

# ON THE ORIGIN OF THE NARROW PEAK AND THE ISOSPIN SYMMETRY BREAKING OF THE $X(3872)^*$

SACHIKO TAKEUCHI

Japan College of Social Work, Kiyose, Tokyo 204-8555, Japan

MAKOTO TAKIZAWA

Showa Pharmaceutical University, Machida, Tokyo 194-8543, Japan

KIYOTAKA SHIMIZU

Department of Physics, Sophia University, Chiyoda-ku, Tokyo 102-8554, Japan

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The  $X(3872)$  formation and decay processes in  $B$  decay are investigated by a  $c\bar{c}$ -two-meson hybrid model. The two-meson state consists of the  $D^0\bar{D}^{*0}$ ,  $D^+D^{*-}$ ,  $J/\psi\rho$ , and  $J/\psi\omega$  channels. The  $c\bar{c}(2P)$  state couples to the two  $D\bar{D}^*$  channels. The energy-dependent decay widths of the  $\rho$  and  $\omega$  mesons are introduced in the two-meson propagators. The isospin symmetry breaking in the present model comes from the mass difference of the charged and neutral  $D$  and  $D^*$  mesons. It is found that very narrow  $J/\psi\rho$  and  $J/\psi\omega$  peaks appear around the  $D^0\bar{D}^{*0}$  threshold. The size of the  $J/\psi\pi^3$  peak that we calculated is 1.27–2.24 times as large as that of  $J/\psi\pi^2$ , which is comparable to the experimental results. It is also found that ratios of the transfer strengths provide information on the size of the  $c\bar{c}-D\bar{D}^*$  coupling as well as the  $X(3872)$  binding energy.

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## 1. Introduction

The  $X(3872)$  peak was first found by Belle in the  $J/\psi\pi\pi K$  observation from  $B$  decay [3]. Its mass is  $3871.69 \pm 0.17$  MeV, which is very close to the  $D^0\bar{D}^{*0}$  threshold,  $3871.80 \pm 0.12$  MeV [4]. The full width is less than 1.2 MeV [5], which is very narrow for such a highly excited resonance. Recently, its quantum numbers were determined to be  $J^{PC} = 1^{++}$  [6].

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It is found that the  $X(3872)$  decays both to the  $J/\psi\rho$  and  $J/\psi\omega$  states. This isospin mixing is very large compared to the usual degrees of the breaking. The decay fraction of  $X(3872)$  into  $\pi^+\pi^-J/\psi$  is comparable to that into  $\pi^+\pi^-\pi^0J/\psi$  [7, 8] as

$$\frac{\text{Br}(X \rightarrow \pi^+\pi^-\pi^0J/\psi)}{\text{Br}(X \rightarrow \pi^+\pi^-J/\psi)} = 1.0 \pm 0.4 \pm 0.3 \text{ (Belle)}, \quad 0.8 \pm 0.3 \text{ (BABAR)}. \quad (1)$$

The  $X(3872)$  is discussed in many theoretical references [9, 10]. As for the  $J/\psi\rho$  or  $J/\psi\omega$  spectrum, Coito *et al.* have shown that a thin peak can be reproduced by employing the resonance spectrum expansion [11, 12]. The shape of the  $D^0\bar{D}^{*0}$  spectrum around the threshold in these works is essentially the same as that of the present work. In this work, we argue that the  $X(3872)$  is a hybrid state of  $c\bar{c}$  and the two-meson molecule: a superposition of the  $c\bar{c}(2P)$  quarkonium and the  $D^0\bar{D}^{*0}$ ,  $D^+D^{*-}$ ,  $J/\psi\rho$  and  $J/\psi\omega$  molecular states. We have found that this picture explains many of the observed properties of the  $X(3872)$  quantitatively [1, 2]: the fact that the  $X(3872)$  can be a shallow bound state (or an  $S$ -wave virtual state), that a thin peak appears at around the  $D^0\bar{D}^{*0}$  threshold, and the absence of the  $\chi_{c1}(2P)$  peak in the  $J^{PC} = 1^{++}$  spectrum. We also found that the mass difference of the charged and neutral  $D$  and  $D^*$  mesons can give the observed size of the isospin symmetry breaking due to the large decay widths of the  $\rho$  and  $\omega$  mesons. Moreover, we define two kinds of ratios of the transfer strengths, which reflect the size of the  $c\bar{c}-D\bar{D}^*$  coupling or the binding energy of  $X(3872)$ . Or, conversely, we argue that the size of the coupling or the attraction between  $D$  and  $D^*$  mesons can be estimated by the observed ratios of the transfer strengths though in a model-dependent way. This will enable us to discuss various systems with the heavy mesons quantitatively.

