Hidden Charm Pentaquark $P_c(4380)$ and Doubly Charmed Baryon $\Xi_{cc}(4380)$ as Hadronic Molecule States

Yuki Shimizu$^1$ and Masayasu Harada$^1$

$^1$Department of Physics, Nagoya University, Nagoya, 464-8602, Japan

(Dated: August 17, 2017)

We study hadronic molecular states in a coupled system of $J/\psi N - \Lambda_c \bar{D}^{(*)} - \Sigma_c^{(*)} \bar{D}^{(*)}$ in $I(J^P) = \frac{1}{2}(3/2^-)$ channel, using the complex scaling method combined with the Gaussian expansion method. We construct the potential including one pion exchange and one $D^{(*)}$ meson exchange with $S$-wave orbital angular momentum. We find that the both mass and width of the pentaquark $P_c(4380)$ can be reproduced within a reasonable parameter region, and that its main decay mode is $\Lambda_c \bar{D}^*$. We extend our analysis to a coupled system of $\Lambda_c D^{(*)} - \Sigma_c^{(*)} D^{(*)}$ in $I(J^P) = \frac{1}{2}(3/2^-)$ channel. We find that there exists a doubly charmed baryon of $ccqqq$ type as a hadronic molecule, the mass and width of which are quite close to those of $P_c(4380)$.

I. INTRODUCTION

In 2015, the LHCb experiment announced the observation of the hidden charm pentaquark $P_c(4380)$ and $P_c(4450)$ [1,2]. The mass and width of $P_c(4380)$ are $M = 4380 \pm 8 \pm 29$ MeV and $\Gamma = 205 \pm 18 \pm 86$ MeV and those of $P_c(4450)$ are $M = 4449.8 \pm 1.7 \pm 2.5$ and $\Gamma = 39 \pm 5 \pm 19$ MeV. Their spins and parities are not well determined; most likely $J^P = (3/2^-, 5/2^+)$. Some theoretical works were done before the LHCb result in Refs. [3,8]. After the LHCb announcement, there are many theoretical analyses based on the hadronic molecule picture [9–25], diquark-diquark-antiquark (diquark-triquark) picture [26–31], compact pentaquark states [32–34], and triangle singularities [35–40]. The decay behaviors are studied in Refs. [41–44].

In Ref. 20, effect of $\Sigma_c^* D - \Sigma_c D^*$ coupled channel is studied in the hadronic molecule picture for the hidden charm pentaquark with $I(J^P) = 1/2(3/2^-)$, by using the one-pion exchange potential with $S$-wave orbital angular momentum. It was shown that there exists a bound state with the binding energy of several MeV below $\Sigma_c^* D$ threshold, which is mainly made from a $\Sigma_c^*$ and a $D$. In Ref. 21, the coupled channel effect to $\Lambda_c \bar{D}^{(*)}$ was shown to be important to investigate the $P_c$ pentaquarks. In Ref. 44, decay behaviors of hadronic molecule states of $\Sigma_c^* D$ and $\Sigma_c D^*$ to $J/\psi N$ are studied and it was shown that the contribution of $J/\psi N$ is small for the $P_c(4380)$ as the $\Sigma_c^* D$ molecule. However, in our best knowledge, study of the effect of $J/\psi N$ in full coupled channel analysis, which reproduce both the mass and width of $P_c(4380)$, was not done so far.

In this paper, we make a coupled channel analysis including $J/\psi N$ in addition to $\Lambda_c \bar{D}^{(*)} - \Sigma_c^{(*)} \bar{D}^{(*)}$ with $S$-wave orbital angular momentum. Here we construct a relevant potential from exchange of one pion and $D^{(*)}$ mesons. Our result shows that both the mass and width of $P_c(4380)$ are within experimental errors for reasonable parameter region, and that the effect from $J/\psi N$ channel is very small. In other word, the observed mass and width of $P_c(4380)$ are well reproduced dominantly by one-pion exchange potential for $\Lambda_c \bar{D}^{(*)} - \Sigma_c^{(*)} \bar{D}^{(*)}$ coupled channel.

