T_{cc} states of D^*D^* and $D^*_sD^*$ molecular nature

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Summary. — The newly observed T_{cc} state can be explained as a molecular state of D^*D in the chiral unitary approach. An extension to D^*D^* and $D^*_sD^*$ systems in the $J^P = 1^+$ will be discussed in the present work. We make predictions that D^*D^* system leads to a bound state with a binding of the order of MeV and similar width, while the $D^*_sD^*$ system develops a strong cusp around threshold.

1. – Motivation

The newly observed T_{cc} state is close to the D^*D threshold and the width is very small [1]. This state can be explained as a molecular state of D^*D in the chiral unitary approach [2], both the width and the $D^0D^0\pi^+$ mass distribution are in remarkable agreement with the experiment [1]. In the theoretical framework of D^*D system [2], the chiral unitary coupled channel approach ($D^{*+}D^0$, $D^{*0}D^+$) are utilized and the interaction was obtained from exchange of vector mesons in a straight extrapolation of the local hidden gauge approach. This approach has been successfully applied to the charm sector [3], in which the only parameter was a cutoff regulator in the Bethe-Salpeter equation.

Encouraged by this D^*D work, we make an extension of the above case to D^*D^* and $D^*_sD^*$ systems [4]. There are three reasons for the extension. First, heavy quark spin symmetry allows to relate the D and D^* sectors. Second, it was ever found that the D^*D^* system in $I = 0, J^P = 1^+$, and the $D^*_sD^*$ system in $I = \frac{1}{2}, J^P = 1^+$, both cases have attractive potentials, strong enough to support bound states [5]. Third, the new T_{cc} experimental information can provide valuable information to fix the regulator of the meson-meson loop function [1].

In the present work, since the vector-vector (VV) states with 1^+ cannot decay to pseudoscalar-pseudoscalar (PP) if we want to conserve spin and parity, thus we consider instead the decay into vector-pseudoscalar (VP) channel which will give a width to the bound states that we find.

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2. – Formalism

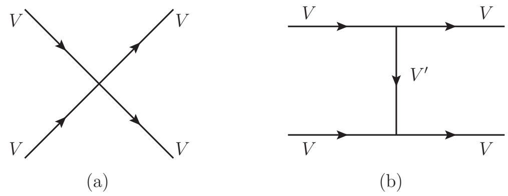

Fig. 1. – Terms for the VV interaction: (a) contact term; (b) vector exchange

The mechanisms for the interaction are depicted in Fig. 1, and the corresponding Lagrangians are given

$$\mathcal{L}^{(c)} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle\,, \quad \mathcal{L}_{VVV} = ig\,\langle V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu\rangle\,, \tag{1}$$

with $g = \frac{M_V}{2f}$ $(M_V = 800\,\mathrm{MeV},\ f = 93\,\mathrm{MeV})$, where$\mathcal{L}^{(c)}$ is a contact term and $\mathcal{L}_{VVV}$ stands for the three vector vertex. The V_μ is the $q\bar{q}$ matrix written in terms of vector mesons

$$V_\mu = \begin{pmatrix} \frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu . \tag{2}$$

The interaction between vectors exchanging vector mesons will generate the bound states or resonances [6, 7]. Extrapolated to the charm sector, it predicted the pentaquark states [3], which were later confirmed by the LHCb experiments [8, 9].

From Refs. [6, 7], we can obtain the potential for D^*D^* system

$$V_{D^*D^*\to D^*D^*} = \frac{g^2}{4}(\frac{2}{m^2_{J/\psi}} + \frac{1}{m^2_\omega} - \frac{3}{m^2_\rho})\{(p_1+p_4).(p_2+p_3) + (p_1+p_3).(p_2+p_4)\}\,, \tag{3}$$

and potential for $D_s^*D^*$ system

$$V_{D_s^*D^*\to D_s^*D^*} = -\frac{g^2(p_1+p_4).(p_2+p_3)}{m^2_{K^*}} + \frac{g^2(p_1+p_3).(p_2+p_4)}{m_{J/\psi^2}}\,. \tag{4}$$

We further solve the Bethe-Salpeter equation

$$T = [1 - VG]^{-1}V \tag{5}$$

with G the loop function which can be regularized by the value of the cutoff.

In order to obtain the imaginary part for $D^*D^* \to D^*D$ $(I = 0)$ case, we consider total 32 decay box diagrams In Fig. 2, where the meaning of the right-hand side is that the set of diagrams must be completed exchanging the vectors $D^*(p_3) \leftrightarrow D^*(p_4)$ in the final state, given the identity of the two D^* in the final state and when $p_3, \boldsymbol{\epsilon}_3 \leftrightarrow p_4, \boldsymbol{\epsilon}_4$ ($\boldsymbol{\epsilon}_i$ is the polarization vector of particle i) are exchanged, there is a relative (-1) sign[4].

