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Heavy $K^*(4307)$ Meson with Hidden Charm in the $KD\bar{D}^*$ System

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We report on a robust prediction of heavy K^* meson, which can be viewed as excited kaon state with hidden charm, through a study of the three-body system $KD\bar{D}^*$ using the fixed-center approximation to the Faddeev equations. The two-body interactions are stringently constrained by the experimental as well as theoretical investigations and leave little space for uncertainties. Concrete coupled channel three-body calculations yield the heavy K^* meson, $4307 \pm 2 - i(9 \pm 2)$ MeV with $I(J^P) = 1/2(1^-)$. Similar to the recent discovery of the pentaquark states with hidden charm content, our findings could inspire the experimental community to study the so far unexplored heavy strange physics, help improve our understanding of nonperturbative strong interactions.

KEYWORDS: Exotic hadrons, Three-body systems, Heavy quark symmetry

1. Introduction

A large number of hadronic states, especially the exotic XYZ states, provide an ideal playground to deepen our insights into the nature of the low-energy quantum chromodynamics (QCD) [1, 2]. Recently, the exotic hadrons with the open/hidden heavy quark components at energies of $4 \sim 5$ GeV, such as $X(3872)$, $Z_c(3900)$, $P_c(4380)$, and $P_c(4450)$, have attracted great attention from the experimental and theoretical physicists [3,4]. However, in the strange sector, there is no experimental data available on heavy K or K^* meson states around this energy region, leaving the heavy strange physics experimentally unexplored.

In Ref. [5], we explored the possibility of such heavy K^* meson in the $KD\bar{D}^*$ system. This is a unique system, in which all the two-body interactions, KD, $K\bar{D}^*$, and $D\bar{D}^*$, are stringently constrainted by a large number of experimental ($D^*_{s0}(2317)$, $D^*_{s1}(2460)$, $X(3872)$, and $Z_c(3900)$) as well as the lattice QCD data. Using the so-called fixed-center approximation (FCA) [6] to the Faddeev equations, which can be reliably applied to the $KD\bar{D}^*$ system, we find a heavy K^* meson around 4307 MeV with the hidden charm.

2. Formalism

The general criteria of fixed center approximation to the Faddeev equations is that the mass of the third particle P_3 should be smaller than a stable cluster composed of the two other particles P_1 and

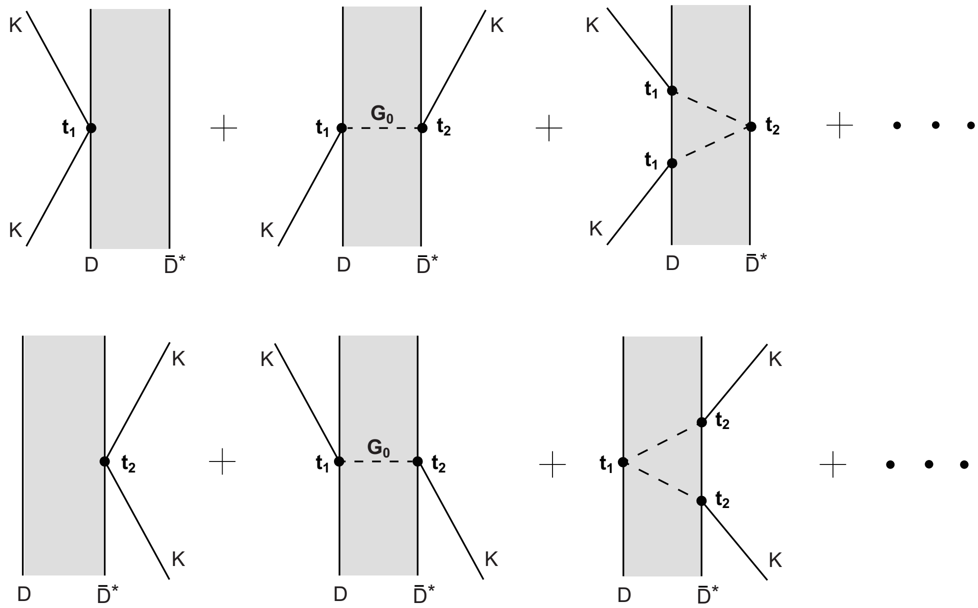

Fig. 1. Interaction of $KD\bar{D}^*$ system in the FCA of the Faddeev equations.