## 2. Method

The model space consists of the two-meson state ( $P$ ) and the  $c\bar{c}$  quarkonium ( $Q$ ), which is treated as a bound state embedded in the continuum (BSEC) [13]. The model Hamiltonian,  $H$ , can be written as

$$H = \begin{pmatrix} H_0^{(P)} + V_P & V_{PQ} \\ V_{QP} & E_0^{(Q)} \end{pmatrix}, \quad (2)$$

where  $H^{(P)} = H_0^{(P)} + V_P$  is a nonrelativistic Hamiltonian for the two-meson systems, and  $V_{PQ}$  and  $V_{QP}$  are the transfer potentials between the  $P$ - and  $Q$ -spaces.  $E_0^{(Q)}$  is a  $c$ -number and corresponds to the bare BSEC mass: the

$c\bar{c}$  mass before the  $c\bar{c}-D\bar{D}^*$  coupling is switched on.  $V_P$  and  $V_{QP}$  are

$$V_{P;ij}(\mathbf{p}, \mathbf{p}') = v_{ij} f_\Lambda(p) f_\Lambda(p') Y_{00}(\Omega_p) Y_{00}^*(\Omega_{p'}), \quad (3)$$

$$V_{QP;i}(\mathbf{p}) = g_i \sqrt{\Lambda} f_\Lambda(p) Y_{00}^*(\Omega_p) \quad \text{with} \quad f_\Lambda(p) = \frac{1}{\Lambda} \frac{\Lambda^2}{p^2 + \Lambda^2}. \quad (4)$$

We use a typical hadron size for the value of the cutoff,  $\Lambda$ . The  $v_{ij}$  and  $g_i$  are the strengths of the potentials and assumed to be

$$\{v_{ij}\} = \begin{Bmatrix} v & 0 & u & u \\ 0 & v & u & -u \\ u & u & v' & 0 \\ u & -u & 0 & v' \end{Bmatrix} \quad \text{and} \quad \{g_i\} = \{ g \quad g \quad 0 \quad 0 \} \quad (5)$$

for the  $D^0\bar{D}^{*0}$ ,  $D^+D^{*-}$ ,  $J/\psi\omega$ , and  $J/\psi\rho$  channels, respectively.

The parameter sets that we used are listed in Table I [2]. As for the parameter set A,  $v$  is taken to be as attractive as possible on the condition that there is no bound state in the  $B\bar{B}^*$  system if the same potential but without  $b\bar{b}-B\bar{B}^*$  coupling is applied there. The  $u$  is taken from a quark model, while  $g$  is a free parameter to produce the  $X(3872)$  peak at the observed energy. In QM,  $v$  and  $v'$  are also taken from the quark model.

TABLE I

Model parameters for the interaction,  $v$ ,  $v'$ ,  $u$ , and  $g$ , defined by Eq. (5). The  $g_0 = 0.0482$  is the strength of the  $c\bar{c}-D\bar{D}^*$  coupling which gives the correct  $X(3872)$  mass when  $v = v' = 0$  and  $u = 0.1929$ . For all the parameter sets,  $\Lambda = 500$  MeV, and  $E_0^{(Q)} = 3950$  MeV.

	$v$	$v'$	$u$	$g$	$(g/g_0)^2$
A	-0.1886	0	0.1929	0.0390	0.655
B	-0.2829	0	0.1929	0.0331	0.472
C	-0.1886	0	0.2894	0.0338	0.491
QM	0.0233	-0.2791	0.1929	0.0482	1.003

We solve Lippmann–Schwinger equation for the case with the BSEC, and obtain the transfer strength from the  $c\bar{c}$  to the  $f^{\text{th}}$  channel of the two-meson state,  $W(c\bar{c} \rightarrow f)$ , as [2, 13]

$$\frac{dW(c\bar{c} \rightarrow f)}{dE} = \frac{2}{\pi} \mu_f \int \frac{k^2 dk \mu_f \Gamma_f}{\left(k_f^2 - k^2\right)^2 + (\mu_f \Gamma_f)^2} \left| \langle\langle f; k | V_{PQ} \tilde{G}_Q | c\bar{c} \rangle\rangle \right|^2, \quad (6)$$

$$|f; k_f\rangle\rangle = \left(1 + \tilde{G}^{(P)} V_P\right) |f; k_f\rangle, \quad (7)$$