The isospin doublets $(D^+, -D^0)$ and $(D^{*+}, -D^{*0})$

$$|D^*D^*, I=0\rangle = -\frac{1}{\sqrt{2}}|D^{*+}D^{*0} - D^{*0}D^{*+}\rangle \,. \tag{6}$$

This D^*D^* system can decay into $D^{*+}D^0$ or $D^{*0}D^+$. We find some diagrams with the same structure and only the isospin coefficients are different, thus these diagrams can be classified into 4 kinds with weight of each kind of diagrams $\frac{1}{4}(1+2+2+4+4+2+2+1) = \frac{18}{4} = \frac{9}{2}$.

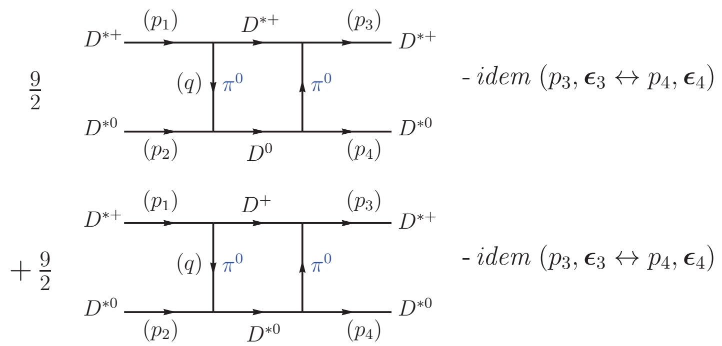

Fig. 2. – Diagrams to be calculated with their respective weights.

We find that two new vertices for the box diagrams will need to be evaluated. Finally, using the projectors into the different spin states of $J = 1, 2, 3$, $\mathcal{P}^{(0)}$,$\mathcal{P}^{(1)}$,$\mathcal{P}^{(2)}$, the product of all four vertices will be calculated [6]. Altogether for the $J^P = 1^+$ state, we obtain the contribution for the four diagrams, keeping the positive energy part of the propagators of the heavy particles and performing the q^0 analytically

$$\mathrm{Im}V_{\mathrm{box}} = -\frac{6}{8\pi}\frac{q^5}{\sqrt{s}}E_{D^*}^2(\sqrt{2}g)^2\left(\frac{G'}{2}\right)^2\left[\frac{1}{(p_2^0 - E_D(\boldsymbol{q}))^2 - \boldsymbol{q}^2 - m_\pi^2}\right]^2 F^4(q)F_{HQ}\,, \tag{7}$$

where

$$q = \frac{\lambda^{1/2}(s, m_{D^*}^2, m_D^2)}{2\sqrt{s}}, \qquad F(q) = e^{((q^0)^2 - \boldsymbol{q}^2)/\Lambda^2}, \qquad q^0 = p_1^0 - E_{D^*}(\boldsymbol{q}), \qquad E_{D^*} = \frac{\sqrt{s}}{2}\,,$$
$$F_{HQ} = \frac{m_{D^*}^2}{m_{K^*}^2}, \qquad G' = \frac{3\,g'}{4\pi^2 f}, \qquad g' = -\frac{G_V m_\rho}{\sqrt{2}f^2}, \qquad G_V = 55\,\mathrm{MeV}\,.$$

Next we continue to consider another decay box diagrams in Fig. 3 to obtain the imaginary part for $D_s^*D^* \to D_s^*D + D_sD^*$ case.

$$\begin{aligned}\mathrm{Im}V_{\mathrm{box}} = &-\frac{1}{3}\frac{1}{8\pi}\frac{1}{\sqrt{s}}(2g)^2\left(\frac{G'}{\sqrt{2}}\right)^2(E_1E_3 + E_2E_4)\\ &\times q^5\left[\frac{1}{(p_2^0 - E_{D_s}(\boldsymbol{q}))^2 - \boldsymbol{q}^2 - m_K^2}\right]^2 F^4(q)F_{HQ}\,,\end{aligned} \tag{8}$$

where

$$q^0 = p_2^0 - E_{D_s}(\boldsymbol{q}), \qquad q = \frac{\lambda^{1/2}(s, m_{D^*}^2, m_{D_s}^2)}{2\sqrt{s}}, \qquad p_2^0 = \frac{s + m_{D^*}^2 - m_{D_s^*}^2}{2\sqrt{s}}$$

