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Long-distance structure of the $X(3872)$

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Abstract. We investigate heavy quark symmetries for heavy meson hadronic molecules, and explore the consequences of assuming the $X(3872)$ and $Z_b(10610)$ as an isoscalar $D\bar{D}^*$ and an isovector $B\bar{B}^*$ hadronic molecules, respectively. The symmetry allows to predict new hadronic molecules, in particular we find an isoscalar 1^{++} $B\bar{B}^*$ bound state with a mass about 10580 MeV and the isovector charmonium partners of the $Z_b(10610)$ and the $Z_b(10650)$ states. Next, we study the $X(3872) \to D^0\bar{D}^0\pi^0$ three body decay. This decay mode is more sensitive to the long-distance structure of the $X(3872)$ resonance than its $J/\psi\pi\pi$ and $J/\psi 3\pi$ decays, which are mainly controlled by the short distance part of the $X(3872)$ molecular wave function. We discuss the $D^0\bar{D}^0$ final state interactions, which in some situations become quite important. Indeed in these cases, a precise measurement of this partial decay width could provide precise information on the interaction strength between the $D^{(*)}\bar{D}^{(*)}$ charm mesons.

1. Heavy quark symmetries and hidden charm meson molecules

Heavy hadron molecules are a type of exotic hadron theorized more than thirty years ago [1, 2]. Their main component is a pair of heavy hadrons instead of a quark–antiquark pair. The experimental advances in heavy quarkonium spectroscopy have identified several molecular candidates among the recently observed XYZ states. The most promising ones are the $X(3872)$ [3] and the twin $Z_b(10610)$ and $Z_b(10650)$ states, to be called Z_b and Z_b', respectively [4, 5]. Among many different interpretations of the $X(3872)$, the one assuming it to be[1] a $\left(D\bar{D}^* - D^*\bar{D}\right)/\sqrt{2}$, hadronic molecule with quantum numbers $J^{PC} = 1^{++}$ [6] is the most promising. Heavy quark symmetries deduced from QCD provide new insights into the hadron spectrum. Thus, heavy quark spin symmetry (HQSS) implies that molecular states may appear in HQSS multiplets. From heavy flavor symmetry (HFS), we know that the interaction among heavy hadrons is roughly independent on whether they contain a charm or a bottom quark. Combining both HQSS and HFS, various partners of the $X(3872)$ and the isovector $Z_b'^{s}$ states can be predicted [7, 8, 9, 10, 11, 12, 13, 14]. Some of these predictions from [14]

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[1] From now on, when we refer to $D^0\bar{D}^{*0}, D^+D^{*-}$, or in general $D\bar{D}^*$ we are actually referring to the combination of these states with their charge conjugate ones in order to form a state with well-defined C-parity.

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are collected in table 1. Moreover, owing to heavy antiquark-diquark symmetry, the doubly heavy baryons have approximately the same light-quark structure as the heavy antimesons. As a consequence and thanks to this approximate symmetry the existence of a heavy meson-antimeson molecules implies the possibility of a partner composed of a heavy meson and a doubly-heavy baryon (triply-heavy pentaquarks) [19]. Indeed, HQSS heavily constrains also the low-energy interactions among heavy hadrons [8, 10, 12, 13, 20]. As long as the hadrons are not too tightly bound, they will not probe the specific details of the interaction binding them at short distances. Moreover, each of the constituent heavy hadrons will be unable to see the internal structure of the other heavy hadron. This separation of scales can be used to formulate an effective field theory (EFT) description of hadronic molecules [10, 12] compatible with the approximate nature of HQSS. At leading order (LO) the EFT is particularly simple and it only involves energy-independent contact range interactions, since pion exchanges and coupled-channel effects can be considered subleading [12]. Thus, at very low energies, the interaction between a heavy and anti-heavy meson ($D^{(*)}\bar{D}^{(*)}$ or $B^{(*)}\bar{B}^{(*)}$) can be accurately described just in terms of a contact-range potential. The LO Lagrangian respecting HQSS contains four independent terms in the SU(3) flavor limit [13]. These are determined by the isoscalar C_{0A} and C_{0B} and the isovector C_{1A} and C_{1B} low energy constants (LEC's). The contact interaction potential is used as kernel of a two body elastic Lippmann-Swinger equation (LSE). The LSE shows an ill-defined ultraviolet (UV) behaviour, and it requires a regularization and renormalization procedure (we employ a standard Gaussian regulator as in [13, 14]). Bound states ($D^{(*)}\bar{D}^{(*)}$ or $B^{(*)}\bar{B}^{(*)}$ molecules) correspond to poles of the T-matrix below threshold on the real axis in the first Riemann sheet of the complex energy.