Since the one-pion exchange potential for $\Lambda_c \bar{D}^{(*)} - \Sigma_c^{(*)} \bar{D}^{(*)}$ coupled channel is same as the one for $\Lambda_c \bar{D}^{(*)} - \Sigma_c^{(*)} \bar{D}^{(*)}$ coupled channel, we expect the existence of a doubly charmed baryon with $I(J^P) = \frac{1}{2}(3/2^-)$ having the mass and width close to those of $P_c(4380)$, which we call $\Xi_{cc}(4380)$. In the latter half of this paper, we demonstrate that $\Xi_{cc}(4380)$ does exist in our model, which actually has the mass and width quite close to those of $P_c(4380)$.

This paper is organized as follows: In Sec. III we show the potentials which we use in our analysis. We study the pentaquarks $P_c(4380)$ in Sec. III and the doubly charmed baryon $\Xi_{cc}(4380)$ in Sec. IV. Finally, we will give a brief summary and discussions in Sec. V.

II. POTENTIAL

In this section, we construct a potential for our coupled channel analysis based on the heavy quark symmetry and the chiral symmetry. We include one-pion exchange contribution for $\Lambda_c \bar{D}^{(*)} - \Sigma_c^{(*)} \bar{D}^{(*)}$ coupled channel and $D^{(*)}$ meson exchange for adding $J/\psi N$ channel.

For constructing effective interactions of $D$ and $D^*$ mesons, it is convenient to use the following heavy meson field $H$ defined as [45–48]

$$H = \frac{1 + \gamma_5}{2} [D^{(*)} \gamma^\mu + i D \gamma_5] , \quad (1)$$

$$\bar{H} = \gamma_0 H^\dagger \gamma_0 . \quad (2)$$

where $D$ and $D^*$ are the pseudoscalar and vector meson fields, respectively, and $v$ denotes the velocity of the heavy mesons.
The pion field is introduced by the spontaneous chiral symmetry breaking SU(2)_R \times SU(2)_L \rightarrow SU(2)_V. The fundamental quantity is

$$A_\mu = \frac{i}{2} (\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger) \ ,$$

(3)

where \( \xi = \exp(i\pi/\sqrt{2}f_\pi) \). The pion decay constant is \( f_\pi \sim 92.4 \text{ MeV} \) and the pion field \( \pi \) is defined by a \( 2 \times 2 \) matrix

$$\pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} & \frac{\pi^+}{\sqrt{2}} \\ -\frac{\pi^0}{\sqrt{2}} & \frac{\pi^-}{\sqrt{2}} \end{pmatrix} \ .$$

(4)

The interaction Lagrangian for the heavy meson and pions with least derivatives \([46, 48]\) is given by

$$\mathcal{L}_{HH\pi} = g_T \text{Tr} \left[ \bar{H} H \gamma_\mu \gamma_5 A_\mu \right] \ ,$$

(5)

where \( g \) is a dimensionless coupling constant. The explicit interaction terms can be written as

$$\mathcal{L}_{D^*D^*\pi} = \frac{\sqrt{2i}g}{f_\pi} \mu_{\rho\sigma} D^\rho_\mu D^\sigma_\nu \bar{\pi} v_\sigma \ ,$$

$$\mathcal{L}_{D\bar{D}\pi} = \frac{\sqrt{2i}g}{f_\pi} \left( \bar{D}_\mu D^\mu \bar{\pi} - D^\mu \bar{D}_\mu \bar{\pi} \right) \ ,$$

(6)

(7)

by expanding the \( A_\mu \) and \( H \) fields. Note that the \( D\bar{D} \pi \) interaction term is prohibited by the parity invariance. The coupling constant \( g \) is determined as \( |g| = 0.59 \) from the decay of \( D^* \rightarrow D\pi ) [49] \). The sign of \( g \) cannot be decided by the above decay; however, we use \( g = 0.59 \) in the following analysis.

For introducing \( \Sigma_c \) and \( \Sigma_c^* \) we define the following superfield \( S_\mu \) for \( \Sigma_c \) and \( \Sigma_c^* \) \([51]\):

$$S_\mu = \Sigma_{\mu c}^* - \sqrt{\frac{1}{3}} (\gamma_\mu + \nu_\mu) \gamma_5 \Sigma_c \ ,$$

(8)

where the single heavy baryon fields \( \Lambda_c \) and \( \Sigma_c \) are expressed by the \( 2 \times 2 \) matrices as

$$\Lambda_c = \begin{pmatrix} 0 & \Lambda_c^+ \\ -\Lambda_c^+ & 0 \end{pmatrix} \ , \quad \Sigma_c = \begin{pmatrix} \Sigma_{++}^+ & \sqrt{\frac{2}{3}} \Sigma_0^+ \\ \sqrt{\frac{1}{3}} \Sigma_0^+ & \Sigma_{00}^+ \end{pmatrix} \ ,$$

