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X(3872) and Bound State Problem of $D^0\bar{D}^{*0}$ ($\bar{D}^0 D^{*0}$) *

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Abstract：We have performed a dynamical calculation of the bound state problem of $D^0\bar{D}^{*0}$ by considering the pion and sigma meson exchange potential. Our preliminary analysis disfavors the molecular interpretation of X(3872) if we use the experimental $D^* D\pi$ coupling constant $g=0.59$ and a reasonable cutoff around 1 GeV, which is the typical hadronic scale. In contrast, there probably exists a loosely bound S-wave $B\bar{B}^*$ molecular state. Such a molecular state would be rather stable since its dominant decay mode is the radiative decay through $B^* \to B\gamma$.

Key words：X(3872)；bound state；molecule

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1　Introduction

The quark model (QM) is very successful in classifying hadrons. In this model, a meson is composed of a quark and an anti-quark, while a baryon is composed of three quarks. On the other hand, QCD permits the existence of other hadronic states, such as multiquark states, glueballs and hybrids. There are lots of efforts in searching for hadrons beyond QM. Unfortunately, no such a particle has been established.

In recent years, many new hadrons at different scales were observed. Unexpected new charmonium-like states[1—4] are particularly interesting. Some of them are exotic candidates. For example, $Z^+(4430)$ could be a multiquark state. In this talk, we will focus on the most intriguing state X(3872).

Belle first discovered this state in the $\pi^+\pi^- J/\psi$ channel of B decay in 2003[5]. Thereafter, CDF[6], D0[7], and BaBar[8] collaborations have confirmed its existence. The mass is (3871.2 ± 0.5) MeV[9]. The X(3872) is almost on the threshold of $D^0 D^{*0}$ and is close to the thresholds of $\rho J/\psi$, $\omega J/\psi$ and $D^+ D^{*-}$. Its width is very narrow ($\Gamma < 2.3$ MeV from PDG[9]), up to the detector resolution. The measurements from Belle[10] and CDF[11] favor the quantum numbers $J^{PC}=1^{++}$, but 2^{-+} have not been ruled out yet. In the search for a charged X state, BaBar excluded the isovector hypothesis[12].

In addition, experiments have accumulated much information about the decay of the X(3872). The analysis from CDF[13] supports that the two pions in the channel $X(3872) \to \pi^+\pi^- J/\psi$ come

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from the ρ meson. Besides, Belle observed the 3π decay $\pi^+\pi^-\pi^0 J/\psi$ and the radiative decay $\gamma J/\psi$[14]. BaBar also reported the evidence of the latter mode[15]. The measured ratios include[14]

$$\frac{\mathcal{B}(X(3872)\to\pi^+\pi^-\pi^0 J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}=1.0\pm0.4\pm0.3\ , \tag{1}$$

$$\frac{\mathcal{B}[X(3872)\to\gamma J/\psi]}{\mathcal{B}[X(3872)\to J/\psi\,\pi^+\pi^-]}=0.14\pm0.05\ , \tag{2}$$

and[8, 15, 16]

$$\frac{\mathcal{B}[X(3872)\to\gamma J/\psi]}{\mathcal{B}[X(3872)\to J/\psi\,\pi^+\pi^-]}\approx0.3\ . \tag{3}$$

The ratio between the 3π mode and the dipion mode in Eq. (1) indicates the large isospin violation when X(3872) decays, from which we know X(3872) is not a pure charmonium.

Recently, Belle announced a new near-threshold enhancement with $M=(3875.4\pm0.7^{+1.2}_{-2.0})$ MeV in the channel $B\to X(3875)\,K\to D^0\overline{D}^0\pi^0 K$[17]. This state has been confirmed by BaBar[18]. It is unclear whether these two X states are the same one or not. If the X(3875) is identical to the X(3872), there are two more ratios[17]

$$\frac{\mathcal{B}[X\to D^0\overline{D}^0\pi^0]}{\mathcal{B}[X\to\pi^+\pi^- J/\psi]}=8.8^{+3.1}_{-3.6}, \tag{4}$$

$$\frac{\mathcal{B}[B^0\to XK^0]}{\mathcal{B}[B^+\to XK^+]}\approx1.6\ . \tag{5}$$

Up to now, there are many interpretations for X(3872). They include a molecular state[19—23], a cusp[24], an S-wave threshold effect[25], a hybrid charmonium[26], a four quark state[27, 28], a vector glueball mixed with some charmonium components[29] and a dynamically generated resonance[30]. In addition, there are discussions that the puzzles for the X(3872) may possibly be resolved in the scheme of mixing[31—35]. Among these schemes, the most popular one is the molecular picture.