where  $E$  is the energy of the system when the center of mass of  $D^0\bar{D}^{*0}$  is at rest.  $\mu_f$ ,  $k_f$ , and  $\Gamma_f$  are the reduced mass, the momentum, and the energy-dependent width of the  $f^{\text{th}}$  channel.  $\tilde{G}^{(P)}$  ( $\tilde{G}_Q$ ) is the full propagator of the two-meson state (the  $c\bar{c}$  state) with the  $\omega$  and  $\rho$  widths.  $|f; k\rangle$  is the plane wave function with the momentum  $k$ . Here, we define two kinds of ratios of the transfer strengths around the  $X(3872)$  mass,  $m_{X(3872)}$

$$R_\Gamma = \frac{I_{J/\psi\omega}(\epsilon_X)}{I_{J/\psi\rho}(\epsilon_X)} \frac{\Gamma_{\omega\rightarrow 3\pi}}{\Gamma_\omega}, \quad r_{D^0\bar{D}^{*0}} = \frac{I_{D^0\bar{D}^{*0}}(\epsilon)}{I_{J/\psi\rho}(\epsilon)} \quad (8)$$

with

$$I_f(\epsilon) = \int_{m_{X(3872)} - \epsilon}^{m_{X(3872)} + \epsilon} dE' \frac{dW(c\bar{c} \rightarrow f)}{dE'}. \quad (9)$$

### 3. Results and discussions

The transfer strength,  $dW/dE$ , from the  $c\bar{c}$  quarkonium to each of the final two-meson states,  $D^0\bar{D}^{*0}$ ,  $D^+D^{*-}$ ,  $J/\psi\rho$  and  $J/\psi\omega$  is shown in Fig. 1 (a) for the parameter set A. The lines for  $D^0\bar{D}^{*0}$ ,  $D^+D^{*-}$ , and  $J/\psi\rho$  correspond to the observed spectrum though the overall factor arising from the weak interaction should be multiplied. In order to obtain the  $J/\psi\pi^3$  spectrum, the fraction  $\Gamma_{\omega\rightarrow 3\pi}/\Gamma_\omega = 0.892$  [4] should be multiplied furthermore to the  $J/\psi\omega$  spectrum. In Fig. 1 (b), we plot the same spectra around the  $D^0\bar{D}^{*0}$  threshold on a different scale. We choose  $g$  to have a bound  $X(3872)$  at

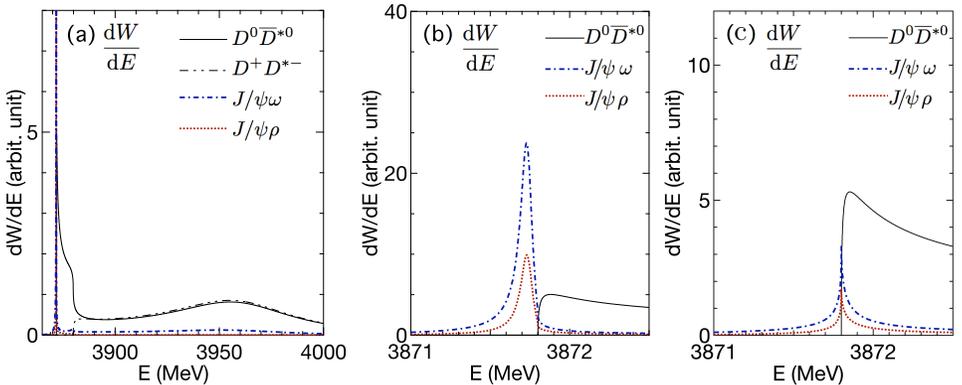


Fig. 1. The transfer strength from the  $c\bar{c}$  quarkonium to the two-meson states. Figs. (a) and (b) show the same spectra with the parameter set A with different scales on the vertical and horizontal axes. In Fig. (c), the result with the  $0.9(g/g_0)^2$  is shown. All the figures are taken from Ref. [2].

3871.69 MeV, which gives rise to a peak in the  $J/\psi\pi^n$  spectrum with a small but nonzero width due to the  $\omega$  and  $\rho$  meson widths. Figure 1 (c) corresponds to the parameter set A with a weakened  $c\bar{c}-D\bar{D}^*$  coupling:  $0.9(g/g_0)^2$ . Though the bound state exists no longer, a sharp peak is still found at the  $D^0\bar{D}^{*0}$  threshold. In both of the cases, the peak in the  $J/\psi\pi^n$  spectrum is lighter in the energy and has a smaller decay width than the peak in the  $D^0\bar{D}^{*0}$  spectrum; this feature is consistent with the experiments [14, 15].

