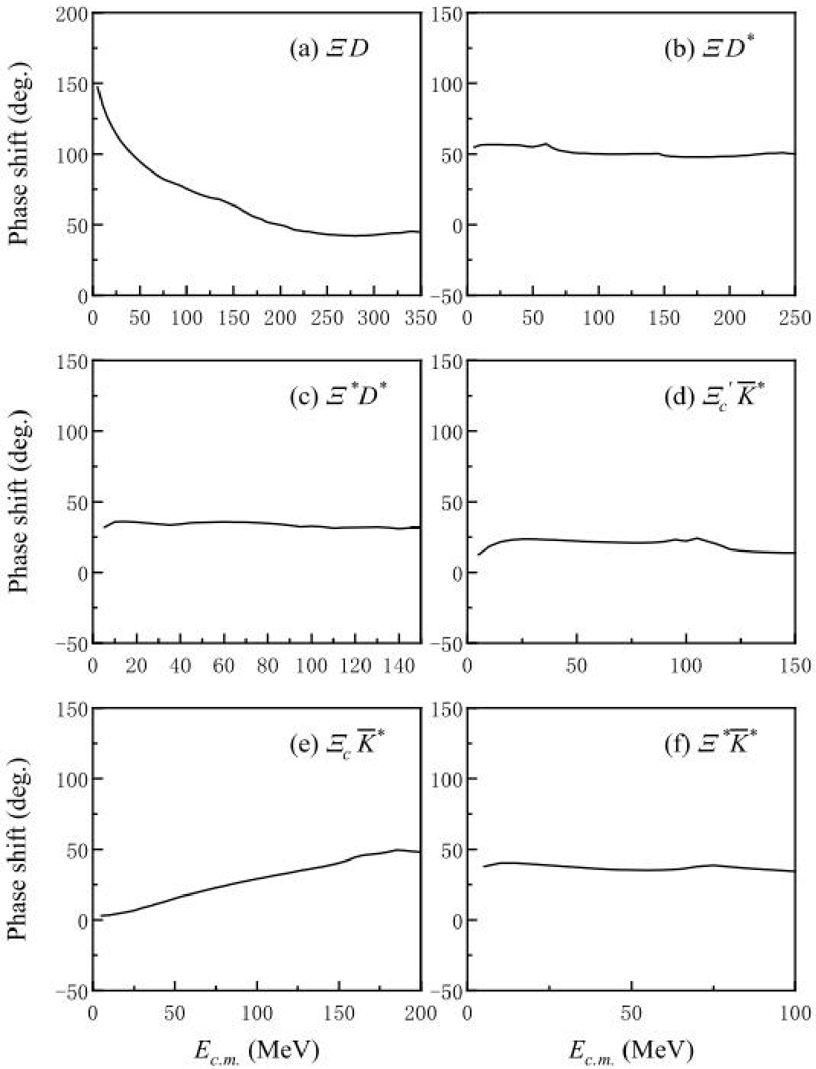
Further, RMS cluster spacing of the ΞD: 1.9 fm,

Therefore Ωc(3185) can be interpreted as ΞD **molecular state** with $J^P = \frac{1}{2}^-$