If we assume that the $X(3872)$ and the isovector $Z_b(10610)$ resonances are $\left(D\bar{D}^* - D^*\bar{D}\right)/\sqrt{2}$ and $\left(B\bar{B}^* + B^*\bar{B}\right)/\sqrt{2}$ bound states, respectively, and use the isospin breaking information of the decays of the $X(3872)$ into $J/\psi\pi\pi$ and $J/\psi\pi\pi\pi$, we can determine three linear combinations among the four LECs C_{0A}, C_{0B}, C_{1A} and C_{1B} with the help of HQSS and HFS [13, 14]. Note the complex isospin dynamics of the $X(3872)$ state implied by the experimental ratio $\mathcal{B}_X = \Gamma\left[X \to J/\Psi\,\rho\right]/\Gamma\left[X \to J/\Psi\,\omega\right] = 1.3 \pm 0.5$ [21]. The isospin properties of the $X(3872)$ molecule are mainly determined by its mass, which is only few hundreds of keV below the $D^0\bar{D}^{*0}$ threshold, making relevant the around 8 MeV difference between the threshold of the neutral and of the charged (D^+D^{*-}) channels. Further details are discussed in [13, 22].

2. $X(3872) \to D^0\bar{D}^0\pi^0$ decay

As it is discussed in [23], in the hadronic molecular picture, the decay channels of the $X(3872)$ with a charmonium in the final state ($J/\psi\pi\pi$, $J/\psi 3\pi$, $J/\psi\gamma$ and $\psi'\gamma$) are mainly sensitive to the short distance part of the $X(3872)$ wave-function. This is because the heavy quarks of the $D\bar{D}^*$ meson pair have to recombine to get the charmonium in the final state. The transition from the charm–anti-charm meson pair into the J/ψ plus pions (or a photon), occurs at a distance much smaller than both the size of the $X(3872)$ as a hadronic molecule and the range of forces between the D and $\bar{D}^*$ mesons. However, in the case of the $X(3872) \to D^0\bar{D}^0\pi^0$ decay, one of the constituent hadrons (D^0) is in the final state and the rest of the final particles are products of the decay of the other constituent hadron ($\bar{D}^{*0}$) of the $X(3872)$ molecule. Thus, in this decay the relative distance between the $D\bar{D}^*$ mesons can be as large as allowed by the size of the $X(3872)$ resonance, since the final state is produced by the decay of the $\bar{D}^*$ meson instead of a rescattering transition. Actually, it can be proved that within some approximations, the $d\Gamma/d|\vec{p}_{D^0}|$ distribution is related to the $X(3872)$ wave-function $\Psi(\vec{p}_{D^0})$ [23].

To estimate the $X(3872) \to D^0\bar{D}^0\pi^0$ decay width, we have evaluated the diagrams depicted in figure 1. The tree level contribution corresponds to the mechanism depicted in the first diagram

Table 1. Heavy meson–heavy meson combinations having the same contact term as the $X(3872)$ and $Z_b(10610)$, and the predictions of the masses, which are understood to correspond to bound states except if we write "V" in parenthesis for denoting a virtual state. †: increasing the strength of the potential to account for the various uncertainties, the virtual pole evolves into a bound state. Masses are given (MeV units) for two UV regulators. For further details see [14].

$I(J^{PC})$	States	Thresholds	M ($\Lambda = 0.5$ GeV)	M ($\Lambda = 1$ GeV)	Measurements
$0(1^{++})$	$\frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D})$	3875.87	3871.68 (input)	3871.68 (input)	3871.68 ± 0.17 [15]
$0(2^{++})$	$D^*\bar{D}^*$	4017.3	4012^{+4}_{-5}	4012^{+5}_{-12}	?
$0(1^{++})$	$\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})$	10604.4	10580^{+9}_{-8}	10539^{+25}_{-27}	?
$0(2^{++})$	$B^*\bar{B}^*$	10650.2	10626^{+8}_{-9}	10584^{+25}_{-27}	?
$0(2^{+})$	D^*B^*	7333.7	7322^{+6}_{-7}	7308^{+16}_{-20}	?
$1(1^{+-})$	$\frac{1}{\sqrt{2}}(B\bar{B}^* + B^*\bar{B})$	10604.4	10602.4 ± 2.0 (input)	10602.4 ± 2.0 (input)	10607.2 ± 2.0 [4]
					10597 ± 9 [16]
$1(1^{+-})$	$B^*\bar{B}^*$	10650.2	10648.1 ± 2.1	$10648.1^{+2.1}_{-2.5}$	10652.2 ± 1.5 [4]
					10649 ± 12 [16]
$1(1^{+-})$	$\frac{1}{\sqrt{2}}(D\bar{D}^* + D^*\bar{D})$	3875.87	3871^{+4}_{-12} (V)	3837^{+17}_{-35} (V)	$3899.0 \pm 3.6 \pm 4.9$ [17]
					$3894.5 \pm 6.6 \pm 4.5$ [18]
$1(1^{+-})$	$D^*\bar{D}^*$	4017.3	4013^{+4}_{-11} (V)	3983^{+17}_{-32} (V)	?
$1(1^{+})$	D^*B^*	7333.7	$7333.6^{\dagger}_{-4.2}$ (V)	7328^{+5}_{-14} (V)	?

of this figure. The amplitude is fully determined by the $D^0\bar{D}^{*0}\pi$ vertex, the $X(3872)$ mass and its coupling constant to the neutral $D^0\bar{D}^{*0}$ channel, which is determined by the residue of the $T-$matrix element at the $X(3872)$ pole. We find [23] $\Gamma(X(3872) \to D^0\bar{D}^0\pi^0)_{\text{tree}} = 44.0^{+2.4}_{-7.2}\left(42.0^{+3.6}_{-7.3}\right)$ keV, where the values outside and inside the parentheses are obtained with UV cutoffs of $\Lambda = 0.5$ and 1 GeV, respectively, and the uncertainty reflects the uncertainty in the inputs ($M_{X(3872)}$ and the ratio of decay amplitudes for the $X(3872) \to J/\psi\rho$ and $X(3872) \to J/\psi\omega$ decays), and it is represented by the grey bands in figure 2.