In this picture, Swanson assumed it is a molecule of $D^0\overline{D}^{*0}$, mixed with $\omega J/\psi$ and $\rho J/\psi$[22]. This picture can naturally explain the mass, the quantum numbers and the isospin violating decay. The 3π prediction is also consistent with experimental measurement. Besides, it can explain the non-observation of the $\eta J/\psi$ decay. According to the dynamical calculation of Swanson[22] and Wong[21], X(3872) can be interpreted as a molecular state.

However, the interpretation is still inconclusive. For example, the prediction for the ratio $\frac{\mathcal{B}[X(3872)\to\gamma J/\psi]}{\mathcal{B}[X(3872)\to J/\psi\,\pi^+\pi^-]}\approx7\times10^{-3}$ is much smaller than the experimental measurements in Eqs. (2) and (3). If X(3875) and X(3872) are the same state, the values in Eqs (4) and (5) are also much larger than the theoretical predictions. $\frac{\mathcal{B}[X\to D^0\overline{D}^0\pi^0]}{\mathcal{B}[X\to\pi^+\pi^- J/\psi]}$ from the molecular assumption is 0.05 and $\frac{\mathcal{B}[B^0\to XK^0]}{\mathcal{B}[B^+\to XK^+]}$ is less than 0.1[36]. To understand X(3872) further, we re-examine the molecular assumption. We also study its bottom analog by replacing a c quark with a b quark.

2　Bound State Problem

Before the presentation of our calculation, we give a brief discussion for the bound state problem. A bound state composed of two mesons was named deuson by Tornqvist[37]. If X(3872) is really a molecule, the wavefunction should be[2, 38]

$$X(3872)=\frac{a_0}{\sqrt{2}}\left[D^0\,\overline{D}^{*0}-c\,D^{*0}\overline{D}^0\right]+\frac{a_1}{\sqrt{2}}\left[D^+\,D^{*-}-c\,D^{*+}D^-\right]+\cdots\ . \tag{6}$$

The ellipsis denotes other hadronic components. To interpret the isospin violating decay, a_0 is assumed to be much larger than other coefficients. As a preliminary work, we study the bound state problem of $D^0\overline{D}^{*0}$. Since X is the eigenstate of C parity while charmed mesons not, we encounter a problem of the relative sign between the two components. There are two possibilities. We call them X_D and $\widetilde{X}_D$,

$$|X_D\rangle=\frac{1}{\sqrt{2}}\left[|D^0\,\overline{D}^{*0}\rangle-|D^{*0}\overline{D}^0\rangle\right]\ , \tag{7}$$

$$|\widetilde{X}_{\mathrm{D}}\rangle=\frac{1}{\sqrt{2}}[|\mathrm{D}^0\overline{\mathrm{D}}^{*0}\rangle+|\mathrm{D}^{*0}\overline{\mathrm{D}}^0\rangle]. \quad (8)$$

In fact, the negative sign should be correct.

Here we give a proof in the field theory. The interpolating currents for D, D^* and X mesons are

$$J_{X_{\mathrm{D}}}=\frac{1}{\sqrt{2}}(J_1-J_2)\ , \quad (9)$$

$$J_1=(\bar{u}^a\gamma_5 c^a)(\bar{c}^b\gamma^\mu u^b)\ , \quad (10)$$

$$J_2=(\bar{c}^a\gamma_5 u^a)(\bar{u}^b\gamma^\mu c^b)\ , \quad (11)$$

where a and b are color indices. Under the C parity transformation, J_1 changes to $-J_2$ and the sign of $J_{X_{\mathrm{D}}}$ does not change. Therefore, X_{D} corresponds to positive C parity, while $\widetilde{X}_D$ corresponds to negative C parity. This convention is opposite to that used in the literature. Such a result is consistent with $\hat{C}V\hat{C}^{-1}=-\overline{V}$. One may understand this choice from the $SU(4)$ symmetry where the C-parity transformation coefficient can be chosen as the C-parity of ρ^0.

In the actual calculation, we found $\widetilde{X}_{\mathrm{D}}$ would be much looser than X_{D}[38]. In the following part, we study whether the bound state X_{D} exists with the potential model at the hadronic level.