(9)

and the matrix field of \( \Sigma_c^* \) is defined similarly to the \( \Sigma_c \). The interaction Lagrangian for the heavy baryon and pions is given by \([47, 48]\):

$$\mathcal{L}_{BB\pi} = \frac{3ig_1}{2} v_\sigma \epsilon_{\mu\rho\sigma\sigma} \text{Tr} \left[ \bar{S}_\mu A_\mu S_\rho \right] + g_4 \text{Tr} \left[ \bar{S}_\mu A_\mu \Lambda_c \right] + H.c. \ ,$$

(10)

where \( g_1 \) and \( g_4 \) are dimensionless coupling constants. We use \( g_4 = 0.999 \) determined from the \( \Sigma_c^* \rightarrow \Lambda_\pi \) decay. The value of \( g_1 \) cannot be determined by experimental decay, so we use \( g_1 = \sqrt{2} \) \([50]\), as a reference value, and vary its value about 20%, 0.753 - 1.13.

We include \( J/\psi \) together with \( c\bar{c} \) spin doublet field \( \mathcal{J} \) as \([51, 52]\):

$$\mathcal{J} = \frac{1 + \gamma_5}{2} (\langle \overline{J/\psi} \rangle \gamma_\mu - \eta_c \gamma_\mu) \frac{1 - \gamma_5}{2} \ .$$

(11)

In the following analysis, we use only \( \langle \overline{J/\psi} \rangle \gamma_\mu \) field. The interaction of \( \mathcal{J} \) to the heavy mesons \( D^{(*)} \) and its anti-particles \( \bar{D}^{(*)} \) is expressed as \([51]\):

$$\mathcal{L}_{JHH} = G_1 \text{Tr} \left[ \mathcal{J} \bar{H} A_\mu \gamma_5 \mu \bar{H} + H.c. \right] \ ,$$

(12)

where \( \bar{\partial}_\mu = \partial_\mu - \bar{\partial}_\mu \). The field \( H \) is defined in Eq. (11), and its anti-particle field \( \bar{H} \) is defined as

$$\bar{H} = \left[ \bar{D}_\mu \gamma_5 + i \bar{\gamma}_5 \right] \frac{1 - \gamma_5}{2} \ .$$

(13)

We estimate the value of the coupling constant \( G_1 \) by comparing it with the \( \phi KK \) coupling. Regarding the strange hadrons as heavy hadrons, we can write the effective Lagrangian for \( \phi KK \) in the same form as the one in Eq. (12). Using the value of \( \phi KK \) coupling \( G_{1(\phi KK)} \) determined from the \( \phi \rightarrow KK \) decay: \( G_{1(\phi KK)} = 4.48 \text{[GeV}^{-3/2}] \), we estimate the value of \( G_1 \) as

$$G_1 = G_{1(\phi KK)} \sqrt{\frac{m_\phi m_K^2}{m_{J/\psi} m_D^2}} = 0.679 \text{[GeV}^{-3/2}] \ .$$

(14)

The Lagrangian for the interactions among single heavy baryons, \( D^{(*)} \) mesons and nucleons is given by

$$\mathcal{L}_{BBHN} = G_2 \left( \tau_2 \bar{S}_\mu \right) \bar{H} \gamma_5 \gamma_\mu N + H.c. + G_3 \left( \tau_2 \bar{\Lambda}_c \right) HN + H.c. \ .$$

(15)

We estimate the values of \( G_2 \) and \( G_3 \) using \( g_{EC, DN} = 2.69 \) and \( g_{\Lambda_c, DN} = 13.5 \[42, 44, 53, 54]\). Considering the differences of the normalization of a heavy meson field by \( \sqrt{m_D} \), we estimate them as

$$G_2 = -\frac{g_{EC, DN}}{\sqrt{3} m_D} = -1.14 \text{[GeV}^{-1/2}] \ ,$$

$$G_3 = \frac{g_{\Lambda_c, DN}}{\sqrt{m_D}} = 9.88 \text{[GeV}^{-1/2}] \ .$$

(16)

(17)

Here the factor \( -\frac{1}{\sqrt{3}} \) comes from the coefficient in Eq. (8). The estimations of the values of \( G_{1,2,3} \) are very rough. We will discuss the effects of ambiguities in the following sections.

