

$\pi J/\psi - D\bar{D}^*$ potential described by the quark exchange diagram

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Abstract. Exotic hadrons reported in the heavy flavor sector have attracted much interest in hadron and nuclear physics. Especially near the thresholds, the hadron-hadron interaction is important to understand these exotic structures. In this talk, the short range $\pi J/\psi - D\bar{D}^*$ potential whose importance is indicated by the Lattice QCD is studied by the $D^{(*)}$ meson exchange model, and the Born-order quark exchange model. We find the large difference between the results of the $D^{(*)}$ meson exchange and the quark exchange calculations.

1 Introduction

Exotic hadrons reported in the heavy flavor sector have been one of the interesting topics in hadron and nuclear physics. In the experiments, such as BaBar, Belle, BESIII, and LHCb, unexpected mesons called XYZ states have been reported, whose mass spectra have not been explained by the standard constituent quark picture being qqq as a baryon and $q\bar{q}$ as a meson [1, 2]. Especially for the exotic meson near the thresholds, those states could be realized as a hadronic molecule which is a loosely bound or resonant state of multi-mesons. For instance, $X(3872)$ reported by Belle in 2003 has been discussed as the $D\bar{D}^*$ molecule [3, 4]. On the other hand, some of the exotics near the thresholds might be a cusp by the kinematical effect [2], which is not a physical bound state.

$Z_c(3900)$ is also an exotic state reported in the $Y(4260) \rightarrow \pi\pi J/\psi$ decay by BESIII [5], Belle [6] and other facilities [7, 8]. One of the interesting properties of $Z_c(3900)$ is that it has nonzero electric charge which cannot be possessed by the standard $c\bar{c}$ state. Therefore, $Z_c(3900)$ is a genuine exotic state which must have a multi-quark component such as $c\bar{c}u\bar{d}$. There have been various studies of the structure of $Z_c(3900)$, such as multi-quark state [2, 9, 10] and hadronic molecules [11, 12]. Non bound state explanation by the kinematic effect has also been studied in [13–15].

Recently HALQCD collaboration performed Lattice QCD simulation for the coupled-channel system including $\pi J/\psi - \rho\eta_c - D\bar{D}^*$ corresponding to $Z_c(3900)$ at the non physical pion mass $m_\pi = 410 - 700$ MeV [15]. This simulation indicates that $Z_c(3900)$ is a virtual state, and it is induced by the strong $\pi J/\psi - D\bar{D}^*$ potential. It is an interesting result because such charm quark (charmed meson) exchange process is expected to be suppressed due to the large mass of the exchange particle.

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In this talk, we study the short range $\pi J/\psi - D\bar{D}^*$ interaction for the quantum number $J^{PC} = 1^{+-}$, with the total angular momentum J , parity P and C -parity C . The $\pi J/\psi - D\bar{D}^*$ interaction is described by (i) the meson exchange model, and (ii) quark exchange model, and we compare the results obtained by these models. In the meson exchange model, the $D^{(*)}$ meson exchange is introduced in the $\pi J/\psi - D\bar{D}^*$ off-diagonal term. In the quark exchange model, the $\pi J/\psi - D\bar{D}^*$ interaction is given by the Born-order quark exchange diagram [16, 17].

2 Meson exchange model

The meson exchange potential is given as the Born term of the t -channel scattering amplitude. The amplitude is obtained by the effective Lagrangians respecting to the heavy quark and chiral symmetries [18, 19]. The Lagrangians of the $\pi D^{(*)}D^{(*)}$ and $J/\psi D^{(*)}D^{(*)}$ couplings are given by

$$\mathcal{L}_{\pi HH} = -\frac{g_\pi}{2f_\pi} \text{Tr} \left[H_1 \gamma_\mu \gamma_5 \partial^\mu \hat{\pi} \bar{H}_1 \right], \quad (1)$$

$$\mathcal{L}_{\psi HH} = g' \text{Tr} \left[\mathcal{J} \bar{H}_2 \overleftrightarrow{\partial}_\mu \gamma^\mu \bar{H}_1 \right] + \text{H.c.}, \quad (2)$$

with $g_\pi = 0.59$, $g' = 4/\sqrt{m_\psi m_D^2}$, and the pion decay constant $f_\pi = 93$ MeV. The heavy meson fields H and \mathcal{J} are

$$H_1 = \frac{1+b}{2} \left[D^{*\mu} \gamma_\mu + iD\gamma_5 \right], \quad (3)$$

$$H_2 = \left[\bar{D}^{*\mu} \gamma_\mu + i\bar{D}\gamma_5 \right] \frac{1-b}{2}, \quad (4)$$

$$\mathcal{J} = \frac{1+b}{2} \left[\psi^\mu \gamma_\mu + i\eta_c \gamma_5 \right] \frac{1-b}{2}. \quad (5)$$