3　S-wave $\mathbf{D^0\overline{D}^{*0}-D^{*0}\overline{D}^0}$ System

The procedure for our calculation is as follows[39]: (1) first, one should compose Lagrangians satisfying the chiral and heavy quark symmetries; (2) then we calculate scattering matrix elements; (3) one derives the potential in momentum space with Breit approximation and performs Fourier transformation to coordinate space; (4) finally, we get the binding energy by solving the Schrödinger equation.

In the heavy quark limit, charmed mesons form degenerate doublets. D and D^* mesons belong to the same doublet. The lagrangian used is very simple[40, 41],

$$\mathscr{L}=\mathrm{i}g\mathrm{Tr}\,[H_b \not{A}_{ba}\gamma_5\overline{H}_a]+g_\sigma\mathrm{Tr}\,[H\sigma\overline{H}], \quad (12)$$

where

$$H_a=\frac{1+\not{v}}{2}[P_a^{*\mu}\gamma_\mu-P_a\gamma_5], \quad (13)$$

$A^\mu_{ab}=\frac{1}{2}(\xi^\dagger\partial^\mu\xi-\xi\partial^\mu\xi^\dagger)_{\mathrm{ab}}=\frac{\mathrm{i}}{f_\pi}\partial^\mu\mathscr{M}_{ab}+\cdots$ with $\xi=\exp(\mathrm{i}\mathscr{M}/f_\pi)$, $f_\pi=132$ MeV and

$$\mathscr{M}=\begin{pmatrix}\frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & \pi^+ & K^+\\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & K^0\\ K^- & \overline{K}^0 & -\frac{2\eta}{\sqrt{6}}\end{pmatrix}. \quad (14)$$

We also present the part related with the sigma exchange interaction. In Ref. [40], the coupling constant $g=0.75$ was estimated roughly within the quark model. A different set of coupling constants can be found in Ref. [42]. With our notation, $g=0.6$[42]. In fact, the coupling constant g was studied using many theoretical approaches such as QCD sum rules[43—46]. Despite so many theoretical estimates of the coupling constant g, we use the value

$$g=0.59\pm0.07\pm0.01 \quad (15)$$

in this work. The above value was extracted by fitting the precise experimental width of D^{*}[47]. In order to estimate the values of the coupling constant g_σ, we compare the Lagrangian with that in Ref. [42] and get $g_\sigma=g_\pi/2\sqrt{6}$ with $g_\pi=3.73$.

With this lagrangian, we calculate the scattering matrix elements. The pion exchange occurs only in the crossed process while the sigma exchange only in the direct process (see Fig. 1).

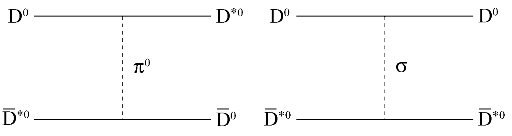

Fig. 1 The scattering of $\mathrm{D}^0-\overline{\mathrm{D}}^{*0}$ by exchanging the π and σ mesons.

The resulting potential has two parts (we missed a minus sign in the sigma meson exchange potential in Ref. [38]),

$$V(\boldsymbol{r}) = -g_\sigma^2\, Y_\sigma(\boldsymbol{r}) + \frac{g^2}{6f_\pi^2}\, Y_\pi(\boldsymbol{r}), \qquad (16)$$

where

$$Y_\sigma(\boldsymbol{r}) = \frac{1}{4\pi\, r}\, \mathrm{e}^{-m_\sigma r},$$

$$Y_\pi(\boldsymbol{r}) = -\delta(\boldsymbol{r}) - \frac{\mu^2}{4\pi r}\cos(\mu\, r) \qquad (17)$$

with $\mu = \sqrt{q_0^2 - m_\pi^2}$ and $q_0 = M_D^{*0} - M_D^0$. The relative sign between one sigma exchange potential (OSEP) and one pion exchange potential (OPEP) is determined by the relative sign in the wave function in Eq. (7). The sigma part is exactly Yukawa type. The pion part is obtained with the principal integration. The contact interaction should be regulated since $\delta(\boldsymbol{r})$ is an illegal operator for the numerical evaluation.