We construct the one-pion exchange potential and one \( D^{(*)} \) meson exchange potential from the above interaction Lagrangians. We introduce the monopole-type form factor,

$$F(q) = \frac{A^2 - m_n^2}{A^2 + |q|^2} \ ,$$

(18)

at each vertex, where \( A \) is a cutoff parameter, \( m_n \) and \( q \) are the mass and momentum of exchanging particle,
respectively. Although the cutoff parameter $\Lambda$ may be different for pion and $D^{(*)}$ meson, we use the same value in the present analysis for simplicity. Including this form factor, the exchange potentials are written as

$$V_{ij}^{a}(r) = G_{ij} C_{a}(r, \Lambda, m_{a}) \ ,$$

where $G_{ij}$ denotes the coefficients, coupling constants, spin factors, and isospin factors for each $(i, j)$ channel.

The resultant complex energies are shown in Table I. $C_{a}(r, \Lambda, m_{a})$ is defined as

$$C_{a}(r, \Lambda, m_{a}) = \frac{m_{a}^{2}}{4\pi} \left[ e^{-m_{a}r} - e^{-\Lambda r} \right] - \frac{\Lambda^{2} - m_{a}^{2}}{2\Lambda} e^{-\Lambda r} \ .$$

(20)

The explicit forms of potential are shown in the following sections.

III. NUMERICAL RESULT FOR PENTAQUARK $P_{c}(4380)$

We consider the $J/\psi N - \Lambda_{c} D^{*} - \Sigma_{c}^{*} \bar{D} - \Sigma_{c} \bar{D}^{*} - \Sigma_{c}^{*} \bar{D}^{*}$ coupled system with $S$-wave orbital angular momentum. We solve the coupled channel Schrödinger equation, using the potential $V(r)$ given by a $5 \times 5$ matrix expressed as

$$V(r) = \begin{pmatrix}
0 & G_{1} G_{3} (C_{D} + C_{D^{*}}) & -2\sqrt{6} G_{1} G_{2} C_{D^{*}} & \sqrt{2} G_{1} G_{2} (3C_{D} - C_{D^{*}}) & 2\sqrt{10} G_{1} G_{2} C_{D^{*}} \\
G_{1} G_{3} (C_{D} + C_{D^{*}}) & 0 & -\frac{g_{q}}{\sqrt{6}f_{q}^{2}} C_{\pi} & \frac{g_{q}}{3\sqrt{2}f_{q}^{2}} C_{\pi} & -\frac{\sqrt{10} g_{q}}{f_{q}^{2}} C_{\pi} \\
-2\sqrt{6} G_{1} G_{2} C_{D^{*}} & -\frac{g_{q}}{\sqrt{6}f_{q}^{2}} C_{\pi} & 0 & -\frac{g_{q}}{2\sqrt{3}f_{q}^{2}} C_{\pi} & -\frac{\sqrt{5} g_{q}}{f_{q}^{2}} C_{\pi} \\
\sqrt{2} G_{1} G_{2} (3C_{D} - C_{D^{*}}) & \frac{g_{q}}{3\sqrt{2}f_{q}^{2}} C_{\pi} & -\frac{g_{q}}{2\sqrt{3}f_{q}^{2}} C_{\pi} & -\frac{g_{q}}{2f_{q}^{2}} C_{\pi} & -\frac{\sqrt{2} g_{q}}{f_{q}^{2}} C_{\pi} \\
2\sqrt{10} G_{1} G_{2} C_{D^{*}} & -\frac{\sqrt{15} g_{q}}{f_{q}^{2}} C_{\pi} & -\frac{\sqrt{5} g_{q}}{f_{q}^{2}} C_{\pi} & -\frac{\sqrt{2} g_{q}}{f_{q}^{2}} C_{\pi} & 0
\end{pmatrix}$$

(21)

We use $m_{\pi} = 137.2$, $m_{N} = 938.9$, $m_{D} = 1867.2$, $m_{D^{*}} = 2008.6$, $m_{\Lambda_{c}} = 2286.5$, $m_{\Sigma_{c}} = 2453.5$, $m_{\Sigma_{c}^{*}} = 2518.1$ and $m_{J/\psi} = 3096.9$ MeV for the hadron masses [49]. The thresholds for the hadronic molecules are shown in Table II. In this calculation, we vary the cutoff parameter $\Lambda$ from 1000 to 1500 MeV. For the coupling constant $g_{1}$, we use $g_{1} = 0.942$ estimated in a quark model [51] as a reference value, and study the $g_{1}$ dependence of the results using $g_{1} = 0.753$ and 1.13. To obtain the bound and resonance solutions, we use the complex scaling method [55–57] and Gaussian expansion method [58, 59].