The last two diagrams in figure 1 account for the $D\bar{D} \to D\bar{D}$ final state interaction (FSI) effects, which are considered by means of the appropriated linear combinations of the isoscalar and isovector $T-$matrices. Those are obtained by solving a LSE in coupled channels with a LO contact potential determined by the LEC's C_{0A}, C_{0B}, C_{1A} and C_{1B} introduced above [13, 23]. As mentioned, the inputs (masses of the $X(3872)$ and $Z_b(10610)$ resonances and the ratio of $X(3872) \to J/\psi\pi\pi$ and $X(3872) \to J/\psi\pi\pi\pi$ branching fractions) determine only three of the four couplings, that describe the heavy meson-antimeson S-wave interaction at LO in the heavy quark expansion. The value of the contact term parameter C_{0A} is undetermined, and thus the $D\bar{D}$ FSI effects on this decay are not fully determined. As can be seen in figure 2, these effects might be quite large, because for a certain range of C_{0A} values, a near-threshold isoscalar pole could be dynamically generated in the $D\bar{D}$ system [13, 12]. If the partial decay width is measured in future experiments, a significant deviation from the predicted value at tree level will indicate a FSI effect, which could eventually be used to extract the value of C_{0A}.

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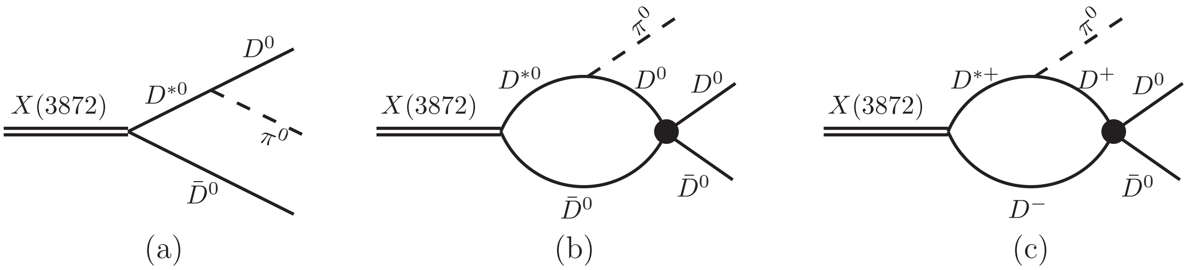

Figure 1. Feynman diagrams for the decay $X(3872) \to D^0\bar{D}^0\pi^0$. The charge conjugate channel is not shown but included in the calculations.

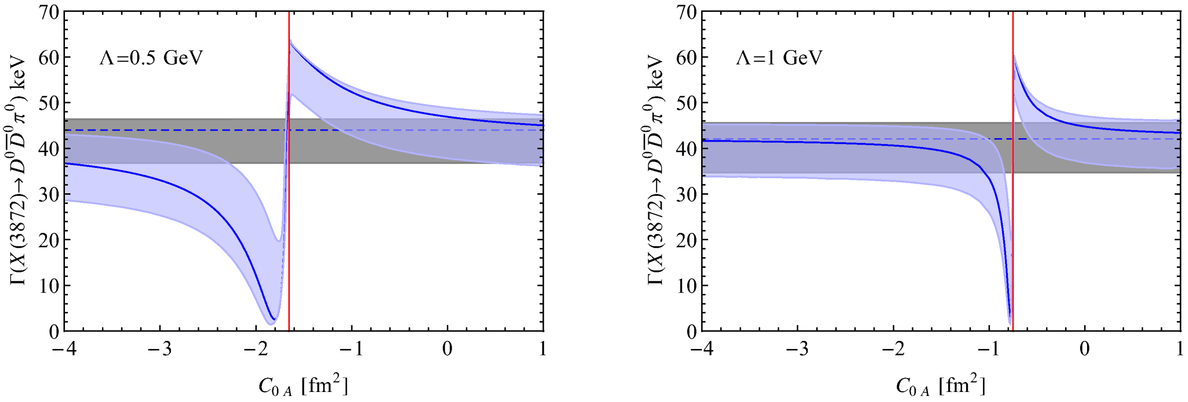

Figure 2. $X(3872) \to D^0\bar{D}^0\pi^0$ partial decay width as a function of C_{0A}. The UV cutoff is set to $\Lambda = 0.5$ GeV (1 GeV) in the left (right) panel. The blue error bands contain $D\bar{D}$ FSI effects, while the grey bands stand for the tree level predictions (see Ref [23] for details).

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