We use two approaches to regulate the potential. In the first approach, a monopole type form factor (FF) is introduced at each vertex,

$$F(q) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}, \qquad (18)$$

where $\Lambda \approx 1$ GeV denotes a phenomenological cutoff. m and q are the mass and the four-momentum of the exchanged meson respectively. In the second approach, we use the smearing technique,

$$V(\boldsymbol{r}) = \int V(\boldsymbol{r}')\delta(\boldsymbol{r} - \boldsymbol{r}')\mathrm{d}\boldsymbol{r}'$$

$$\delta(\boldsymbol{r} - \boldsymbol{r}') \to \left(\frac{\beta}{\pi}\right)^{3/2} \mathrm{e}^{-\beta(\boldsymbol{r}-\boldsymbol{r}')^2}, \qquad (20)$$

where $\sqrt{\beta} \approx 1$ GeV, corresponding to the short range cutoff, i. e., the short-distance structure is indiscriminate. Though these two approaches look different, they are essentially the same, that is, imposing a short-distance cutoff to improve the singularity of the effective potential.

The regulated potentials in the first approach are:

$$Y_\sigma(r) = \frac{1}{4\pi r}\left(\mathrm{e}^{-m_\sigma r} - \mathrm{e}^{-\Lambda r}\right) - \frac{\eta'^2}{8\pi\Lambda}\,\mathrm{e}^{-\Lambda r}, \quad (21)$$

$$Y_\pi(r) = -\frac{\mu^2}{4\pi r}\left[\cos(\mu\, r) - \mathrm{e}^{-\alpha r}\right] - \frac{\eta^2\alpha}{8\pi}\,\mathrm{e}^{-\alpha r}, \qquad (22)$$

where $\eta = \sqrt{\Lambda^2 - m_\pi{}^2}$, $\eta' = \sqrt{\Lambda^2 - m_\sigma{}^2}$ and $\alpha = \sqrt{\Lambda^2 - q_0^2}$. The potential in the second approach is

$$\begin{aligned} V(r)_{\text{smearing}} = {} & \frac{g_\sigma^2}{8\pi r}\mathrm{e}^{-\beta r^2}\left[\mathrm{e}^{\frac{(m_\sigma - 2\beta r)^2}{4\beta}}\,\mathrm{erf}\left(\frac{m_\sigma - 2\beta r}{2\sqrt{\beta}}\right) - \right. \\ & \left. \mathrm{e}^{\frac{(m_\sigma + 2\beta r)^2}{4\beta}}\,\mathrm{erf}\left(\frac{m_\sigma + 2\beta r}{2\sqrt{\beta}}\right)\right] - \\ & \frac{g^2}{6f_\pi^2}\left(\frac{\beta}{\pi}\right)^{3/2}\mathrm{e}^{-\beta r^2} - \frac{g^2\mu^2\mathrm{e}^{-\beta r^2}}{48 f_\pi^2 \pi r} \times \\ & \left[\mathrm{e}^{\frac{(2\beta r - \mathrm{i}\mu)^2}{4\beta}}\,\mathrm{erf}\left(\frac{2\beta r - \mathrm{i}\mu}{2\sqrt{\beta}}\right) + \text{c. c.}\right]. \end{aligned} \qquad (23)$$

We will illustrate our calculation for the case of the form factor. Fig. 2 gives the potentials. One sees the contribution from OSEP is small.

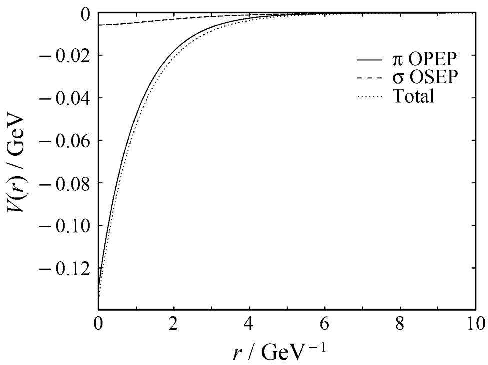

Fig. 2 The regulated potentials related with X(3872) in the case of FF. The solid line corresponds to OPEP. $g = 0.59$, $g_\sigma = 0.76$ and $\Lambda = 1.0$ GeV are used.

For the numerical evaluation, we first consider only OPEP. We present the results in Table 1. From that table, if the coupling constant g is fixed to be the experimental value $g = 0.59$, the possible bound state solution with a negative eigenvalue can only be found when $\Lambda > 5.6$ GeV. This requirement is much larger than the commonly used reasonable value ~ 1.0 GeV. In other words, the OPEP alone does not bind the $D^0\ \bar{D}^{*0}$ pair into a molecular state with the physical values of g and Λ.