The resultant complex energies are shown in Table II. When the cutoff parameter $\Lambda$ becomes larger, the mass and width become smaller. In our ranges of $\Lambda$ and $g_{1}$, the bound state solution which has the real energy below the $J/\psi N$ threshold does not appear. The solutions of $\Lambda = 1200$ and 1300 MeV for $g_{1} = 0.942$ can reproduce the observed mass of $P_{c}(4380)$, 4380 ± 8 ± 29MeV and width, $205 \pm 18 \pm 86$ MeV. However, there exists another resonance state solution, the mass of which is 4283.1 MeV for $\Lambda = 1200$ MeV and 4227.1 MeV for $\Lambda = 1300$ MeV. These lower states are not observed in LHCb experiment, therefore, we consider that these parameter sets are unlikely.

On the other hand, for the $\Lambda = 1000$ MeV and $g_{1} = 0.753$, we obtain only one resonance state which corresponds to $P_{c}(4380)$. Its mass, 4390.2 MeV, is slightly above the $\Sigma_{c}^{*} \bar{D}$ threshold, so this state is interpreted as a resonance state of $\Sigma_{c}^{*} \bar{D}$ molecule.

IV. DOUBLY CHARMED BARYON $\Xi_{cc}^{*}(4380)$

We study the doubly charmed baryon as a hadronic molecular state in this section. Replacing $\bar{D}^{(*)}$ with $D^{(*)}$ and excluding the $J/\psi N$ channel from the calculation in Sec. III, we construct the $ccqq\bar{q}$ state which has the same flavor quantum number as the $ccq$ baryon has. The interactions of one-pion exchange is not changed by the replacement of $D^{(*)}$ meson. Therefore, the corresponding
TABLE I. Energy eigen values in $J/\psi N - \Lambda_c \bar{D}^* - \Sigma_c^* \bar{D} - \Sigma_c D^* - \Sigma_c^* D^*$ coupled system with S-wave states in $J^P = 3/2^-$. We show the thresholds of each hadronic molecular state in the last line of the table for a reference.

| $g_1$ | 1000 | 1100 | 1200 | 1300 | 1400 | 1500 |
|------|------|------|------|------|------|------|
| 0.753 | 4390.2 + i109 | 4352.5 + i61.4 | 4312.2 + i36.5 | 4449.4 - i172 | 4397.1 - i80.8 | 4344.0 - i31.4 |
| 0.942 | 4333.6 - i66.4 | 4308.5 - i36.3 | 4283.1 - i12.1 | 4397.2 - i100 | 4345.0 - i51.5 | 4314.3 - i21.0 |
| 1.13 | 4422.8 - i99.6 | 4382.5 - i70.9 | 4359.6 - i53.2 | 4295.7 - i26.3 | 4226.6 - i7.19 | 4149.6 - i3.20 |

The wave function has four components:

$$\Psi(r) = \begin{pmatrix} \psi_{\Lambda_c D^*} \\ \psi_{\Sigma_c^* \bar{D}} \\ \psi_{\Sigma_c D^*} \\ \psi_{\Sigma_c^* D^*} \end{pmatrix}. \quad (24)$$

V. SUMMARY AND DISCUSSIONS

We investigated the coupled channel of the $J/\psi N - \Lambda_c \bar{D}^* - \Sigma_c^* \bar{D} - \Sigma_c D^* - \Sigma_c^* D^*$ in $J^P = 3/2^-$ with S-wave orbital angular momentum. We constructed the one-pion exchange and one-$D^{(*)}$ meson exchange potential and solved the complex scaled Schrödinger-type equation. We showed that, for $\Lambda_c$ = 1200-1300 MeV, there exists another state having mass and with smaller than $P_c(4380)$, while for $\Lambda_c$ = 1000 MeV and $g_1 = 0.753$, there exists only one molecular state having the mass and width within errors of experimental values. This shows that hidden charm pentaquark $P_c(4380)$ can be explained as a S-wave hadronic molecular state.