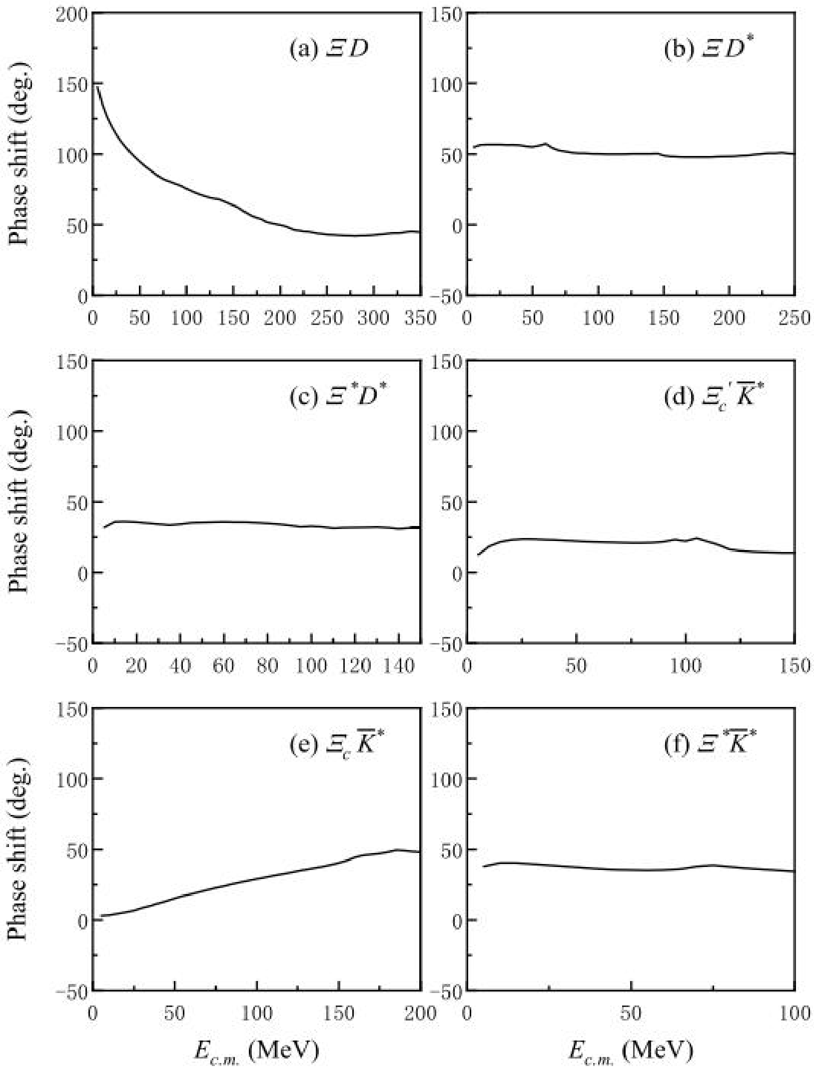
The phase shifts of other open channels



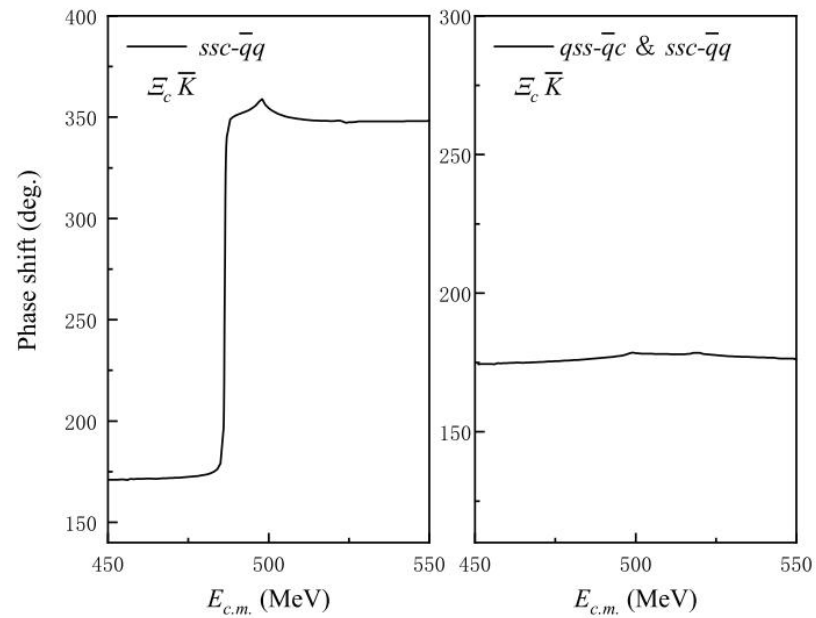
The phase shifts of other open channels

No other resonance state is identified

What happened to $\Omega_c\omega,\ \Omega_c^*\omega$?



