CHARMED HADRON INTERACTIONS AND CORRELATION FUNCTIONS*

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We give predictions of the DD^* and $D\bar{D}^*$ correlation functions in high-energy collisions based on the pure hadronic molecule picture of T_{cc}^+ and $X(3872)$. The potentials of DD^* and $D\bar{D}^*$ are fixed based on the empirical data, and the momentum correlation functions of the D^0D^{*+} and $D^0\bar{D}^{*0}$ pairs are computed with the coupled-channel effects. Since the pole positions of T_{cc}^+ and $X(3872)$ are close to the D^0D^{*+} and $D^0\bar{D}^{*0}$ thresholds, scattering lengths are large in magnitude and the correlation functions show strong enhancement at small relative momenta. When the compact multiquark components are nonnegligible in T_{cc}^+ and $X(3872)$, the scattering length and the correlation function will be suppressed. Thus, comparison of the present predictions and the data to be measured in the near future will elucidate the nature of the exotic states.

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1. Introduction

Exotic hadrons including a $c\bar{c}$ or $cc(\bar{c}\bar{c})$ pair have been attracting huge interest of researchers. Starting from the first observation of $X(3872)(c\bar{c}q\bar{q})$ in 2003 [1], charmed pentaquark ($P_c(c\bar{c}qqq)$) states [2] and a doubly charmed tetraquark state ($T_{cc}^+(cc\bar{q}\bar{q})$) [3, 4] have been observed in addition to many X, Y, and Z states containing $c\bar{c}$ [5]. The masses of these hadrons deviate from the quark model predictions with $q\bar{q}$ and qqq configurations and are expected to contain additional quarks and anti-quarks. Some of them are manifestly exotic, *i.e.* minimum number of constituent quarks and anti-quarks is larger than three.

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While a bunch of studies have been devoted to understand these exotic states, their structure still remains to be elucidated. Several types of exotic hadron structure have been proposed. First, compact multiquark states including diquarks are expected. Since flavor-anti-symmetric and spin-singlet diquarks (good diquarks) gain energy proportional to $(m_{q1}m_{q2})^{-1}$ with m_{qi} being the quark mass in the diquark, $T_{cc}^{+}(cc\bar{u}\bar{d})$ is expected to have the structure of cc-$[\bar{u}\bar{d}]$, where $[\bar{u}\bar{d}]$ denotes a good (anti)diquark. Second, hadronic molecules should appear around the corresponding thresholds provided that the hadron–hadron interaction is attractive [6]. The deuteron is a weakly bound state of a proton and a neutron, and $\Lambda(1405)$ is considered to be a bound state of $\bar{K}N$ [7]. Since the distance between hadrons needs to be larger than the size of hadrons, hadronic molecule states are expected to appear around the corresponding hadron-pair thresholds. T_{cc}^{+} and $X(3872)$ masses are very close to the D^0D^{*+} and $D^0\bar{D}^{*0}$ thresholds, respectively, so they will have some hadronic molecule components. The third candidate mechanism of the "peak" in the invariant mass spectrum is the kinematical threshold effects [8]. When two channels couple, a cusp may appear in the invariant mass spectrum at the upper channel thresholds. The triangle singularity also tends to emerge at around the threshold. The fourth type of structure, the normal hadron component, should not be forgotten for the cryptoexotic hadrons, in which $q\bar{q}$ annihilation couples the $Q\bar{Q}q\bar{q}$ and $Q\bar{Q}$ states.

One of the goals of exotic hadron physics is to elucidate the structure of exotic hadrons and their candidates. It is also desired to determine the weights of the types of structure. For T_{cc}^{+}, the compact multiquark component is expected to dominate [9], while the hadronic molecule component may admix. For $X(3872)$, the $D\bar{D}^*$ molecule structure is proposed in many works [5]. The hadronic molecule picture may be supported by the recent observation by the CMS Collaboration [10], where the $X(3872)/\psi(2S)$ ratio was found to be around unity in Pb+Pb collisions in contrast to that around 0.1 in pp collisions. The above enhancement in heavy-ion collisions is consistent with the coalescence model prediction for loosely bound hadronic molecule states [11]. The normal $c\bar{c}$ component is also found to be necessary from the production cross section [12].