P_2. In this sense, we can freeze P_1 and P_2 as a cluster and simplify the coupled three-body system to the effective two-body (P_3-cluster) system. For the $KD\bar{D}^*$ system, we take the light kaon as the third particle to scatter off the cluster of $D\bar{D}^*$. The scattering process is presented in Fig. 1.

In the following, we briefly introduce the basic equations in the FCA framework. The details can be found in Ref. [5]. The total scattering amplitude is decomposed into two Faddeev partitions,

$$\begin{aligned} T &= T_{31} + T_{32}, \\ T_{31} &= t_{31} + t_{31}G_0t_{32} + t_{31}G_0t_{32}G_0t_{31} + \cdots = t_{31} + t_{31}G_0T_{32}, \\ T_{32} &= t_{32} + t_{32}G_0t_{31} + t_{32}G_0t_{31}G_0t_{32} + \cdots = t_{32} + t_{32}G_0T_{31}, \end{aligned} \tag{1}$$

where the two-body amplitudes, t_{31} and t_{32}, are the functions of the isospin 0 and 1 s-wave interactions of the KD and $K\bar{D}^*$ subsystems [7,8]. The loop function G_0 is the K propagator inside the $D\bar{D}^*$ cluster with mass M_c,

$$G_0 = \frac{1}{2M_c}\int \frac{d^3\boldsymbol{q}}{(2\pi)^3}\frac{F(\boldsymbol{q})}{q^{0\,2} - \boldsymbol{q}^2 - m_K^2 + i\epsilon}, \tag{2}$$

with the on-shell energy of the kaon, q_0, in the center-of-mass frame of the kaon and the cluster. The form factor of $D\bar{D}^*$ cluster, $F(\boldsymbol{q})$ is introduced to take into account the molecular dynamics of the s-wave cluster,

$$F(\boldsymbol{q}) = \frac{1}{\mathcal{N}}\int_\Omega d^3\boldsymbol{p}\, f(\boldsymbol{q})\, f(\boldsymbol{p}-\boldsymbol{q}), \quad \Omega := \{|\boldsymbol{p}|, |\boldsymbol{p}-\boldsymbol{q}| \le \Lambda\}, \tag{3}$$

where $f(\boldsymbol{p})$ denotes as

$$f(\boldsymbol{p}) = \frac{1}{\omega_D(\boldsymbol{p})\omega_{\bar{D}^*}(\boldsymbol{p})}\frac{1}{M_c - \omega_D(\boldsymbol{p}) - \omega_{\bar{D}^*}(\boldsymbol{p})}, \tag{4}$$

and the normalization factor is $\mathcal{N} = F(\boldsymbol{q} = \boldsymbol{0})$. It is worth noting that the three-momentum cutoff Λ is chosen to be the same as the cutoff used to regularize the $D\bar{D}^*$ loop to get the cluster.

In the $K[D\bar{D}^*]$ system, since both of the $X(3872)$ and $Z_c(3900)$ states can be produced from the $D\bar{D}^*$ subsystem [9,10], one has to consider $KX(3872)$ and $KZ_c(3900)$ as the coupled channels, which

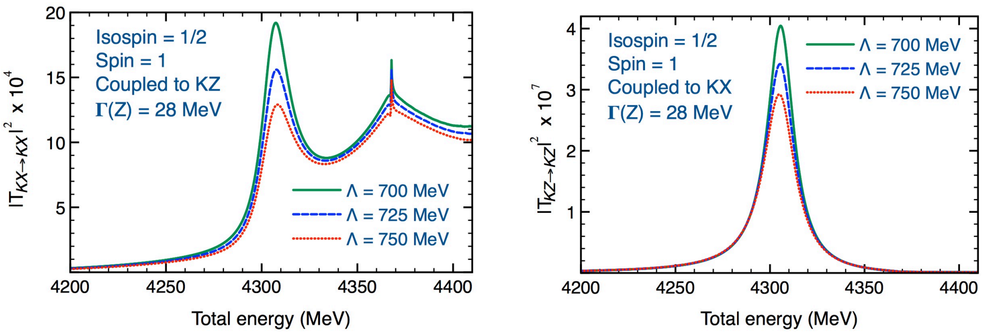

Fig. 2. Modulus squared of the KX and KZ scattering amplitudes in $I = 1/2$ with different cutoffs. A cusp related to the three-body $KD\bar{D}^*$ threshold is observed in the $KX \to KX$ amplitude.

