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Isospin symmetry breaking in X(3872)*

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Abstract. In this work, we employ a quark model as well as a meson model to investigate the isospin symmetry breaking of X(3872). We find that the quark model, in which the isospin breaking occurs because of the u and d quark mass difference and of the electromagnetic force, can give a shallow bound state where the isospin is mixed but mostly 0. The meson model, where the width of the ρ or ω meson is taken into account, can also give the X(3872) $\to$ $J/\psi\rho$ and $J/\psi\omega$ transition strength with a sharp peak around the $D^0\overline{D}^{*0}$ threshold. Their strength is comparable in size, which is consistent with the experiment.

1 Introduction

X(3872) is a heavy meson first observed by Belle in 2003 in the B decay, $B^\pm \to K^\pm J/\psi\,\pi\pi(\pi)$ [1]. It has a mass of (3872.3±0.8) MeV and a width of (3.0+2.1−1.7) MeV [2]. It seems difficult to explain the properties of this particle if one assumes a simple $c\bar{c}$ state. Its rather low mass and small width as well as the momentum distribution of the final π's suggest that X(3872) may be J^{PC}=1^{++} and probably has a large four-quark component, $q\bar{q}c\bar{c}$ [3–5]. Another notable property is that it decays into both $J/\psi\,\pi^2$ and $J/\psi\,\pi^3$ in comparable size [6]:

$$\frac{Br(X(3872) \to \pi^+\pi^-\pi^0 J/\psi)}{Br(X(3872) \to \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.3, \tag{1}$$

which means that X(3872) is a mixed state of the isospin 0 and 1.

Table 1. Relevant threshold energy close to X(3872) [2]. All entries are in MeV.

	$m_{X(3872)}$	$m_{D^0} + m_{\bar{D}^{*0}}$	$m_{J/\psi} + m_\rho$	$m_{J/\psi} + m_\omega$	$m_{D^+} + m_{D^{*-}}$
exp.	3872.3±0.8	3871.8	3872.4	3879.6	3879.9

As seen in Table 1, there are four thresholds which are very close to X(3872). It is natural to consider that X(3872) has large components of those two-meson states. Because of the D^+D^{*-} threshold is by about 8 MeV higher than that of

* This work has been done with in collaboration with Dr. Makoto Takizawa and Dr. Kiyotaka Shimizu.

$D^0\overline{D}^{*0}$, the tail of the wave function of X(3872) probably consists mainly of $D^0\overline{D}^{*0}$. This causes the isospin symmetry breaking in X(3872).

The decay into $J/\psi\rho$ or $J/\psi\omega$ requires recoupling of the quarks, thus occurs at the short range. So, it is still nontrivial whether the above threshold difference also affects the short-range part enough to explain the decay ratio shown in eq. (1). To clarify this point, we investigate the situation quantitatively by a quark model as well as by a meson model in the following.

2 Quark model picture

A constituent quark model is an effective model for the low energy hadron physics [7]. There the quarks are treated as dynamical variables whereas the gluon effects are reduced mostly to the single particle energy of quarks or the potential between quarks. The masses of light quarks are considered to increase up around to 300 MeV due to the chiral symmetry breaking.

This picture is more reliable when the concerning quarks are heavy. For example, the summation of $D^{(*)}$ mass and $B_s^{(*)}$ mass is almost the same that of $B^{(*)}$ and $D_s^{(*)}$ (Table 2). This suggests that the bulk effects of the gluon or the sea quark degrees of freedom are effectively included in the single particle energy of the quarks.

Table 2. Mass of (u+s+c+b) systems (in MeV).

	$m_{K^{(*)}} + m_{B_c^{(*)}}$	$m_{D^{(*)}} + m_{B_s^{(*)}}$	$m_{B^{(*)}} + m_{D_s^{(*)}}$
pseudo-scalar mesons	6770	7231	7247
vector mesons	892+?	7420	7437

The difference between the above entries, for example, $(m_D + m_{B_s}) - (m_B + m_{D_s})$, comes from the interaction between quarks. The 0th order terms are considered to be color-Coulomb and the linear confinement terms, which are established in both of the empirical and theoretical ways.