The phase shifts of other open channels



The phase shifts of the open channel $\Xi_c \bar{K}$ with $ssc - \bar{q}q$ structure coupling (left) and $qss - \bar{q}c$ & $ssc - \bar{q}q$ structure coupling (right)

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

single-channel

Structure	χ^{f_i}	χ^{σ_j}	Channel	E_{th}^{Theo}	E_{sc}	E_B	E_{th}^{Exp}	E'
$qss-\bar{q}c$	$i=2$	$j=4$	ΞD^*	3319	3323	ub	3325	3329
	$i=2$	$j=5$	$\Xi^* D$	3357	3362	ub	3405	3410
	$i=2$	$j=6$	$\Xi^* D^*$	3441	3446	ub	3543	3548
$qsc-\bar{q}s$	$i=2$	$j=4$	$\Xi_c' \bar{K}^*$	3449	3457	ub	3469	3477
	$i=2$	$j=4$	$\Xi_c \bar{K}^*$	3379	3386	ub	3359	3366
	$i=2$	$j=5$	$\Xi_c^* \bar{K}$	3147	3153	ub	3140	3146
	$i=2$	$j=6$	$\Xi_c^* \bar{K}^*$	3466	3472	ub	3537	3543
$ssc-\bar{q}q$	$i=1$	$j=4$	$\Omega_c \omega$	3548	3546	-2	3477	3475
	$i=1$	$j=6$	$\Omega_c^* \omega$	3558	3554	-4	3548	3544

coupled-channel

Coupled-structure	E_{th}^{Theo} (Channel)	E_{cc}	E_B	E_{th}^{Exp}	E'
$qss-\bar{q}c$	3319 (ΞD^*)	3322	ub	3325	3328
$qsc-\bar{q}s$	3147 ($\Xi_c^* \bar{K}$)	3150	ub	3140	3143
$ssc-\bar{q}q$	3548 ($\Omega_c \omega$)	3546	-2	3477	3475
$qss-\bar{q}c,\ ssc-\bar{q}q$	3319 (ΞD^*)	3321	ub	3325	3327
$qss-\bar{q}c,\ qsc-\bar{q}s,\ ssc-\bar{q}q$	3147 ($\Xi_c^* \bar{K}$)	3145	-2	3140	3138

