Exotic behaviors of $\Omega_c(1P)$ under the unquenched model

罗肆强

2021年5月18日

Based on [Phys. Rev. D 103, 074027 (2021)]

Cooperators: Bing Chen, Xiang Liu, and Takayuki Matsuki

第七届XYZ粒子研讨会　青岛

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1. Background

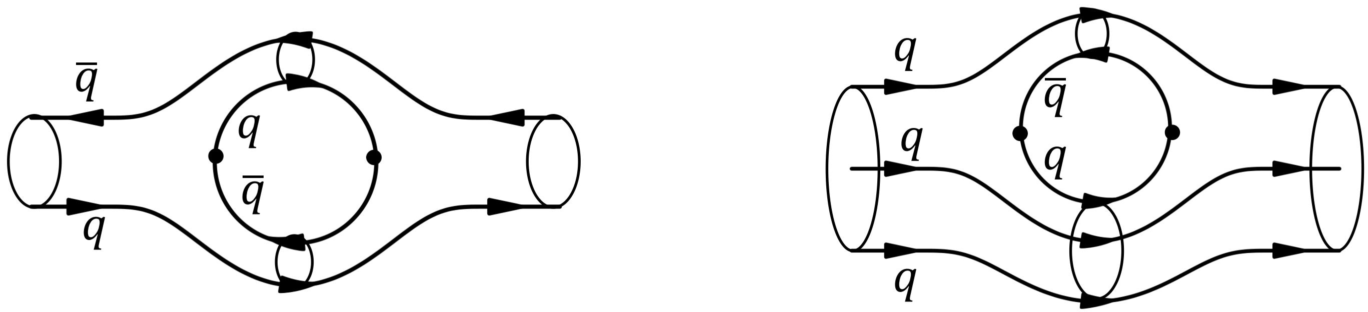
The conventional quenched quark model has achieved great successes in hadron physics. But it is difficult to interpret the masses of $D_{s0}^*(2317)$, $D'_{s1}(2460)$, $X(3872)$, $\Lambda_c(2940)$, et al.

	$D_{s0}^*(2317)$	$D'_{s1}(2460)$	$X(3872)$	$\Lambda_c(2940)$
PDG [1] (MeV)	2317.8 ± 0.5	2459.5 ± 0.6	3871.69 ± 0.17	$2939.6^{+1.3}_{-1.5}$
potential model [2-4] (MeV)	2484	2556	3950	3035

The experimental measurements are about 100 MeV less than the potential model calculations .

[1] PTEP 2020, 083C01 (2020)
[2] Phys. Rev. D 32, 189 (1985)
[3] Phys. Rev. D 93, 034035 (2016)
[4] Phys. Rev. D 34, 2809 (1986)

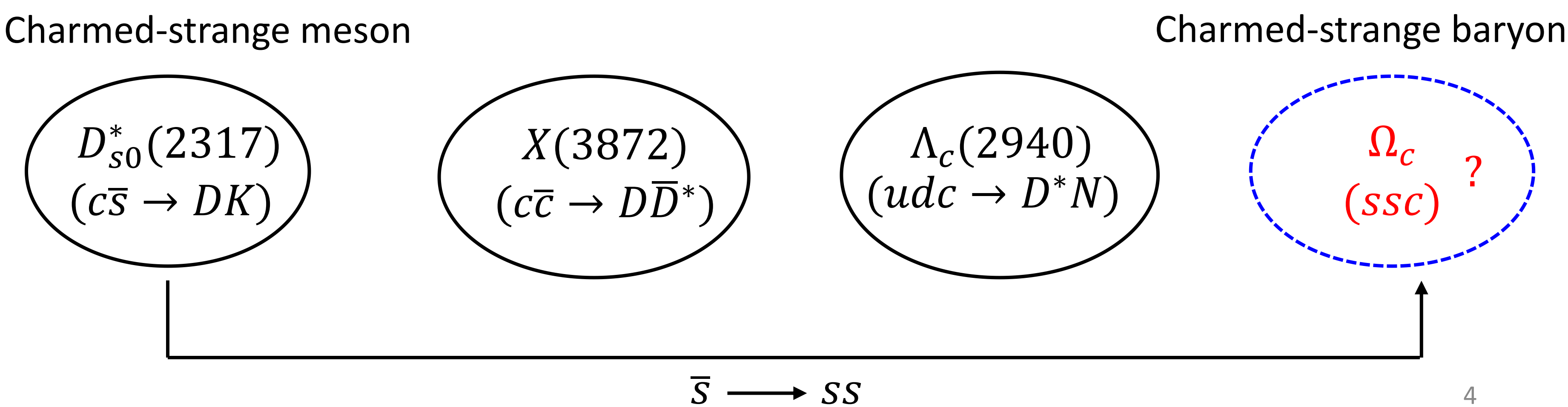
In order to understand the masses of $D_{s0}^*(2317)$, $D'_{s1}(2460)$, $X(3872)$, $\Lambda_c(2940)$, et al., the coupled-channel effect was introduced in hadron physics.