We studied the coupled channel of the $\Lambda_c D^* - \Sigma_c^* D - \Sigma_c D^* - \Sigma_c^* D^*$ in $J^P = 3/2^-$ with S-wave orbital angular momentum. Since the one-pion interactions for $D^{(*)}$ mesons are the same as the ones for $D^{(*)}$ mesons, we obtain a $\Xi_{cc}$ state with $J^P = \frac{3}{2}^-$ as a resonance state whose mass and width are very close to those of $P_c(4380)$, which we call $\Xi_{cc}^*(4380)$.

We think that the same mechanism applies for $P_c(4450)$: When $P_c(4450)$ is described as a hadronic molecular state, there exists a doubly charmed baryon which has a mass and a width quite close to $P_c(4450)$.

Although we do not evaluate the partial decay width for $J/\psi N$ in this paper, we can see that the partial width is much narrower than that for $\Lambda_c \bar{D}^*$ in the following way: When we omit the contribution from $J/\psi N$ channel to $P_c(4380)$, the relevant potential become the same as that for $\Xi_{cc}^*(4380)$. This implies that the resultant mass and width without $J/\psi N$ channel is already close to the ones with $J/\psi N$ channel. This is consistent with the analysis of decay behaviors in Ref. [44].

Comparing the results of $P_c(4380)$ and $\Xi_{cc}^*(4380)$, we can see that the contribution of the $J/\psi N$ channel to $P_c(4380)$ is small. This is consistent with the naive prospect of the suppression of $D^{(*)}$ meson exchange potentials. Our evaluation of the coupling to the $J/\psi N$ was very rough, so that the values used in this analysis include some ambiguities. Furthermore, there may exist other contributions which couple the $J/\psi N$ channel to $\Lambda_c D^* - \Sigma_c^* D - \Sigma_c D^* - \Sigma_c^* D^*$. We think that these ambiguities do not change our results, since the contribution...
from $J/\psi N$ channel is very small consistently with the result in Ref. [44].

In the present analysis, we do not include the decay of $\Sigma^{*+}_c \to \Lambda_c \pi$ for $\Sigma^{*+}_c D^{(*)}$ state. The width of this decay is about 15 MeV [49], so it makes the total width of $P_c(4380)$ broader [44].

We used only one-pion exchange potential for $\Lambda_c D^{(*)} - \Sigma^{(*)}_c D^{(*)}$ coupled channel in the analysis of $\Xi^{*+}_{cc}(4380)$, which is the same as the one for $\Lambda_c \bar{D}^{(*)} - \Sigma^{(*)}_c \bar{D}^{(*)}$ coupled channel in the analysis of $P_c(4380)$. Then, we obtained the mass and width of $\Xi^{*+}_{cc}(4380)$ very close to those of $P_c(4380)$. When we include the effects of $\omega$ meson exchange, difference between $DD\omega$ and $DD\bar{\omega}$ will generate some differences of the mass and width [61].

There are some theoretical predictions of ordinary $ccq$-type baryons in $J^P = 3/2^-$ [61, 67]. In Ref. [67], the mass of $3P$-state spin-$\frac{3}{2}$ $\Xi_{cc}$ is predicted to be about 4.41 GeV. This state might mix with $\Xi^{*+}_{cc}(4380)$ predicted in this analysis.

We expect that the precise properties of $P_c$ pentaquarks and the existence of excited $\Xi_{cc}$ baryons would be revealed in future experiments.

Acknowledgments

We would like to thank Yuji Kato for useful discussion. The work of Y.S. is supported in part by JSPS Grant-in-Aid for JSPS Research Fellow No. JP17J06300. The work of M.H. is supported in part by the JSPS Grant-in-Aid for Scientific Research (C) No. 16K05345.