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

single-channel

Structure	χ^{f_i}	χ^{σ_j}	Channel	E_{th}^{Theo}	E_{sc}	E_B	E_{th}^{Exp}	E'
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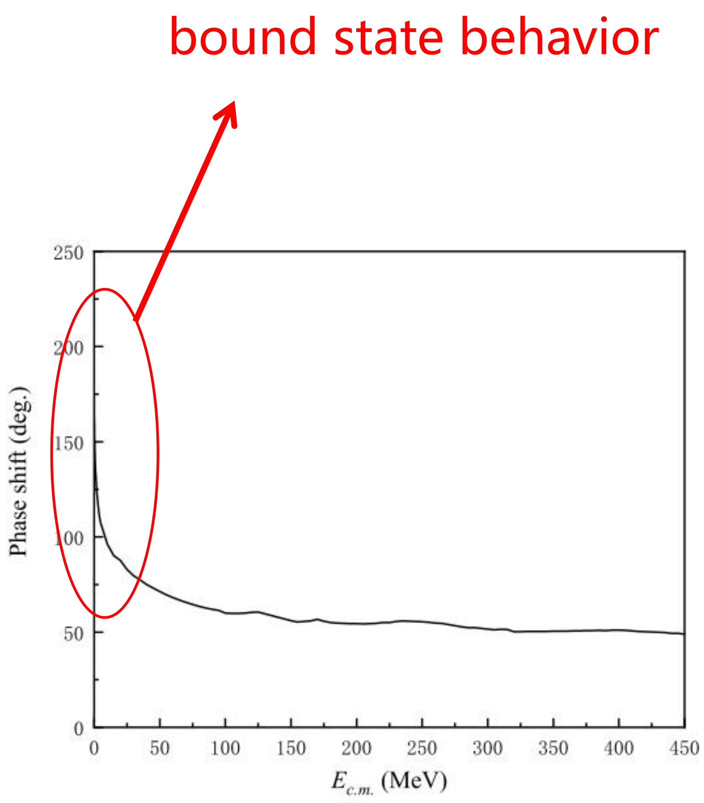
	$i=2$	$j=5$	$\Xi^* D$	3357	3362	ub	3405	3410
	$i=2$	$j=6$	$\Xi^* D^*$	3441	3446	ub	3543	3548
$qsc-\bar{q}s$	$i=2$	$j=4$	$\Xi_c' \bar{K}^*$	3449	3457	ub	3469	3477
	$i=2$	$j=4$	$\Xi_c \bar{K}^*$	3379	3386	ub	3359	3366
	$i=2$	$j=5$	$\Xi_c^* \bar{K}$	3147	3153	ub	3140	3146
	$i=2$	$j=6$	$\Xi_c^* \bar{K}^*$	3466	3472	ub	3537	3543
$ssc-\bar{q}q$	$i=1$	$j=4$	$\Omega_c \omega$	3548	3546	-2	3477	3475
	$i=1$	$j=6$	$\Omega_c^* \omega$	3558	3554	-4	3548	3544

coupled-channel

a bound state

Coupled-structure	E_{th}^{Theo} (Channel)	E_{cc}	E_B	E_{th}^{Exp}	E'
$qss-\bar{q}c$	3319 (ΞD^*)	3322	ub	3325	3328
$qsc-\bar{q}s$	3147 ($\Xi_c^* \bar{K}$)	3150	ub	3140	3143
$ssc-\bar{q}q$	3548 ($\Omega_c \omega$)	3546	-2	3477	3475
$qss-\bar{q}c,\ ssc-\bar{q}q$	3319 (ΞD^*)	3321	ub	3325	3327
$qss-\bar{q}c,\ qsc-\bar{q}s,\ ssc-\bar{q}q$	3147 ($\Xi_c^* \bar{K}$)	3145	-2	3140	3138



The phase shift of open channel $\Xi_c^* \bar{K}$

The bound state is dominated by the $\Xi_c^* \bar{K}$

corrected mass: 3138 MeV,

width: narrow Phys. Rev. C **83**, 015202 (2011)