Coupled-channel effects of hadrons.

The hadron loops could affect the masses of hadrons.

$$m = m_0 + \delta m$$



2. The interpretation of the $D_{s0}^{*}(2317)$ under the unquenched model

(1) Making the calculations for Ω_c more reliable;

(2) Determining the parameters in the model.

In the unquenched model, the physical state of $D_{s0}^{*}(2317)$ could be denoted as

$$|D_{s0}^{*}(2317)\rangle = c_{c\bar{s}}|c\bar{s}(1^3P_0)\rangle + \int d^3\mathbf{p}\; c_{DK}(\mathbf{p})|DK,\mathbf{p}\rangle.$$

physical state — bare state — intermediate DK channel

The full Hamiltonian of the physical $D_{s0}^*(2317)$ state could be written as

$$\hat{H} = \begin{pmatrix} \hat{H}_0 & \hat{H}_I \\ \hat{H}_I & \hat{H}_{DK} \end{pmatrix}.$$

The $\widehat{H}_0$ is the Hamiltonian of the bare state with

$$\widehat{H}_0|c\bar{s}(1^3P_0)\rangle = M_0|c\bar{s}(1^3P_0)\rangle.$$

bare mass

The $\widehat{H}_I$ is the Hamiltonian of $c\bar{s}(1^3P_0) \to DK$ with

$$\mathcal{M}_{c\bar{s}(1^3P_0)\to DK}(p) = \langle DK, \mathbf{p}|\hat{H}_I|c\bar{s}(1^3P_0)\rangle.$$

amplitude

Without including the interaction of D and K, the Hamiltonian of the intermediate DK channel could be obtained by

$$\hat{H}_{DK}|DK, \mathbf{p}\rangle = \left(\sqrt{m_D^2 + p^2} + \sqrt{m_K^2 + p^2}\right)|DK, \mathbf{p}\rangle.$$

Then, one could obtain the coupled-channel equation

$$M - M_0 - \Delta M(M) = 0.$$

The $\Delta M(M)$ is the mass shift with definition

$$\Delta M(M) = \mathrm{Re} \int_0^\infty p^2 \mathrm{d}p \frac{|\mathcal{M}_{c\bar{s}(1^3P_0)\to DK}(p)|^2}{M - \sqrt{M_D^2 + p^2} - \sqrt{M_K^2 + p^2}}.$$

(1) M_0: nonrelativistic potential model

(2) $\mathcal{M}_{c\bar{s}(1^3P_0)\to DK}(p)$: QPC model

Nonrelativistic potential model:

$$\hat{H}_0 = \sum_{i=1}\left(m_i + \frac{p_i^2}{2m_i}\right) + \sum_{i<j} V_{ij}$$

$$V_{ij} = H_{ij}^{\text{conf}} + H_{ij}^{\text{hyp}} + H_{ij}^{\text{so(cm)}} + H_{ij}^{\text{so(tp)}}$$

spin-independent terms:

$$H_{ij}^{\text{conf}} = -\frac{4}{3}\frac{\alpha_s}{r_{ij}} + br_{ij} + C$$

spin-dependent terms:

$$H_{ij}^{\text{hyp}} = \frac{4\alpha_s}{3m_i m_j}\left(\frac{8\pi}{3}\mathbf{s}_i \cdot \mathbf{s}_j \tilde{\delta}(r) + \frac{1}{r_{ij}^3} S(\mathbf{r}_{ij}, \mathbf{s}_i, \mathbf{s}_j)\right)$$