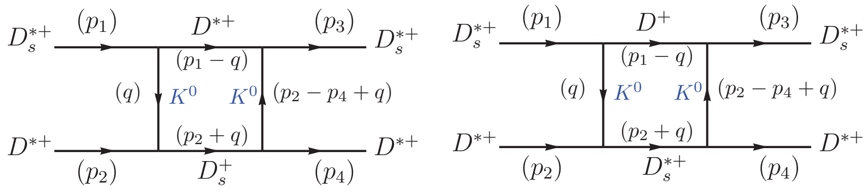

Fig. 3. – Diagrams for the decay of $D_s^{*+}D^{*+}$ into $D_s^{*+}D^+$ and $D_s^+D^{*+}$.

3. – Results

Now we will solve the Bethe-Salpeter equation

$$V \to V + i\,\mathrm{Im}V_{\mathrm{box}} \tag{9}$$

to obtain the T-matrix. Further by plotting the amplitudes of $|T|^2$, we obtain the mass of the state and its width.

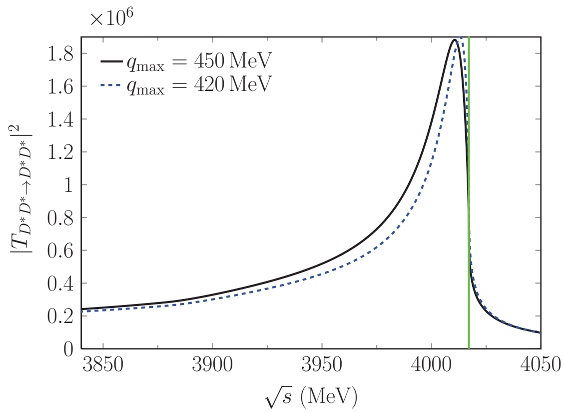

Fig. 4. – The amplitudes $|T|^2$ at $q_{\max} = 420$ MeV and $q_{\max} = 450$ MeV, the vertical line shows the threshold of D^*D at 4017.1 MeV.

In Fig. 4 we show the predictions for D^*D^* system, it is seen the bound states with binding of the order of the MeV, and the width of the D^*D^* system is much larger than the one of the T_{cc} state, since we have the decay channel D^*D, where there is a much larger decay phase space [4]. As noticed, the width of T_{cc} state is only $40 - 50$ keV, due to the very little phase space for $D^* \to D\pi$ decay [2].

In Fig. 5 we show the predictions for $D_s^*D^*$ system, in which no bound state is seen, instead, we find pronounced cusps at the $D_s^*D^*$ threshold. This is a consequence of the weaker potential compared to D^*D^*, because of the different factors of $ImV_{\rm box}$ from π exchange and kaon exchange, respectively.

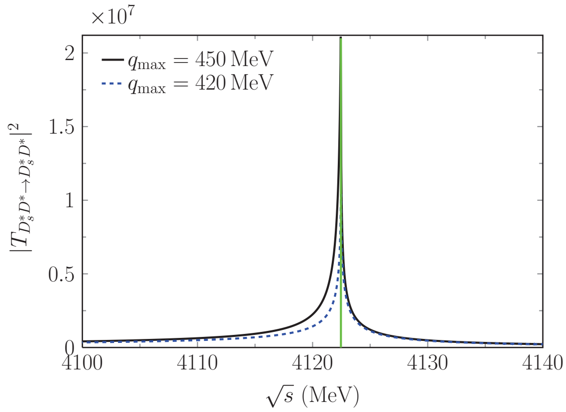

Fig. 5. – The amplitudes $|T|^2$ at $q_{\rm max} = 420$ MeV and $q_{\rm max} = 450$ MeV, the vertical line shows the threshold of $D_s^*D^*$ at 4122.46 MeV.

4. – Summary

Encouraged by the experiment of the T_{cc} state close to the D^*D threshold, which can be explained as a molecular state of D^*D in the chiral unitary approach, we made an extension to D^*D^* with $I = 0$ and $D_s^*D^*$ with $I = \frac{1}{2}$ systems to investigate the possible existence of bound states or resonances. We use the new experimental information from T_{cc} state to fix the cutoff and then evaluate the decay box diagrams to get the width. We find the bound state of D^*D^* system with a binding of the order of MeV and its width is much larger than the one of the T_{cc} state. The $D_s^*D^*$ system develops a strong cusp around threshold, and its width is much smaller than that of the D^*D^* state due to the different exchanges from pion and kaon, respectively.

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