The hadron-hadron interaction arises mostly from the spin-dependent part, which is one of the higher order terms. It is well known that the effective one-gluon exchange gives such a spin-spin term. The interaction is investigated also by the Lattice QCD [8], where the spin-spin term is found to be proportional to $(1/m_1 m_2)$:

$$V_{ss} = \frac{\mathbf{s}_1 \cdot \mathbf{s}_2}{m_1 m_2} V(r) \tag{2}$$

where $V(r)$ is short-ranged ($r < 0.5$ fm) potential.

This spin-spin interaction seems to be modified a little when one of the quarks is the light quark. In Table 3, we listed the observed hyperfine splitting for each

Table 3. Hyperfine splitting of the $q\overline{Q}$ systems (in MeV).

$m_{K^*} - m_K$	$m_{D^*} - m_D$	$m_{D_s^*} - m_{D_s}$	$m_{B^*} - m_B$	$m_{B_s^*} - m_{B_s}$
398	141	144	46	47

$q\overline{Q}$ system[1]. It, however, is still clearly seen that the interaction becomes smaller as the heavy quark is heavier. So the properties of the four-quark systems are governed mainly by the interaction between the light quark-light antiquark pairs.

In Table 4, we show the matrix elements of relevant interactions: the color-magnetic interaction (CMI), the pair-annihilating term of OGE (OGE-a), Ins, and an estimate by a typical parameter set used for a quark model. The most attractive pair is the color-singlet, spin 0, flavor-octet, which exists, *e.g.* in the pion. There is another weak but still attractive pair: the color-octet, spin 1, flavor-octet one. $I=0$ pairs may also be attractive if OGE-a and Ins are weak, whose size is not well known. Such pairs may be found in the $q\overline{q}c\overline{c}$ systems. We argue that this attraction leads to X(3872) to have a large four-quark configuration.

Table 4. Matrix elements of the interactions between $q\overline{q}$ pairs. The color-magnetic interaction, $-\langle(\lambda \cdot \lambda)(\sigma \cdot \sigma)\rangle$, is denoted as CMI, the pair-annihilating term of OGE (OGE-a), the spin-color part of the instanton induced interaction (Ins), and estimate value by a typical parameter set, E.

color	spin	flavor	CMI	OGE-a	Ins	E(MeV)	States
1	0	1	−16	0	12	84	η
1	0	8	−16	0	−6	−327	π, K
1	1	1	16/3	0	0	63	ω
1	1	8	16/3	0	0	63	ρ
8	0	1	2	0	3/4	41	
8	0	8	2	0	−3/8	15	
8	1	1	−2/3	9/2	9/4	97	
8	1	8	−2/3	0	−9/8	−34	$c\overline{c}q\overline{q}$ with $J^{PC}=0^{++},1^{+-},1^{++},2^{++}$

3 X(3872) by a quark model

In the quark model, the isospin symmetry breaking occurs due to the u and d quark mass difference and the electromagnetic interaction between quarks. The model hamiltonian and the wave function is taken to be the same as those in ref.[9].

The X(3872) configuration is taken to be $q\overline{q}c\overline{c}$ with a $c\overline{c}$ core. The four quark state is solved by using the resonating group method with a full deformation in

[1] The Table suggests that the $SU(3)_f$ flavor symmetry is good when the one of the quark is heavy, but we do not discuss farther on this topic here.

Table 5. Binding energy and probabilities of each configuration. $(c\bar{c})_1$ $[(c\bar{c})_8]$ stands for the $c\bar{c}$ pair is color-singlet [octet].

B.E.	$(c\bar{c})_1(q\bar{q})_1$		$(c\bar{c})_8(q\bar{q})_8$		$c\bar{c}$
	$I=0$	$I=1$	$I=0$	$I=1$	
5.2 MeV	0.11	0.04	0.44	0.09	0.37

the short distance. So the system can be a molecular state of two mesons with the tetraquark components in the short range region.

It is found that there can be a shallow $J^{PC}=1^{++}$ bound state which is mostly isospin $I=0$. The probability of each component is shown in Table 5. By multiplying larger phase space for $J/\psi\rho$ channel, we may have the branching ratio reported in ref.[6].