$$\tilde{\delta}(r) = \frac{\sigma^3}{\pi^{3/2}} \mathrm{e}^{-\sigma^2 r^2} \qquad S(\mathbf{r}_{ij}, \mathbf{s}_i, \mathbf{s}_j) = \frac{3\mathbf{s}_i \cdot \mathbf{r}_{ij}\mathbf{s}_j \cdot \mathbf{r}_{ij}}{r_{ij}^2} - \mathbf{s}_i \cdot \mathbf{s}_j$$

$$H_{ij}^{\text{so(cm)}} = \frac{4\alpha_s}{3r_{ij}^3}\left(\frac{1}{m_i} + \frac{1}{m_j}\right)\left(\frac{\mathbf{s}_i}{m_i} + \frac{\mathbf{s}_j}{m_j}\right) \cdot \mathbf{L}$$

$$H_{ij}^{\text{so(tp)}} = -\frac{1}{2r_{ij}} \frac{\partial H_{ij}^{\text{conf}}}{\partial r_{ij}} \left(\frac{\mathbf{s}_i}{m_i^2} + \frac{\mathbf{s}_j}{m_j^2}\right) \cdot \mathbf{L}$$

QPC model:

$$\hat{H}_I = -3\gamma \sum_m \langle 1, m; 1, -m|0, 0\rangle \int \mathrm{d}^3\mathbf{p}_i \, \mathrm{d}^3\mathbf{p}_j \, \delta(\mathbf{p}_i + \mathbf{p}_j) \times \mathcal{Y}_1^m\left(\frac{\mathbf{p}_i - \mathbf{p}_j}{2}\right) \omega_0^{(i,j)} \phi_0^{(i,j)} \chi_{1,-m}^{(i,j)} b_i^\dagger(\mathbf{p}_i) d_j^\dagger(\mathbf{p}_j)$$

Parameters:

The parameters in potential model are fixed by the low-lying well established π, K, D, and D_s mesons. The γ value is determined by the width of $D_{s2}^*(2573)$.

potential model:

$m_{u/d} = 0.370$ GeV

$m_s = 0.600$ GeV

$m_c = 1.880$ GeV

$\alpha_s = 0.578$

$b = 0.144\ \mathrm{GeV}^2$

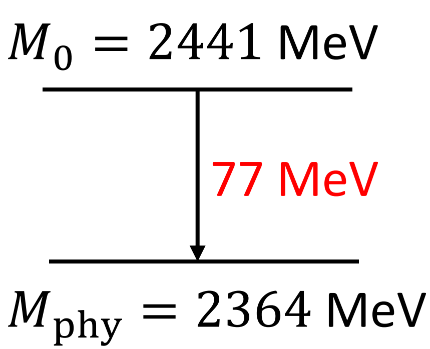
$\sigma = 1.028\ \mathrm{GeV}$

$C = -0.685\ \mathrm{GeV}$

QPC model:

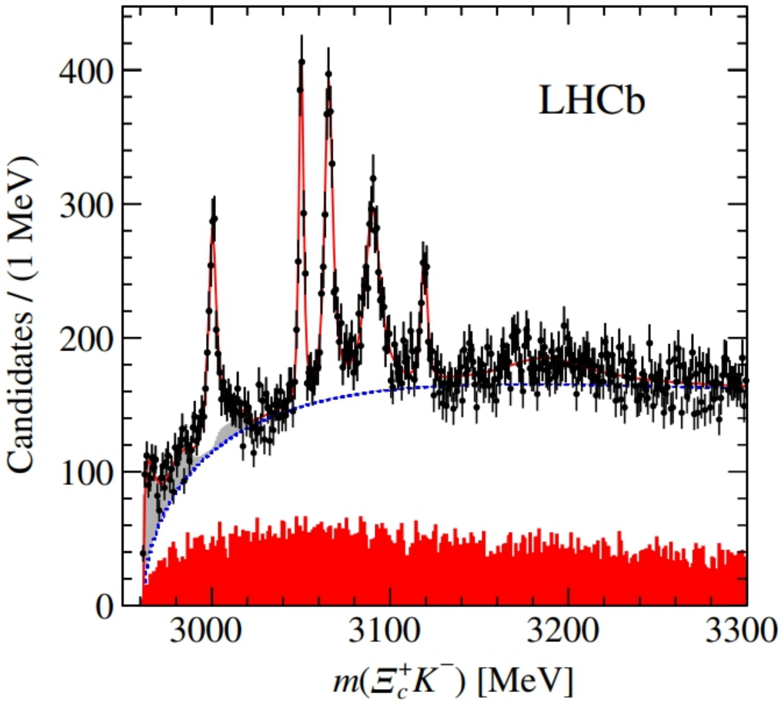
$\gamma = 4.1$

Numerical result:

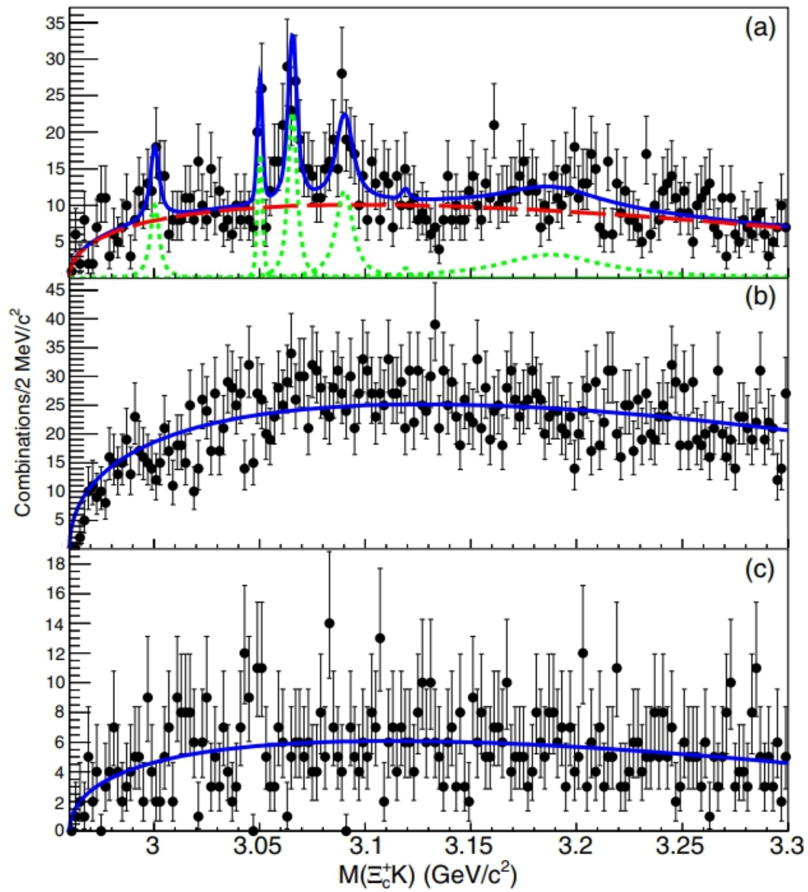


The coupled channel effect plays an important role for $D_{s0}^*(2317)$!

3. The masses of $\Omega_c(1P)$ with the coupled-channel effect

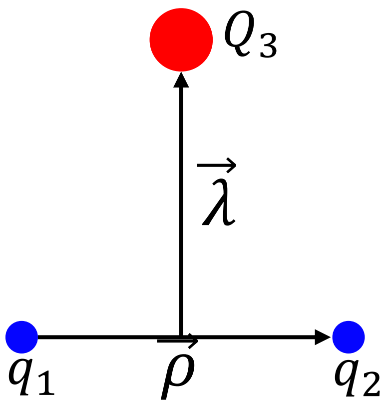


[LHCb] Phys. Rev. Lett. 118, 182001 (2017)



[Belle] Phys. Rev. D 97, 051102 (2018)

It is a good chance for us to study excited Ω_c.



The Jacobi coordinates of a singly heavy flavor baryon.

$$\vec{\rho} = \vec{r}_2 - \vec{r}_1$$

$$\vec{\lambda} = \vec{r}_3 - \frac{m_1\vec{r} + m_2\vec{r}}{m_1 + m_2}$$

Basis in heavy quark symmetry:

$$|s_\ell, L, j_\ell, J\rangle = |[[s_\ell \otimes L]_{j_\ell} \otimes s_Q]_J\rangle$$

