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# Charmonium content of the $X(3872)$

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Scenario for the $X(3872)$ is considered in which the state is generated dynamically in the $DD^* - c\bar{c}$ coupled–channel scheme. Flattè analysis of the data is presented, and the admixture of the $2^3P_1$ charmonium in the $X$ wavefunction is estimated

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Among new charmonium–like states found in last several years the $X(3872)$ meson is most well–studied. The $X$ was first observed in the mode $J/\psi\pi^+\pi^-$ [1], with dipion originated from the $\rho$. Later on, the state was seen in the $J/\psi\pi^+\pi^-\pi^0(J/\psi\omega)$ mode [2], so considerable isospin violation is present. Most probable quantum numbers for the $X(3872)$ is $1^{++}$, though $2^{-+}$ is not excluded. The studies of the $J/\psi\pi^+\pi^-$ mode yield the mass difference between the $X$ and $D^0\bar{D}^{*0}$ threshold of about $-0.4$ MeV. If the state is related to the $D^0\bar{D}^{*0}$ threshold, one therefore encounters a very small binding energy. The $X$ was searched and found in the $D^0\bar{D}^0\pi^0$ mode [3], [4] with the peak mass of about 3875 MeV, so the question was put of whether the state observed in the $J/\psi\pi^+\pi^-$ mode is the same as in the $D^0\bar{D}^0\pi^0$ one.

An important step in the attempt to answer this question was presented in the paper [5]. The Flattè–type parametrization both of the $J/\psi\pi^+\pi^-$ and $D^0\bar{D}^0\pi^0$ data was developed, and it was shown that the structure at 3875 MeV could be related to the $X(3872)$ state only if the $X$ were of dynamical nature, however, not as a bound state, but a virtual state. The analysis of the Ref. [5] points to the strong attraction in the $D^0\bar{D}^{*0}$ channel. However, it does not allow for any conclusions on the mechanism of this attraction, be it $t$–channel exchange force or short–range $s$–channel force due to coupling of bare state to hadronic channel.

It was suggested long ago [6] that one–pion exchange could be responsible for the formation of near–threshold states in the charmonia systems. It was shown that the one–pion exchange is attractive in the $1^{++}$ $D\bar{D}^*$ channel, and calculations [7, 8] confirm this. In these calculations pions enter in a form of a static potential. However, the $D^{*0}$ mass is very close to the $D^0\pi^0$ threshold, so that the pion can go on–shell. In this regard the doubts were cast in Ref. [9] on the ability of the one–pion exchange to provide enough binding in the $D\bar{D}^*$ system.

On the other hand, some admixture of a charmonium component should be present in the wavefunction of the $X$, and this charmonium component should be dominated by the $2^3P_1\chi'_{c1}$ configuration as it is somewhere close to the mass range under consideration. An extreme scenario for the $X$ was suggested in [10], where a microscopic model for $c\bar{c}-DD^{(*)}$ mixing was presented, with the $X$ generated as a virtual state in the $D\bar{D}^*$ channel together with the $2^3P_1$ charmonium resonance. The study of Ref. [10], while being model–dependent, revealed a very peculiar feature of the $1^{++}$ charmonium: in any reasonable quark model its coupling to $D\bar{D}^*$ is very large, much larger than for other $P$–wave charmonia.

The *bona fide* charmonia (such as $J/\psi$, $\psi'$ and $\chi_{c1}$) are known to be produced copiously in the $B\to K$ decay, with branching fractions of several units of $10^{-4}$ [11]. The $X$ is produced in the reaction $B\to KX\to KD^0\bar{D}^0\pi^0$ with the branching fraction of about $10^{-4}$, not too small in comparison to a branching fraction for $\chi_{c1}$; the world average for the latter is [11]

$$Br(B\to K\chi_{c1}) = (4.9\pm 0.5)\cdot 10^{-4}. \qquad (1)$$

For a pure molecule, the branching fraction $B\to KX$ was estimated in [12] to be less than $10^{-5}$. So it seems quite reasonable to assume that it is the $c\bar{c}$ component of the $X$ which is responsible for the $X$ production in $B$ meson decay.