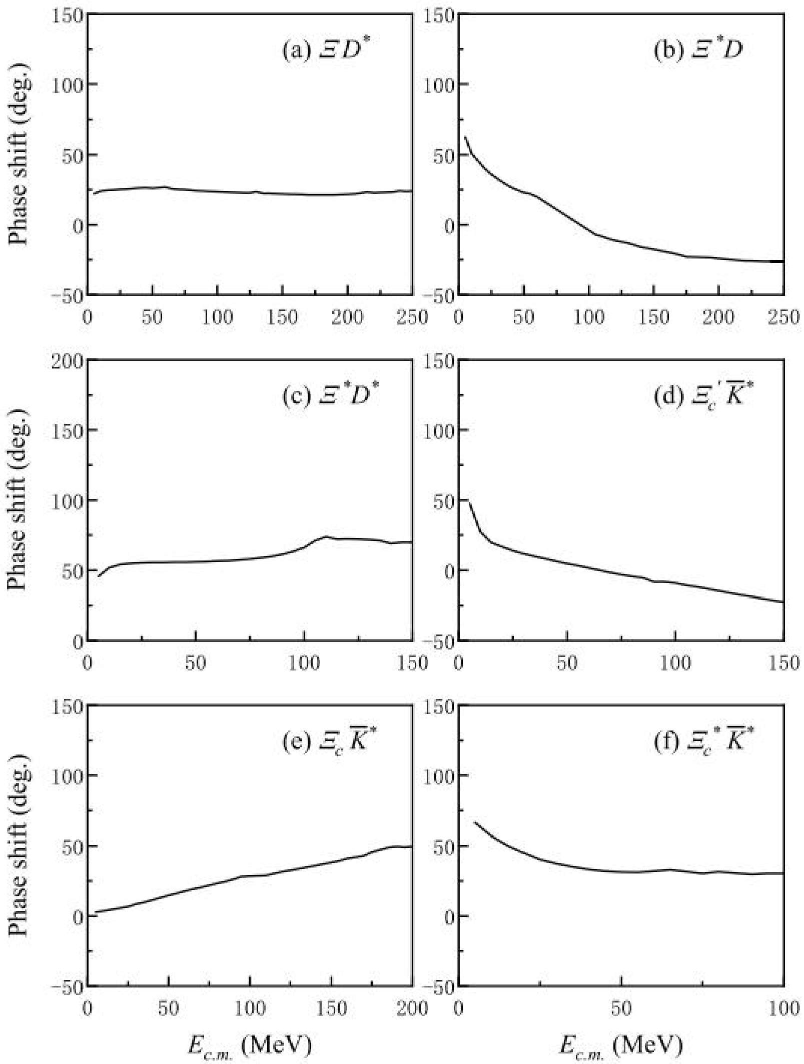
RMS cluster spacing: 1.8 fm

Ωc(3120): mass = 3119.1±0.3±0.9±0.3 MeV,

width = 0.60±0.63 MeV.

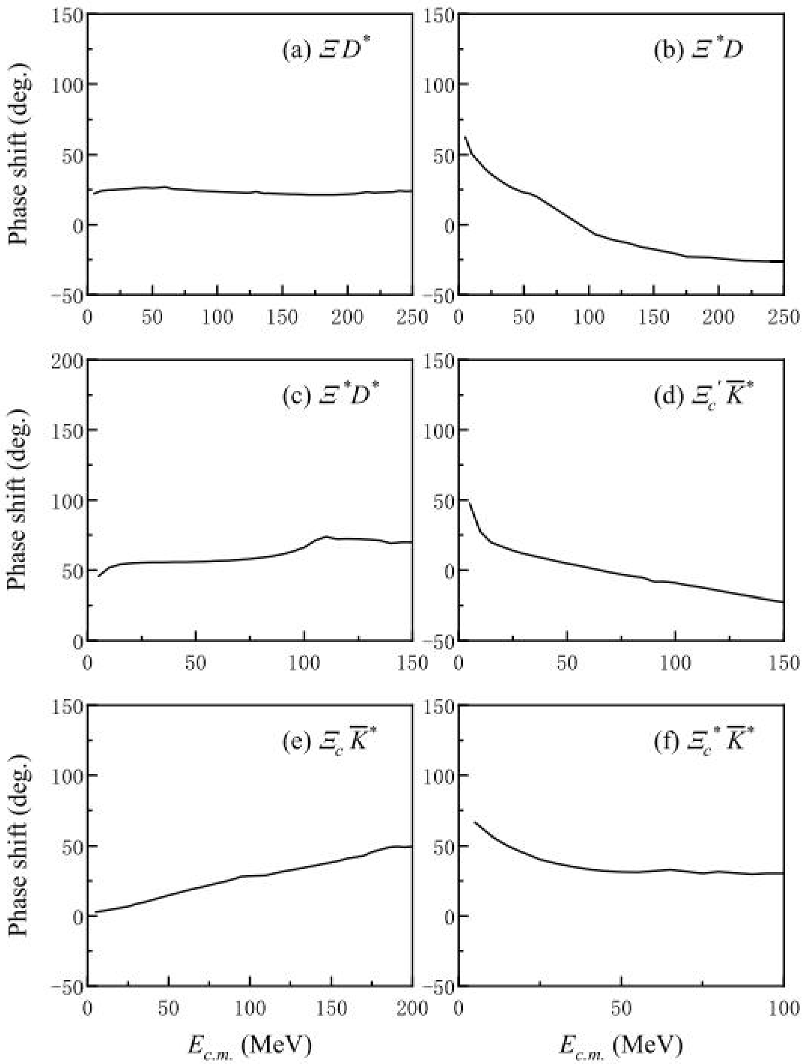
Phys. Rev. Lett. **118**, 182001 (2017)