When we also consider the sigma contribution, the cutoff is a little smaller. One may find the numerical results in Table 2. A cutoff around 5.5 GeV is much larger than the cutoff usually used. So we conclude that no S-wave bound state exists in the $D^0\overline{D}^{*0}$ system with a realistic coupling constant and a reasonable cutoff around 1 GeV. In fact, the results from the smearing case confirm this conclusion.

Table 1 Solutions for various g and Λ in the case of FF with OPEP. Lowest eigenvalues between −5.0 MeV and −0.1 MeV are selected

Coupling constant	Λ / GeV	E_0/ MeV	$r_{\rm rms}$/fm	$r_{\rm max}$/fm
g=0.59	5.7	−0.3	5.8	0.2
	5.8	−2.1	2.2	0.2
g=0.7	4.1	−0.8	3.7	0.2
	4.2	−3.2	1.8	0.2
g=0.8	3.1	−0.1	8.7	0.4
	3.2	−1.6	2.6	0.3
	3.3	−4.9	1.5	0.2
g=0.9	2.5	−0.6	4.2	0.4
	2.6	−2.9	2.0	0.3
g=1.0	2.0	−0.2	7.2	0.5
	2.1	−1.8	2.5	0.4

Table 2 Solutions for various g and Λ in the case of FF with total potential. Lowest eigenvalues between −5.0 MeV and −0.1 MeV are selected. Here g_σ=0.76 is used.

Coupling constant	Λ / GeV	E_0/ MeV	$r_{\rm rms}$/fm	$r_{\rm max}$/fm
g=0.59	5.4	−0.1	10.5	0.4
	5.5	−1.1	3.1	0.3
	5.6	−3.3	1.8	0.2
g =0.7	3.9	−0.7	3.9	0.3
	4.0	−2.6	2.0	0.2
g=0.8	3.0	−0.6	4.1	0.4
	3.1	−2.6	2.1	0.3
g=0.9	2.4	−0.8	3.7	0.4
	2.5	−3.0	1.9	0.3
g=1.0	1.9	−0.1	9.2	0.6
	2.0	−1.4	2.8	0.4
	2.1	−4.4	1.6	0.3

4 Bottom Analogy

Now we study the bottom analog of $X_{\rm D}$. The flavor wave function is

$$|X_{\rm B}\rangle=\frac{1}{\sqrt{2}}\left[|{\rm B}^+{\rm B}^{*-}\rangle-|{\rm B}^{*+}{\rm B}^-\rangle\right]. \quad (24)$$

Because of the heavier masses of the B mesons, the kinematic term has relatively small contribution. The possibility of forming a bound state is larger than that in the $\overline{\rm D}{\rm D}^*$ system. OSEP remains the same as $X_{\rm D}$. But the expression of the OPEP is different now. Because $q_{\rm B}{}^0=m_{{\rm B}^*}-m_{\rm B}<m_\pi$, the potential can be strictly derived and does not have an imaginary part. Following the former procedure, we get the regulated potential,

$$Y_\pi(r)=\frac{\mu_{\rm B}^2}{4\pi r}\left[{\rm e}^{-\mu_{\rm B}r}-{\rm e}^{-\alpha_{\rm B}r}\right]-\frac{\eta^2\alpha_{\rm B}}{8\pi}\,{\rm e}^{-\alpha_{\rm B}r}, \quad (25)$$

where $\alpha_{\rm B}=\sqrt{\Lambda^2-(q_{\rm B}^0)^2}$ and $\eta=\sqrt{\Lambda^2-m_\pi^2}$.

The numerical results for the one pion exchange case indicate the reasonable minimum cutoff is much smaller (around 2 GeV) if we use the coupling constant $g=0.59$. When the sigma exchange potential is included, the cutoff becomes smaller further. The cutoff around 2 GeV is acceptable. So we can conclude that the formation of an S-wave ${\rm B}\overline{\rm B}^*$ molecule is possible. In effect, the results from the smearing case support this conclusion. If this molecule does exist, it should be rather stable since ${\rm B}^*$ does not decay through strong interaction. This state may be found in the ${\rm B}\overline{\rm B}\gamma$ channel and the $\gamma\pi\pi$ channel.

5 Summary

In short summary, we have performed a dynamical study of $D^0\overline{D}^{*0}$ system in the mature meson exchange framework. This preliminary work disfavors the molecular assumption for X(3872) if only considering pion and sigma exchanges. On the other hand, the formation of an S-wave ${\rm B}\overline{\rm B}^*$ molecule is possible. To understand whether X(3872) is a molecular state, much more work is needed[48].

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