In the present paper the data on $B\to KX(3872)$ are analysed in the framework of $DD^*-c\bar{c}$ coupled–channel model. As shown in Ref. [13], the low–energy limit of this model yields the Flattè formulae for the scattering amplitudes. The $B\to D^0\bar{D}^0\pi^0$ differential rate in the Flattè approximation takes the form

$$\frac{dBr(B\to KD^0\bar{D}^0\pi^0)}{dE}=0.62\mathscr{B}\frac{1}{2\pi}\frac{gk_1}{|D(E)|^2}, \tag{2}$$

and the $B\to K\pi^+\pi^-J/\psi$ rate is given by

$$\frac{dBr(B\to K\pi^+\pi^-J/\psi)}{dE}=\mathscr{B}\frac{1}{2\pi}\frac{\Gamma_{\pi^+\pi^-J/\psi}(E)}{|D(E)|^2}, \tag{3}$$

where

$$D(E)=\begin{cases} E-E_f-\dfrac{g\kappa_1}{2}-\dfrac{g\kappa_2}{2}+i\dfrac{\Gamma(E)}{2}, & E<0\\ E-E_f-\dfrac{g\kappa_2}{2}+i\left(\dfrac{gk_1}{2}+\dfrac{\Gamma(E)}{2}\right), & 0<E<\delta\\ E-E_f+i\left(\dfrac{gk_1}{2}+\dfrac{gk_2}{2}+\dfrac{\Gamma(E)}{2}\right), & E>\delta \end{cases} \tag{4}$$

and

$$\delta=M(D^+D^{*-})-M(D^0\bar{D}^{*0})=7.6\ \text{MeV},$$

$$k_1=\sqrt{2\mu_1E},\quad \kappa_1=\sqrt{-2\mu_1E},\quad k_2=\sqrt{2\mu_2(E-\delta)},\quad \kappa_2=\sqrt{2\mu_2(\delta-E)}.$$

Here $g$ is the coupling constant, $\mu_1$ and $\mu_2$ are the reduced masses in the $D^0\bar{D}^{*0}$ and $D^+D^{*-}$ channels respectively, and the energy $E$ is defined relative to the $D^0\bar{D}^{*0}$ threshold. The coefficient 0.62 in Eq. 2 corresponds to the $D^{*0}\to D^0\pi^0$ branching fraction. If one assumes the decay chain to be $B\to K\chi'_{c1}\to KX$, the parameter $\mathscr{B}$ can be identified with the branching fraction $B\to K\chi'_{c1}$.

The term $i\Gamma/2$ in Eq. (4) accounts for non-$D\bar{D}^*$ modes, with

$$\Gamma(E)=\Gamma_{\pi^+\pi^-J/\psi}(E)+\Gamma_{\pi^+\pi^-\pi^0J/\psi}(E)+\Gamma_0. \tag{5}$$

The $\pi^+\pi^-J/\psi$ and $\pi^+\pi^-\pi^0J/\psi$ modes were treated as in the Ref. [5]. $\Gamma_0$ is the bare width of the $\chi'_{c1}$. Indeed, if there is a charmonium admixture in the wavefunction of the $X$, it should bring in charmonium decay modes: radiative $\psi\gamma$, annihilation modes (into light hadrons), and $\chi_{c1}(3515)\pi\pi$ (the latter was estimated in [14] to be of order of 1 keV). If the full width of the $\chi_{c1}(3515)$ was a true guide, then one expects the width of the $\chi'_{c1}$ to be about $1-2$ MeV.

The data on $D^0\bar{D}^0\pi^0$ and $\pi^+\pi^-J/\psi$ modes were analysed under following constraints:

- $Br(B\to KX)<3.2\cdot10^{-4}$, the limit imposed by BaBar data [15]
- $\mathscr{B}=Br(B\to K\chi'_{c1})=(3\div7)\cdot10^{-4}$, i.e. of the same order of magnitude as for the $\chi_{c1}$, see Eq. 1
- $\Gamma_0=1\div2$ MeV

As in Ref. [5], two different assumptions on the $D^0\bar{D}^0\pi^0$ background were used. Namely, the combinatorial background was subtracted, and the rest of the background was taken either as unrelated to the $D^0\bar{D}^{*0}$ mode (case A), or as completely due to the $D^0\bar{D}^{*0}$ mode (case B). The analysis was performed for the data from charged $B$–meson decay modes only, as the signal from neutral $B$–meson decay is much less pronounced in all data sets. The results are shown in Fig. 1.