Therefore, $\Xi_c^* \bar{K}$ with $J^P = \frac{3}{2}^-$ can be a good candidate for the Ωc(3120).



The phase shifts of other open channels

No other resonance state is identified



The phase shifts of other open channels

Formation of the bound state $\Xi_c^* \bar{K}$

↕

Lowest energy of $\Omega_c\omega$, $\Omega_c^*\omega$ being elevated

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

Structure	χ^{f_i}	χ^{σ_j}	Channel	E_{th}^{Theo}	E_{sc}	E_B	E_{th}^{Exp}	E'
$qss-\bar{q}c$	$i=2$	$j=7$	$\Xi^* D^*$	3441	3444	ub	3543	3546
$qsc-\bar{q}s$	$i=2$	$j=7$	$\Xi_c^* \bar{K}^*$	3466	3474	ub	3537	3545
$ssc-\bar{q}q$	$i=1$	$j=7$	$\Omega_c^* \omega$	3558	3555	-3	3548	3545

After channel coupling, a bound state with binding energy of -11 MeV

- A $ssc\bar{q}q$ pentaquark with $J^P = 5/2^-$ and mass of 3526 MeV, is predicted here.
- The lowest energy of the $\Omega_c^* \omega$ is elevated above its threshold

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

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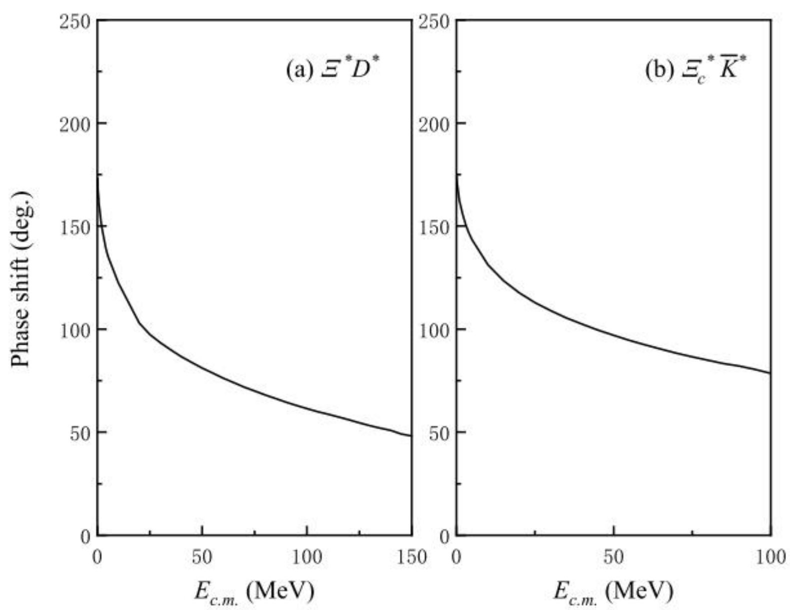

Summary

- The Ωc(3185) can be interpreted as a ΞD **molecular state** with $J^P=\frac{1}{2}^-$.
- The Ωc(3120) can be interpreted as a $\Xi_c^*\bar{K}$ **molecular state** with $J^P=\frac{3}{2}^-$.
- A $ssc\bar{q}q$ pentaquark with $J^P=\frac{5}{2}^-$ and mass of 3526 MeV is predicted.
- Channel coupling plays a crucial role in our work.
- Investigation from an unquenched picture is expcted in the future.

Thanks for your attention !