s_ℓ: spin of the light degree of freedom

L: orbital angular momentum of the light degree of freedom

j_ℓ: angular momentum of the light degree of freedom

s_Q: spin of the heavy quark

$j_\ell(\Xi_c(1S)) = 0$

$j_\ell(\Xi_c'(1S)) = 1$

$j_\ell(\Xi_c^*(1S)) = 1$

$j_\ell(\Omega_c(1S)) = 1$

$j_\ell(\Omega_c^*(1S)) = 1$

$$\lambda\text{-mode excite } \Omega_c(1P) \begin{cases} J^P = 1/2^- \begin{cases} j_\ell = 0:\ \Omega_{c0}(1P, 1/2^-) \\ j_\ell = 1:\ \Omega_{c1}(1P, 1/2^-) \end{cases} \\ J^P = 3/2^- \begin{cases} j_\ell = 1:\ \Omega_{c1}(1P, 3/2^-) \\ j_\ell = 2:\ \Omega_{c2}(1P, 3/2^-) \end{cases} \\ J^P = 5/2^-:\quad j_\ell = 2:\ \Omega_{c2}(1P, 5/2^-) \end{cases}$$

Application: strong decays

singly heavy flavor baryon		singly heavy flavor baryon		light flavor pseudoscalar meson
$A(j_\ell, J, J_z)$	$\rightarrow$	$B(j_\ell', J', J_z')$	$+$	$C(l, l_z)$

(l: orbital angular momentum of BC)

Typical decay channels:

$\Sigma_c \rightarrow \Lambda_c \pi$

$\Xi_c^* \rightarrow \Xi_c \pi$

$\Xi_c(2965) \rightarrow \Lambda_c K$

In heavy quark symmetry, the angular momentum of the light degree of freedom is a conserved quantity in the strong decay process, i.e., $|j_\ell' - l| \leq j_\ell \leq |j_\ell' + l|$.

$$H_{ij}^{\text{conf}} = -\frac{2}{3}\frac{\alpha_s}{r_{ij}} + \frac{b}{2}r_{ij} + C$$

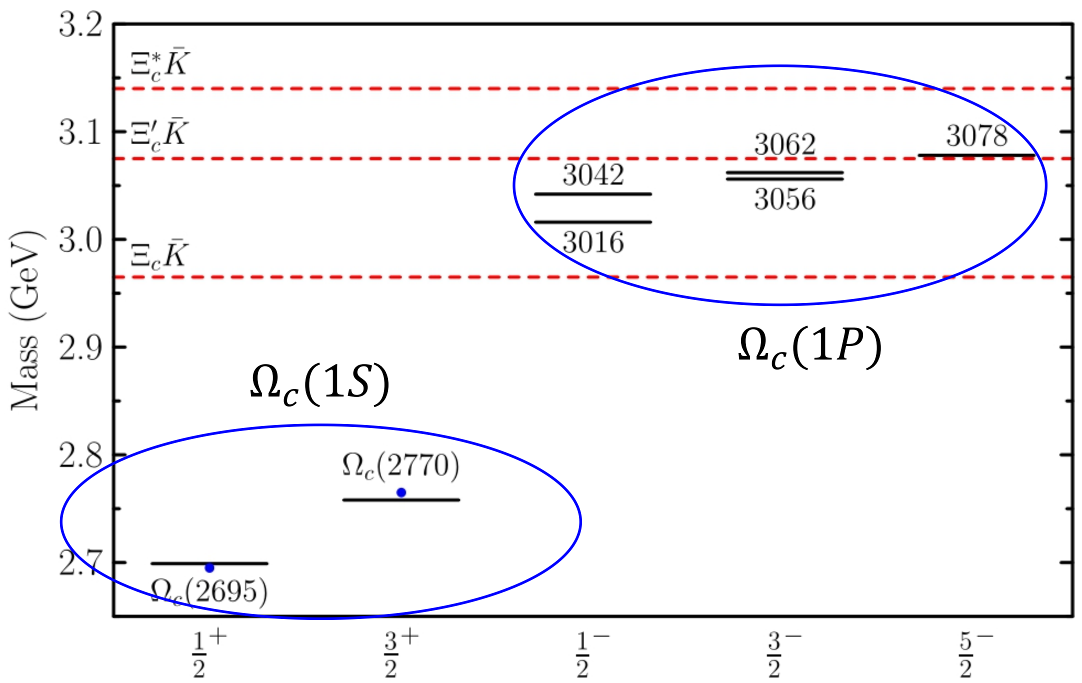
$$H_{ij}^{\text{hyp}} = \frac{2\alpha_s}{3m_i m_j}\left(\frac{8\pi}{3}\mathbf{s}_i \cdot \mathbf{s}_j \tilde{\delta}(r) + \frac{1}{r_{ij}^3}S(\mathbf{r}_{ij}, \mathbf{s}_i, \mathbf{s}_j)\right)$$

$$H_{ij}^{\text{so(cm)}} = \frac{2\alpha_s}{3r_{ij}^3}\left(\frac{\mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_j}{m_j^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_i - \mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_j}{m_i m_j}\right)$$

$$H_{ij}^{\text{so(tp)}} = -\frac{1}{2r_{ij}}\frac{\partial H_{ij}^{\text{conf}}}{\partial r_{ij}}\left(\frac{\mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_j}{m_j^2}\right)$$