From these Lagrangians, the meson exchange potentials are given by

$$V^\pi = -\frac{1}{2} \left(\frac{g_\pi}{f_\pi} \right)^2 \left[\vec{S}_1 \cdot \vec{S}_2 C(r; m_\pi) + S_{12}(\hat{r}) T(r; m_\pi) \right] \vec{\tau}_1 \cdot \vec{\tau}_2, \quad (6)$$

$$V^D = \frac{2}{3} \frac{g_\psi g_\pi}{f_\pi \sqrt{E_\pi}} \left[\vec{S}_1 \cdot \vec{S}_2 C(r; m_D) + S_{12}(\hat{r}) T_D(r; m_D) \right], \quad (7)$$

$$V^{D^*} = \frac{2}{3} \frac{g_\psi g_\pi}{f_\pi \sqrt{E_\pi}} \left[2\vec{S}_1 \cdot \vec{S}_2 C(r; m_{D^*}) - S_{12}(\hat{r}) T(r; m_{D^*}) \right]. \quad (8)$$

The form of the spin operator \vec{S}_i ($i = 1, 2$) in Eqs. (6)-(8) depends on channels. For the $0^- \rightarrow 1^-$ transition, one takes the polarization vector $\vec{\varepsilon}$ defined by $\vec{\varepsilon}^{(\pm)} = (\mp 1/\sqrt{2}, \pm i/\sqrt{2}, 0)$ and $\vec{\varepsilon}^{(0)} = (0, 0, 1)$, while the spin-one operator $\vec{T} = i(\vec{\varepsilon} \times \vec{\varepsilon}^\dagger)$ is taken for the $1^- \rightarrow 1^-$ transition. The operators $S_{12}(\hat{r})$ and $\vec{\tau}_1 \cdot \vec{\tau}_2$ are the tensor operator $S_{12}(\hat{r}) = 3(\vec{S}_1 \cdot \hat{r})(\vec{S}_2 \cdot \hat{r}) - \vec{S}_1 \cdot \vec{S}_2$ and isospin operator, respectively. The functions $C(r; m)$ and $T(r; m)$ are the Yukawa and Tensor functions, respectively,

$$C(r; m) = \int \frac{d^3 \vec{q}}{(2\pi)^3} \frac{m^2}{\vec{q}^2 + m^2} e^{i\vec{q} \cdot \vec{r}} F(\Lambda, \vec{q}), \quad (9)$$

$$S_{12}(\hat{r}) T(r; m) = \int \frac{d^3 \vec{q}}{(2\pi)^3} \frac{-\vec{q}^2}{\vec{q}^2 + m^2} S_{12}(\hat{q}) e^{i\vec{q} \cdot \vec{r}} F(\Lambda, \vec{q}), \quad (10)$$

with the form factor $F(\Lambda, \vec{q})$ introduced in [20–24].

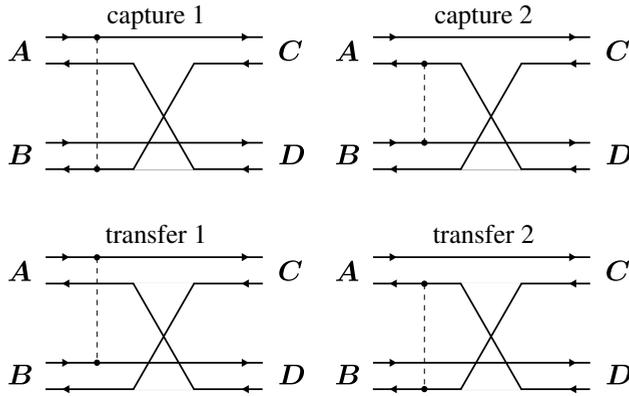


Figure 1. Quark exchange diagrams for “captures” 1,2 and “transfers” 1,2 in the meson-meson scattering $AB \rightarrow CD$

3 Quark exchange model

To describe the short range interaction in $\pi J/\psi - D\bar{D}^*$, the Born-order quark exchange diagram is employed [16, 17]. The scattering amplitude is given by the sum of four diagrams called capture 1, capture 2, transfer 1, and transfer 2, as shown in Fig. 1. The capture (transfer) diagram is induced by the quark-quark and antiquark-antiquark (quark-antiquark) interactions.

For instance, the scattering amplitude of the capture 1 is given by

$$\mathcal{M}_{c1} \propto \int \int d^3 a d^3 c \phi_C^*(2\vec{c} - \vec{C}) \phi_D^*(2\vec{a} - 2\vec{A} - \vec{C}) V_q(\vec{a} - \vec{c}) \phi_A(2\vec{a} - \vec{A}) \phi_B(2\vec{a} - \vec{A} - 2\vec{C}), \quad (11)$$

where $(\vec{A}, \vec{B}, \vec{C}, \vec{D})$ stand for the momenta of mesons A, B, C, D , and $(\vec{a}, \vec{b}, \vec{c}, \vec{d})$ for the momenta of quarks inside mesons, function V_q is the quark-quark interaction by the constituent quark model and ϕ_i ($i = A, B, C, D$) is the meson wave function.