If we can determine the hadron–hadron interaction, it is possible to evaluate the hadronic molecule component fraction. While it is not possible to carry out DD^* or $D\bar{D}^*$ scattering experiment, recent developments in femtoscopy enable us to get the low-energy scattering parameters. For example, the D^-p correlation function data was actually measured and was found to suggest the existence of attractive interaction [13]. The DD^* and $D\bar{D}^*$ correlation functions will be also measurable by the ALICE Collaboration in the near future [14, 15].

In this article, we give predictions of the DD^* and $D\bar{D}^*$ correlation functions [16]. The hadron–hadron interaction is fixed to explain the empirical data in the pure hadronic molecule picture. The comparison with the correlation function data to be measured will enable us to access the deviation from the pure hadronic picture of T_{cc}^+ and $X(3872)$.

2. DD^* and $D\bar{D}^*$ correlation functions

We consider the coupled-channel potential in the channels of D^0D^{*+} and D^+D^{*0} for T_{cc}^+ and in the channels of $\{D^0\bar{D}^{*0}\} = (D^0\bar{D}^{*0} + \bar{D}^0D^{*0})/\sqrt{2}$ $(C=+)$ and $\{D^+D^{*-}\} = (D^+D^{*-} + D^-D^{*+})/\sqrt{2}$ $(C=+)$ for $X(3872)$. For simplicity, we only consider the potentials in the $I=0$ components. The mass difference among the isospin multiplets is taken into account, since the eigenenergies of T_{cc}^+ and $X(3872)$ measured from the lower threshold are smaller in magnitude than the isospin-breaking threshold differences. As shown in Fig. 1, there are several other channels below T_{cc}^+ and $X(3872)$. The decay effect on those channels is renormalized in the imaginary part of the potential. We adopt a spherical Gaussian potential with the range of one-pion exchange. The potential strength is determined to reproduce the empirical data. For the DD^* potential, we use the scattering length $a_0^{D^0D^{*+}} = -7.16 + i1.85$ fm, given in the experimental analysis in Ref. [4]. For the $D\bar{D}^*$ potential, we use the scattering length $a_0^{\{D^0\bar{D}^{*0}\}} = -4.23 + i3.95$ fm determined from the weak-binding relation, $a_0^{\{D^0\bar{D}^{*0}\}} = -i/\sqrt{2\mu E_h}$ [17], with

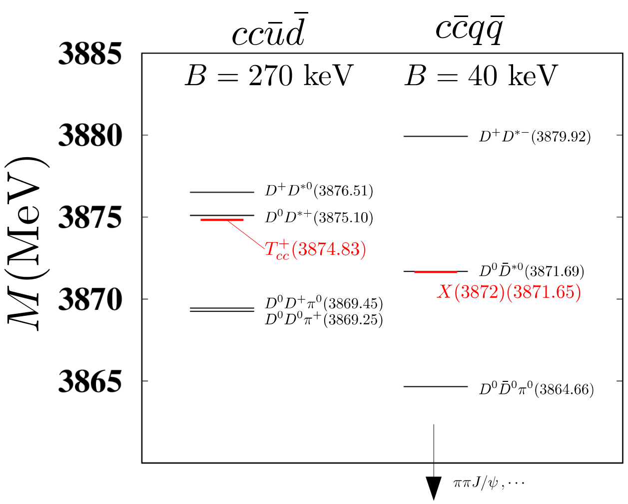

Fig. 1. Thresholds related to T_{cc}^+ and $X(3872)$, which are located 270 keV and 40 keV below the D^0D^{*+} and $D^0\bar{D}^{*0}$ thresholds, respectively.

$E_h = -0.04 - i0.60$ MeV being the eigenenergy from the $D^0\bar{D}^{*0}$ threshold [18]. We use here the high-energy physics convention of the scattering length, where $\delta \simeq a_0 q$ at low energies.

We have calculated the correlation functions of DD^* (D^0D^{*+} and D^+D^{*0}) and of $D\bar{D}^*$ ($D^0\bar{D}^{*0}$ and D^+D^{*-}) pairs with the coupled-channel effects by employing the Koonin–Pratt–Lednicky–Lyuboshitz–Lyuboshitz (KPLLL) formula [19, 20]. The source function is assumed to be a static Gaussian with the source size R, which ranges from ~ 1 fm for the high-multiplicity events in pp collisions to $\sim$ (5–6) fm for the central PbPb collisions.