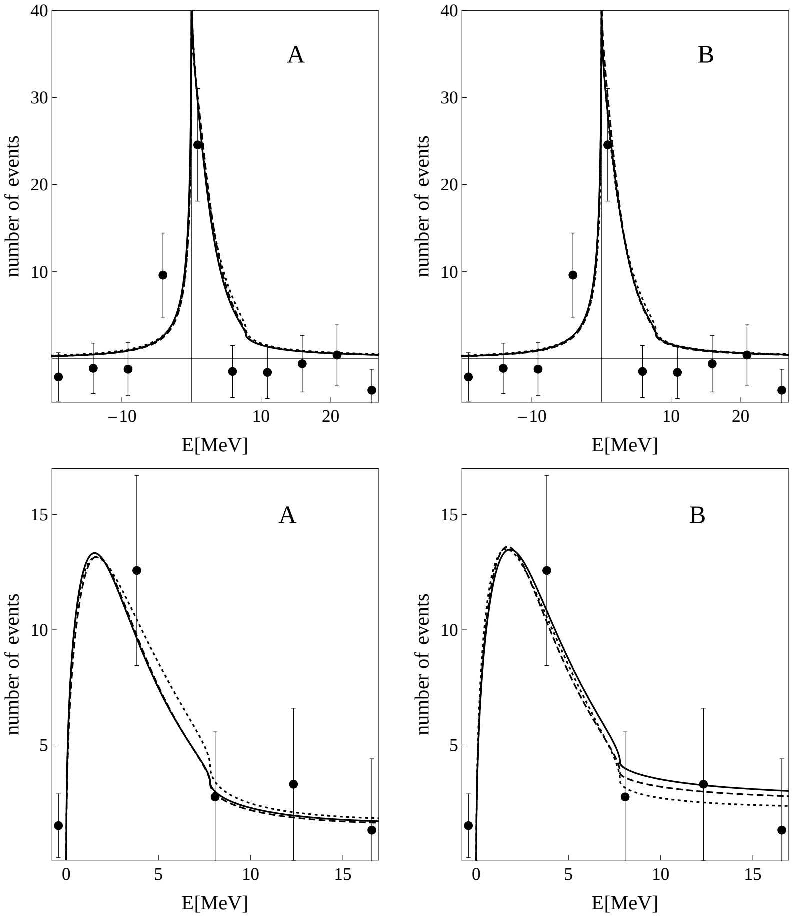

**Figure 1:** Upper plots: Fits to the differential rates for the $\pi^+\pi^- J/\psi$ channel measured by Belle [1], for $\Gamma_0 = 2$ MeV (solid) and $\Gamma_0 = 1$ MeV (dashed). The best fit of Ref. [5] is shown in dotted line. Lower plots: Corresponding fits for the differential rates in the $D^0\bar{D}^0\pi^0$ channel measured by Belle [16]. Fits A (B) correspond to the prescription A (B) for the $D^0\bar{D}^0\pi^0$ background (see text).

With the Flattè parameters found from the fit one can make use of the method suggested in [13] to estimate the admixture of a bare $\chi'_{c1}$ state in the wavefunction of the $X$. In the Flattè limit the probability $w(E)$ to find the bare state in the wavefunction of the physical state is

$$w(E) = \frac{1}{2\pi|D(E)|^2}(gk_1\Theta(E) + gk_2\Theta(E-\delta) + \mathit{\Gamma}). \tag{6}$$

The admixture $W$ of the $\chi'_{c1}$ charmonium in the resonance wavefunction defined as

$$W = \int_{-20MeV}^{20MeV} w(E)dE \tag{7}$$

in presented in Table 1.

Due to the constraint $Br(B \to KX) < 3.2 \cdot 10^{-4}$, with the inclusion of the extra non–$DD^*$ width the results remains similar to the ones given by the best fits of the Ref. [5]. Due to the constraint $\mathscr{B} < 7 \cdot 10^{-4}$, the fits are slightly (but not significantly) worse than the best fits. As seen from

| | $\Gamma_0$, MeV | $a$, fm | $W$ | $\mathscr{B}\cdot 10^4$ | $Br(B\to KX)\cdot 10^4$ |
|---|---|---|---|---|---|
| A | 1 | -3.51-i0.80 | 0.39 | 6.7 | 2.6 |
| A | 2 | -3.38-i1.30 | 0.42 | 7.0 | 2.9 |
| B | 1 | -3.57-i0.99 | 0.39 | 5.0 | 1.9 |
| B | 2 | -3.21-i1.27 | 0.41 | 5.5 | 2.3 |

**Table 1:** The values of $D^0\bar{D}^{*0}$ scatering length $a$, near–threshold fraction of spectral density $W$, $\mathscr{B} = Br(B \to K\chi'_{c1})$ and $Br(B\to KX)$ for various fits.

Table 1, the real part of the $D^0\bar{D}^{*0}$ scattering length for all fits is large nd negative, signalling the presence of virtual state.

To conclude, the data on $D^0\bar{D}^0\pi^0$ and $J/\psi\pi^+\pi^-$ modes of the $X(3872)$ can be described in the framework of the $D\bar{D}^* - c\bar{c}$ coupled–channel scheme. The admixture of the bare $\chi'_{c1}$ state in the resonance wavefunction is not large, and the dominant component appears to be the $D^0\bar{D}^{*0}$ one. This, together with large and negative real part of scattering length, proves the dynamical (molecular) nature of the $X(3872)$.

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