We found that all of the present parameter sets produce a thin  $J/\psi\pi^n$  peak at around the  $D^0\bar{D}^{*0}$  threshold with an appropriate choice of  $g$  [2]. The mechanisms to form  $X(3872)$ , however, can be different from each other. To look into what kinds of observables can be used to distinguish these mechanisms, and to investigate the size of the isospin symmetry breaking, we calculated the values of various ratios of the transfer strengths.

In Fig. 2 (a), we show  $R_\Gamma$ , defined by Eq. (8), where  $\epsilon_X$  is taken to be the upper limit value of  $\Gamma_{X(3872)}$ , 1.2 MeV. This ratio  $R_\Gamma$  is found to be 2.24 for the parameter set A. This result is somewhat larger, but comparable to the experimental results, which are shown in Eq. (1) as well as in the figure.  $R_\Gamma$  varies rather widely according to the parameters  $(g/g_0)^2$ . As the  $c\bar{c}-D\bar{D}^*$  coupling becomes smaller, the ratio  $R_\Gamma$  becomes smaller, and the degree of the isospin symmetry breaking becomes larger. One can estimate the size of the  $c\bar{c}-D\bar{D}^*$  coupling (and therefore the attraction between  $D$  and  $\bar{D}^*$ ) from the observed size of the isospin symmetry breaking. The experimental results suggest that  $(g/g_0)^2 \sim 0.3-0.5$ .

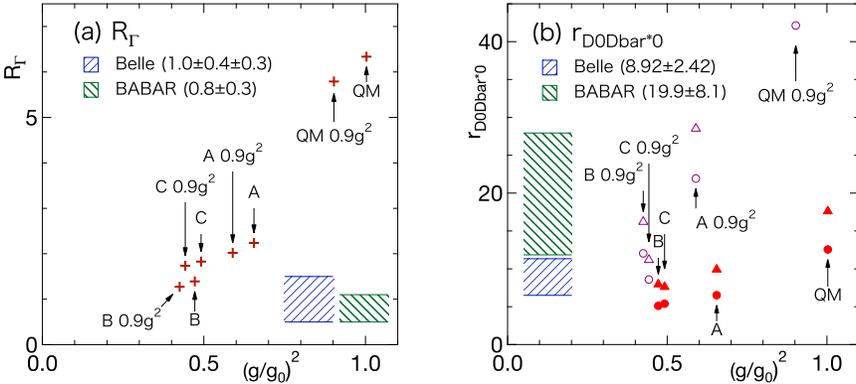


Fig. 2. The  $J/\psi\pi^3-J/\psi\pi^2$  ratio at the  $X(3872)$  peak,  $R_\Gamma$ , and the  $D^0\bar{D}^{*0}-J/\psi\pi^2$  ratio integrated over the scattering state,  $r_{D^0\bar{D}^{*0}}$ . In both Figs. (a) and (b), the values are plotted against  $(g/g_0)^2$ . In Fig. (b), the ratios with the  $\epsilon = 4$  MeV (8 MeV) are denoted by circles (triangles), and those with the bound states are denoted by the solid marks. Fig. (a) is taken from Ref. [2].

The ratio  $r_{D^0\bar{D}^{*0}}$  defined for each parameter set with  $\epsilon = 4$  MeV and 8 MeV is shown in Fig. 2 (b). It is found that for the parameter sets with  $(g/g_0)^2 \sim 0.5$ , this  $r_{D^0\bar{D}^{*0}}$  is about 5.12–9.91 if the  $X(3872)$  is a bound state, while the value is more than 8.59 if there is no bound state. The results suggest that one can judge whether the  $X(3872)$  is a bound state by looking into the ratio  $r_{D^0\bar{D}^{*0}}$ . The experiments for this ratio are still controversial. More precise measurements will help to determine whether the  $X(3872)$  is a bound state or not.

In the present parameter sets, the size of the  $c\bar{c}(2P)$  component in the bound  $X(3872)$  is about 0.02–0.06. An actual size can probably be evaluated from the radiative decay of  $X(3872)$ . The observed size of decay from the  $X(3872)$  to the  $\psi'\gamma$  channel is comparable to that to the  $J/\psi\gamma$  channel [16–18]. Since  $c\bar{c}(2P)$  decays mainly to the  $\psi'\gamma$  state, these experiments support the existence of the  $c\bar{c}(2P)$  component in the  $X(3872)$ . Discussion in detail is on the way.

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