$m_{u/d} = 0.370$ GeV
$m_s = 0.600$ GeV
$m_c = 1.880$ GeV
$\alpha_s = 0.578$
$b = 0.144$ GeV^2

$\sigma = 1.028$ GeV
$C = -0.685$ GeV
$\gamma = 8.66$



The mass spectrum of Ω_c.

The two $J^P = 1/2^-$ of $\Omega_c(1P)$ states could be expanded by $|j_\ell = 0, 1/2^-\rangle$ and $|j_\ell = 1, 1/2^-\rangle$ with the relation

$$\begin{pmatrix} |\frac{1}{2}^-\rangle_1 \\ |\frac{1}{2}^-\rangle_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |j_\ell = 0, \frac{1}{2}^-\rangle \\ |j_\ell = 1, \frac{1}{2}^-\rangle \end{pmatrix},$$

where the θ is the mixing angle.

heavy quark symmetry

$j_\ell(\Xi_c) = 0$

$j_\ell(\Xi_c') = 1$

- $\Omega_{c0}(1P, 1/2^-) \to \Xi_c \bar{K}$ s-wave
- $\Omega_{c0}(1P, 1/2^-) \to \Xi_c' \bar{K}$ forbidden
- $\Omega_{c1}(1P, 1/2^-) \to \Xi_c \bar{K}$ forbidden
- $\Omega_{c1}(1P, 1/2^-) \to \Xi_c' \bar{K}$ s-wave

Then, the coupled-channel Schrödinger equation could be written as

$$\begin{pmatrix} M^{j_\ell=0} & \tilde{V}^{\rm spin} & \int p^2 {\rm d}p \langle \Omega_{c0}|\hat{H}_I|\Xi_c\bar{K}\rangle & 0 \\ \tilde{V}^{\rm spin} & M^{j_\ell=1} & 0 & \int p^2 {\rm d}p \langle \Omega_{c1}|\hat{H}_I|\Xi_c'\bar{K}\rangle \\ \langle \Xi_c\bar{K}|\hat{H}_I|\Omega_{c0}\rangle & 0 & H_{\Xi_c\bar{K}} & 0 \\ 0 & \langle \Xi_c'\bar{K}|\hat{H}_I|\Omega_{c1}\rangle & 0 & H_{\Xi_c'\bar{K}} \end{pmatrix} \begin{pmatrix} c_0 \\ c_1 \\ c_{\Xi_c\bar{K}} \\ c_{\Xi_c'\bar{K}} \end{pmatrix} = M \begin{pmatrix} c_0 \\ c_1 \\ c_{\Xi_c\bar{K}} \\ c_{\Xi_c'\bar{K}} \end{pmatrix}.$$

$$\begin{pmatrix} M^{j_\ell=0} + \Delta M^0(M) & \tilde{V}^{\rm spin} \\ \tilde{V}^{\rm spin} & M^{j_\ell=1} + \Delta M^1(M) \end{pmatrix} \begin{pmatrix} c_0 \\ c_1 \end{pmatrix} = M \begin{pmatrix} c_0 \\ c_1 \end{pmatrix}$$

$$\Delta M^0(M) = {\rm Re} \int_0^\infty p^2 {\rm d}p \frac{|\mathcal{M}_{\Omega_{c0}\to\Xi_c\bar{K}}(p)|^2}{M - \sqrt{M_{\Xi_c}^2 + p^2} - \sqrt{M_K^2 + p^2}}$$

$$\Delta M^1(M) = {\rm Re} \int_0^\infty p^2 {\rm d}p \frac{|\mathcal{M}_{\Omega_{c1}\to\Xi_c'\bar{K}}(p)|^2}{M - \sqrt{M_{\Xi_c'}^2 + p^2} - \sqrt{M_K^2 + p^2}}$$

Numerical results:

(1) $\Omega_{c0}^{d}(1P, 1/2^{-})$:

(The $j_\ell = 0$ component is dominate.)