The meson wave function is obtained by the constituent quark model Hamiltonian [16, 17],

$$H_{ij}^q = K_q + \left(-\frac{3}{4}br + \frac{\alpha_s}{r} - C \right) \vec{F}_i \cdot \vec{F}_j - \frac{8\pi\alpha_h}{3m_i m_j} \left(\frac{\sigma^3}{\pi^{3/2}} e^{-\sigma^2 r_{ij}^2} \right) \vec{S}_i \cdot \vec{S}_j \vec{F}_i \cdot \vec{F}_j. \quad (12)$$

The parameters are fixed to reproduce the meson masses, summarized in Tab. 1. Above K_q is the kinetic term, and $\vec{F}_i = \vec{\lambda}_i/2$ with the Gell-Mann matrix λ_i . In this study, the single Gaussian function is employed for the meson wave function,

$$\phi(r) = (4\pi b_G)^{-3/4} \exp\left(-\frac{r^2}{8b_G}\right). \quad (13)$$

The Gaussian parameter b_G is determined to minimize $E(b_G) = \langle \phi | H^q | \phi \rangle$. The obtained meson masses and Gaussian parameter are summarized in Tab. 2.

4 Numerical results

In this section, the cross section of the $\pi J/\psi - D\bar{D}^*$ transition is shown, and the results of the meson exchange and quark exchange models are compared. In Fig. 2, the $\pi J/\psi - D\bar{D}^*$

Table 1. Parameters of the quark Hamiltonian determined to reproduce the meson masses in [16, 17]. The charm quark mass m_c is also determined to fit the charmed meson masses

m_q [GeV]	m_c [GeV]	α_s	α_h	b [GeV $^{-2}$]	C [GeV]	σ [GeV]
0.375	1.9	0.857	0.840	0.154	-0.4358	0.70

Table 2. The meson masses m and Gaussian parameter b_G obtained in the single Gaussian Approximation

	$(m$ [GeV], b_G [GeV $^{-2}$])		$(m$ [GeV], b_G [GeV $^{-2}$])		$(m$ [GeV], b_G [GeV $^{-2}$])
π	(0.258, 0.854)	D	(1.876, 0.965)	η_c	(2.826, 0.261)
ρ	(0.782, 2.549)	D^*	(2.016, 1.298)	J/ψ	(2.910, 0.290)

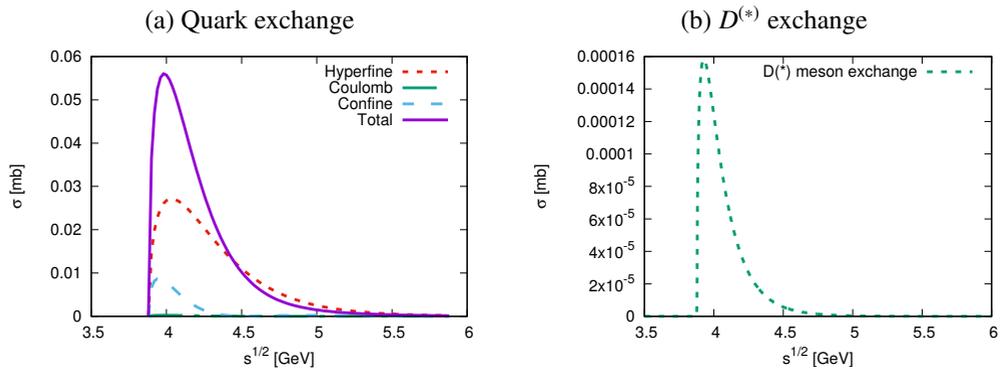


Figure 2. The cross section of the $\pi J/\psi - D\bar{D}^*$ transition by (a) the quark exchange model and (b) $D^{(*)}$ exchange model. In (a), the solid line shows the cross section including all terms, spin-spin (hyperfine), coulomb, and confinement, while the short-dashed line is only for the spin-spin (hyperfine) term, the dashed-dot for coulomb term, and the long-dashed line for the confinement term

cross sections by the quark exchange model and the meson exchange model are displayed in Figs. 2 (a) and (b), respectively. In Fig. 2 (a), the large contribution from the spin-spin term is obtained. This contribution is given by the light quark dynamics, because the spin-spin term in the charm quark interaction is suppressed due to the large mass of the charm quark. Fig. 2 (b) shows the cross section by the meson exchange model. In comparison with the result of the quark exchange, the cross section in the meson exchange model is very small. This observation would be useful to understand the short range $\pi J/\psi - D\bar{D}^*$ interaction. The $D^{(*)}$ exchange potential plays a minor role, while the very short range interaction such as the quark exchange has the important role in the $\pi J/\psi - D\bar{D}^*$ scattering.

5 Summary

We have investigated the short range $\pi J/\psi - D\bar{D}^*$ potential by two models: the quark exchange and the meson exchange models. Understanding the short range interaction is important to investigate the exotic structure which is realized as a bound state or cusp near the hadron thresholds. In this talk, the cross sections in the $\pi J/\psi - D\bar{D}^*$ transition by the two models have been compared. The cross section in the quark exchange is dominated by the spin-spin term which is contributed by the light quark dynamics rather than the charm quark one. In

comparison with the quark exchange, the cross section obtained by the meson exchange is very small. The large difference between two models is obtained, and it would be useful to understand the short range interaction in the $\pi J/\psi - D\bar{D}^*$ channel.

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