Table II. Energy eigenvalues in $\Lambda_c D^* - \Sigma^*_c D - \Sigma^*_c D^* - \Sigma^*_c D^*$ coupled system with $S$-wave states in $J^P = 3/2^-$. We show the thresholds of each hadronic molecular state at the last line of the table for a reference.

| $g_t$ | 1000 | 1100 | 1200 | 1300 | 1400 | 1500 |
|------|------|------|------|------|------|------|
| 0.753 | 4370.1 - i68.7 | 4340.9 - i55.6 | 4302.4 - i15.7 | 4262.3 | 4214.3 | 4166.0 |
| 0.942 | 4350.3 - i69.1 | 4448.9 - i142 | 4424.5 - i122 | 4401.6 - i98.7 | 4367.0 - i70.4 | 4328.4 - i29.7 |
| 1.13 | 4414.0 - i86.0 | 4377.1 - i73.8 | 4342.4 - i27.9 | 4296.7 - i0.2 | 4247.8 | 4185.4 |
| & 4354.5 - i113.3 & 4265.3 - i0.1 & 4265.1 & 4226.5 & 4180.8 & 4117.9 |
| threshold [MeV] | $\Lambda_c D^*(4295.1)$ | $\Sigma^*_c D(4385.3)$ | $\Sigma^*_c D^*(4462.1)$ | $\Sigma^*_c D^*(4526.7)$ |