conserve the total isospin of the three-body system. As proposed in Ref. [5], we introduce the 2×2 matrix for the two-body amplitudes, t_{31} and t_{32}, in the FCA Eq. (1),

$$t_{31} = \begin{pmatrix} (t_{31})_{11} & (t_{31})_{12} \\ (t_{31})_{21} & (t_{31})_{22} \end{pmatrix}, \quad t_{32} = \begin{pmatrix} (t_{32})_{11} & (t_{32})_{12} \\ (t_{32})_{21} & (t_{32})_{22} \end{pmatrix}, \tag{5}$$

where the element (11) denotes $KX \to KX$, the element (12) $KX \to KZ_c$, and so on. The explicit expressions of t_{31} and t_{32} can be found in Ref. [5]. The corresponding loop function G_0 is also a matrix in the coupled channel space,

$$G_0 = \begin{pmatrix} (G_0)_{11} & 0 \\ 0 & (G_0)_{22} \end{pmatrix}. \tag{6}$$

Finally, the total T-matrix appearing in Eq. (1) can be rewritten as a 2×2 matrix in the coupled-channel space,

$$T = T_{31} + T_{32} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}. \tag{7}$$

3. Results and discussion

In the numerical evaluation, the two-body amplitudes, t_{31} and t_{32}, as the only input of the FCA equations, are determined using the heavy quark symmetry in the chiral unitary approach. The s-wave interactions of KD and $K\bar{D}^*$ systems are fixed through the $D^*_{s0}(2317)$ and $D^*_{s1}(2460)$ resonances, as given in Refs. [7, 8]. The momentum cutoff Λ in the form factor is fixed as ~ 700 MeV [9, 10] with varying up to 750 MeV to evaluate the uncertainties. We take the width of $Z_c(3900)$ state as $\Gamma_{Z_c} = 28$ MeV. Through solving the FCA equations in couple channel, the modulus squared of the KX and KZ_c scattering amplitudes in $I = 1/2$ are shown in Fig. 2. The mass and width of the heavy K^* meson in the KX configuration is $M - i\Gamma/2 = (4308 \pm 1) - i(8 \pm 1)$ MeV, and of the KZ_c configuration is $M - i\Gamma/2 = (4306 \pm 1) - i(9 \pm 1)$ MeV. After averaging, the mass of the K^* meson is 4307 ± 2 MeV with a width of 9 ± 2 MeV. Interestingly, our prediction is consistent with the result of Ref. [11], where a very different dynamics for the $KD\bar{D}^*$ system is applied to solve the Schrödinger equation. We also note that the magnitude of the squared amplitude in the KZ_c configuration is around 200 times larger than that found in the KX configuration.

4. Conclusion

The heavy $K^*(4307)$ meson with hidden charm and strangeness is predicted in the $KD\bar{D}^*$ system via solving the Faddeev equations with the fixed center approximation. Since the two-body interactions are stringently constrained by the observed $D_{s0}^*(2317)$, $D_{s1}^*(2460)$, $X(3872)$, and $Z_c(3900)$, our predicted $K^*(4307)$ could be observed in experimental investigations, such as in the BaBar, LHCb facilities. Through the valuable discussion with the experimental experts during the conference, we are working on the $K^*(4307)$ producing process [12]. Furthermore, along this line, the possible bound states with hidden bottom are also reported in the $\bar{K}^{(*)}B^{(*)}\bar{B}^{(*)}$ systems [13]. We expect that our studies [5, 12, 13] will arouse interest to the hadronic states with hidden charm/bottom in the strange sector.

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