$M_0 = 3042$ MeV

97 MeV

$M_{\rm phy} = 2945$ MeV

The coupled-channel effect plays an important role for this state.

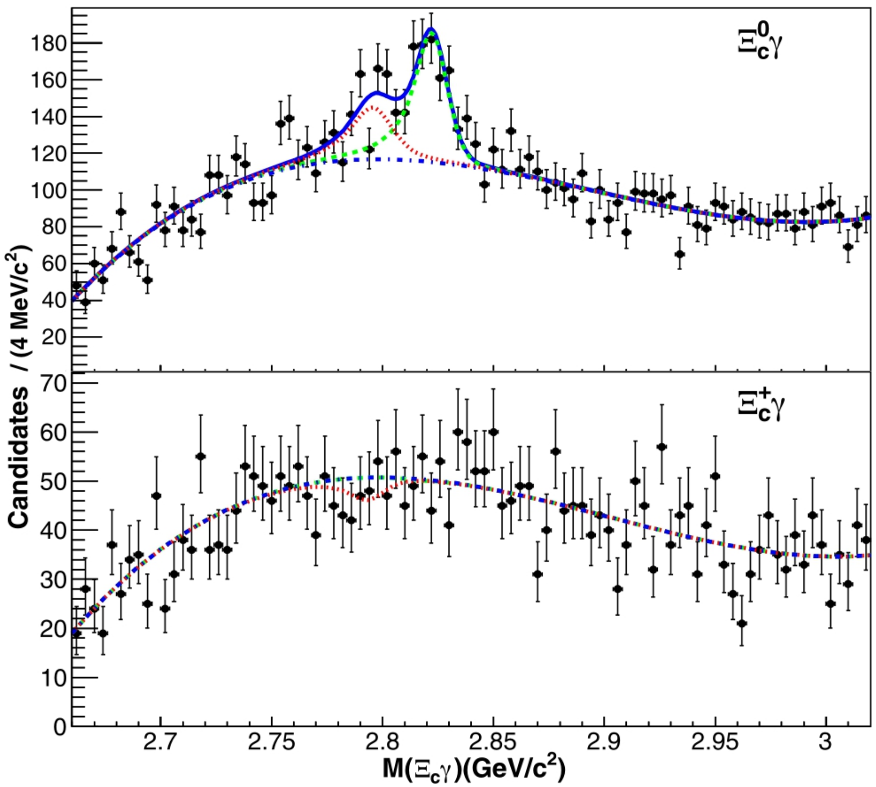
(2) $\Omega_{c1}^{d}(1P, 1/2^{-})$:

(The $j_\ell = 1$ component is dominate.)

$M_0 = 3016$ MeV

25 MeV

$M_{\rm phy} = 2991$ MeV



[Belle] Phys. Rev. D 102, 071103 (2020)

The Belle Collaboration observed P-wave excited states $\Xi_c(2790)^0$ and $\Xi_c(2815)^0$ via the radiative decay $\Xi_c^0\gamma$.

We suggest searching for more possible excited Ω_c states in $\Omega_c^{(*)}\gamma$.

The two $J^P = 3/2^-$ of $\Omega_c(1P)$ states could be expanded by $|j_\ell = 1,3/2^-\rangle$ and $|j_\ell = 2,3/2^-\rangle$ with the relation

$$\begin{pmatrix} |\frac{3}{2}^-\rangle_1 \\ |\frac{3}{2}^-\rangle_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |j_\ell = 1, \frac{3}{2}^-\rangle \\ |j_\ell = 2, \frac{3}{2}^-\rangle \end{pmatrix}.$$

Numerical results:

(1) $\Omega_{c1}^{d}(1P, 3/2^-)$: $M_0 = 3062$ MeV, $M_{\text{phy}} = 3029$ MeV

(2) $\Omega_{c2}^{d}(1P, 3/2^-)$: $M_0 = 3056$ MeV, $M_{\text{phy}} = 3058$ MeV

4. Summary

1. The mass of $D_{s0}^*(2317)$ could be interpreted by the coupled-channel effect.

2. The mass of $J^P = 1/2^- \ \Omega_c(1P)$ with predominate $j_\ell = 0$ is obviously affected by the coupled-channel effect.

3. We suggest searching for more possible excited Ω_c states in $\Omega_c^{(*)}\gamma$.

Thank you for attention.