References

[1] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 115, 072001 (2015).
[2] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 117, no. 8, 082002 (2016).
[3] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 117, no. 8, 082003 (2016).
[4] J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. C 84, 015202 (2011).
[5] Z. C. Yang, Z. F. Sun, J. He, X. Liu and S. L. Zhu, Chin. Phys. C 36, 6 (2012).
[6] W. L. Wang, F. Huang, Z. Y. Zhang and B. S. Zou, Phys. Rev. C 84, 015203 (2011).
[7] J. J. Wu, T.-S. H. Lee and B. S. Zou, Phys. Rev. C 85, 044002 (2012).
[8] T. Uchino, W. H. Liang and E. Oset, Eur. Phys. J. A 52, no. 3, 43 (2016).
[9] R. Chen, X. Liu, X. Q. Li and S. L. Zhu, Phys. Rev. Lett. 115, no. 13, 132002 (2015).
[10] J. He, Phys. Lett. B 753, 547 (2016).
[11] H. X. Chen, W. Chen, X. Liu, T. G. Steele and S. L. Zhu, Phys. Rev. Lett. 115, no. 17, 172001 (2015).
[12] H. Huang, C. Deng, J. Ping and F. Wang, Eur. Phys. J. C 76, no. 11, 624 (2016).
[13] L. Roca, J. Nieves and E. Oset, Phys. Rev. D 92, no. 9, 094003 (2015).
[14] U. G. Meiner and J. A. Oller, Phys. Lett. B 751, 59 (2015).
[15] C. W. Xiao and U.-G. Meiner, Phys. Rev. D 92, no. 11, 114002 (2015).
[16] T. J. Burns, Eur. Phys. J. A 51, no. 11, 152 (2015).
[17] D. E. Kahana and S. H. Kahana, arXiv:1512.01902 [hep-ph].
[18] R. Chen, X. Liu and S. L. Zhu, Nucl. Phys. A 954, 406 (2016).
[19] H. X. Chen, E. L. Cui, W. Chen, X. Liu, T. G. Steele and S. L. Zhu, Eur. Phys. J. C 76, no. 10, 572 (2016).
[20] Y. Shimizu, D. Suenaga and M. Harada, Phys. Rev. D 93, no. 11, 114003 (2016).
[21] Y. Yamaguchi and E. Santopinto, Phys. Rev. D 96, no. 1, 014018 (2017).
[22] J. He, Phys. Rev. D 95, no. 7, 074004 (2017).
[23] P. G. Ortega, D. R. Entem and F. Fernandez, Phys. Lett. B 764, 207 (2017).
[24] K. Azizi, Y. Sarac and H. Sundu, Phys. Rev. D 95, no. 9, 094016 (2017).
[25] L. Geng, J. Lu and M. P. Valderrama, arXiv:1704.06123 [hep-ph].
[26] L. Maiani, A. D. Polosa and V. Riquer, Phys. Lett. B 749, 289 (2015).
[27] R. F. Lebed, Phys. Lett. B 749, 454 (2015).
[28] V. V. Anisovich, M. A. Matveev, J. Nyiri, A. V. Sarantsev and A. N. Semenova, arXiv:1507.07652 [hep-ph].
[31] R. Zhu and C. F. Qiao, Phys. Lett. B 756, 259 (2016).
[32] E. Santopinto and A. Giachino, Phys. Rev. D 96, no. 1, 014014 (2017).
[33] S. Takeuchi and M. Takizawa, Phys. Lett. B 764, 259 (2017).
[34] J. Wu, Y. R. Liu, K. Chen, X. Liu and S. L. Zhu, Phys. Rev. D 95, no. 3, 034002 (2017).
[35] F. K. Guo, U. G. Meiner, W. Wang and Z. Yang, Phys. Rev. D 92, no. 7, 071502 (2015).
[36] X. H. Liu, Q. Wang and Q. Zhao, Phys. Lett. B 757, 231 (2016).
[37] M. Mikhasenko, arXiv:1507.06552 [hep-ph].
[38] X. H. Liu and M. Oka, Nucl. Phys. A 954, 352 (2016).
[39] F. K. Guo, U. G. Meiner, J. Nieves and Z. Yang, Eur. Phys. J. A 52, no. 10, 318 (2016).
[40] M. Bayar, F. Aceti, F. K. Guo and E. Oset, Phys. Rev. D 94, no. 7, 074039 (2016).
[41] G. J. Wang, L. Ma, X. Liu and S. L. Zhu, Phys. Rev. D 93, no. 3, 034031 (2016).
[42] Q. F. Li and Y. B. Dong, Phys. Rev. D 93, no. 7, 074020 (2016).
[43] C. W. Shen, F. K. Guo, J. J. Xie and B. S. Zou, Nucl. Phys. A 954, 393 (2016).
[44] Y. H. Lin, C. W. Shen, F. K. Guo and B. S. Zou, Phys. Rev. D 95, no. 11, 114017 (2017).
[45] A. F. Falk, Nucl. Phys. B 378, 79 (1992).
[46] M. B. Wise, Phys. Rev. D 45, no. 7, R2188 (1992).
[47] P. L. Cho, Phys. Lett. B 285, 145 (1992).
[48] T. M. Yan, H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin and H. L. Yu, Phys. Rev. D 46, 1148 (1992) Erratum: [Phys. Rev. D 55, 5851 (1997)].
[49] C. Patrignani et al. [Particle Data Group], Chin. Phys. C 40, no. 10, 100001 (2016).
[50] Y. R. Liu and M. Oka, Phys. Rev. D 85, 014015 (2012).
[51] B. Wang, H. Xu, X. Liu, D. Y. Chen, S. Coito and E. Eichten, Front. Phys. (Beijing) 11, 111402 (2016).
[52] E. E. Jenkins, M. E. Luke, A. V. Manohar and M. J. Savage, Nucl. Phys. B 390, 463 (1993).
[53] E. J. Garzon and J. J. Xie, Phys. Rev. C 92, no. 3, 035201 (2015).
[54] W. Liu, C. M. Ko and Z. W. Lin, Phys. Rev. C 65, 015203 (2002).
[55] J. Aguilar and J. M. Combes, Commun. Math. Phys. 22, 269 (1971).
[56] E. Balslev and J. M. Combes, Commun. Math. Phys. 22, 280 (1971).
[57] S. Aoyama, T. Myo, K. Kato and K. Ikeda, Prog. Theor. Phys. 116, 1 (2006).
[58] E. Hiyama, Y. Kino and M. Kamimura, Prog. Part. Nucl. Phys. 51, 223 (2003).
[59] E. Hiyama, PTEP 2012, 01A204 (2012).
[60] R. Chen, X. Liu and A. Hosaka, arXiv:1707.08306 [hep-ph].
[61] S. Migura, D. Merten, B. Metsch and H. R. Petry, Eur. Phys. J. A 28, 41 (2006).
[62] T. W. Chiu and T. H. Hsieh, Nucl. Phys. A 755, 471 (2005).
[63] Z. G. Wang, Eur. Phys. J. A 47, 81 (2011).
[64] M. Karliner and J. L. Rosner, Phys. Rev. D 90, no. 9, 094007 (2014).
[65] M. Padmanath, R. G. Edwards, N. Mathur and M. Peardon, Phys. Rev. D 91, no. 9, 094502 (2015).
[66] K. W. Wei, B. Chen and X. H. Guo, Phys. Rev. D 92, no. 7, 076008 (2015).
[67] Z. Shah and A. K. Rai, Eur. Phys. J. C 77, no. 2, 129 (2017).