In Fig. 2, we show the correlation functions of D^0D^{*+} and $D^0\bar{D}^{*0}$, lower mass pairs in DD^* and $D\bar{D}^*$, with source sizes $R = 1, 2, 3,$ and 5 fm. Both of the correlation functions show common source size dependence; strong enhancement at small relative momentum q for a small source and suppression at small q for a large source. This dependence is typical of the systems with a shallow bound state [20]. When the interaction is attractive, the wave function is enhanced in the interaction range and $r \lesssim |a_0|$, so the correlation function is enhanced for a small source. With a shallow bound state, the scattering length a_0 is negative, the wave function has a node around $r \simeq -a_0$, and then the wave function squared is suppressed on average with the source size $R \simeq |a_0|$. The cusp at the threshold of the upper channel (D^+D^{*0} and D^+D^{*-}) is more clearly seen in the $D^0\bar{D}^{*0}$ correlation function [16], where the wave function of D^+D^{*-} is enhanced by the Coulomb potential and the coupling effect appears more strongly.

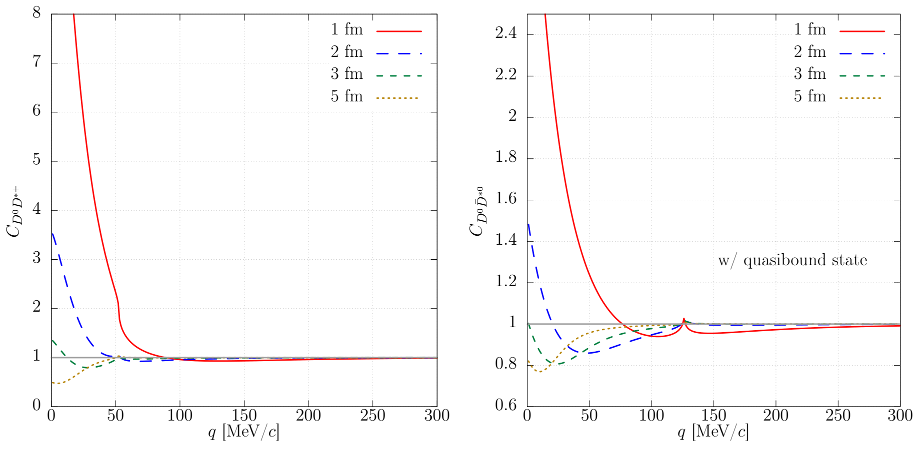

Fig. 2. The correlation functions of the D^0D^{*+} (left) and the $D^0\bar{D}^{*0}$ (right) pairs with the source size $R = 1, 2, 3,$ and 5 fm.

The results shown here are based on the assumptions that T_{cc}^{+} ($X(3872)$) is a hadronic molecule state, a quasibound state generated by the DD^* ($D\bar{D}^*$) interaction. In the case where T_{cc}^{+} and $X(3872)$ are not originated in the hadron–hadron interaction, the scattering length will deviate from the weak-binding relation, $a_0 = -i/\sqrt{2\mu E_h}$ [17], and the correlation functions show the weaker signal and source-size dependence.

3. Summary

We have investigated the DD^* and $D\bar{D}^*$ correlation functions [16]. The potentials in the $I = 0$ channel are assumed to have the Gaussian form with the one-pion-exchange range, while $I = 1$ potentials are ignored. The strengths are determined from the empirical data based on the pure hadronic molecule picture of T_{cc}^{+} and $X(3872)$. Our potential model looks too simple, but the correlation function at small relative momenta is mainly determined by the scattering lengths, the energy from the threshold, and the source size. Thus, provided that the coupled-channel effects with correct thresholds are taken into account, the present treatment may be regarded as a minimum reference model.

The calculated correlation functions show a typical behavior with a loosely bound state. At small relative momenta, the correlation function is strongly enhanced for a small source, while enhancement becomes smaller or suppression is seen for a larger source [16]. Comparison of the present predictions and the data to be measured [14, 15] will help us evaluate how much T_{cc}^{+} and $X(3872)$ contain hadronic molecular components, so-called the "compositeness" [17].

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