4 X(3872) by a meson model

In order to investigate the branching ratio directly, we employ the meson model for X(3872). The mesons, D, D^*, ρ and ω are treated as fundamental degrees of freedom in this model. The isospin breaking comes from the mass difference of mesons [10].

The meson-meson interaction is taken to be the gaussian separable type as

$$V_m(p,p') = v_0 \ \exp[-a^2(p^2+p'^2)/4] \tag{3}$$

with the range a=0.4 fm. As for the coupling between the two-meson channel and the $c\bar{c}$ channel we take

$$V_{m,c\bar{c}}(p) = w_0 \ \exp[-b^2p^2/4] \tag{4}$$

with also b=0.4 fm. As the first try, we fit v_0 and u_0 to produce an appropriate shape for the peak. This interaction does not break the isospin symmetry.

We solve a four-channel coupled scattering problem, $D^0\overline{D}^{*0}$-J/ψ ρ-J/ψ ω-D^+D^{*-}, with the $c\bar{c}$(1P) state as a bound state embedded in the continuum [11], and calculate the transition strength of X(3872) to the final α channel with the $D^0\overline{D}^{*0}$ momentum, q:

$$\frac{dW}{dq} = \frac{M_{K-D^0\overline{D}^{*0}}}{\mu_{D^0\overline{D}^{*0}}}\, q \sum_\alpha \mu_\alpha q_\alpha \left|\langle \text{two mesons } q_\alpha | T_{\alpha,c\bar{c}} \ G_0 | c\bar{c}\rangle\right|^2 \tag{5}$$

The probability can be expressed by the $c\bar{c}$ self energy, $\Sigma_c\bar{c}$, as

$$\sum_\alpha \cdots \propto -\Im\langle c\bar{c}|(T_{\alpha,c\bar{c}} \ G_0)^\dagger G_0 \ T_{\alpha,c\bar{c}} \ G_0|c\bar{c}\rangle \tag{6}$$

$$= -\Im\langle c\bar{c}|G_c\bar{c}^* \ \Sigma_c\bar{c} \ G_c\bar{c}|c\bar{c}\rangle \tag{7}$$

In order to include the effects of the ρ and ω meson width, we substitute of the resolvent of the α channel by that with the observed ρ or ω meson width as:

$$-\Im\langle c\bar{c}|G_0 \ T^*_{c\bar{c},\alpha} \ G_0 \ T_{\alpha,c\bar{c}} \ G_0|c\bar{c}\rangle \to -\Im\langle c\bar{c}|G_0 \ T^*_{c\bar{c},\alpha} \ \tilde{G}_0 \ T_{\alpha,c\bar{c}} \ G_0|c\bar{c}\rangle \tag{8}$$

with $\tilde{G}_0 = (E - K_\alpha + i\Gamma/2)^{-1}$. One of our parameter sets gives the result plotted in Figure 1. A sharp peak appears in the final $J/\psi\,\rho$- or $J/\psi\,\omega$-channel around the $D^0\overline{D}^{*0}$ threshold. Both of the $J/\psi\,\rho$ and $J/\psi\,\omega$ can be found also below the threshold due to the vector meson width. The size of the decay probability to $J/\psi\,\rho$ and $J/\psi\,\omega$ are almost the same around the peak, which is consistent with the experiment.

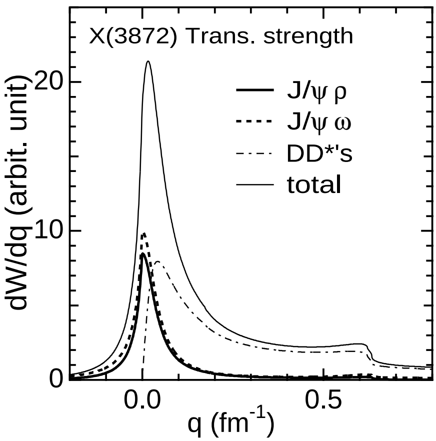

Fig. 1. Transition strength of X(3872) with respect to the $D^0\overline{D}^{*0}$ momentum, q.

We argue that X(3872) can be considered as a meson molecular state with a $c\bar{c}$ core. It is also pointed out that similar heavy mesons above the open charm threshold, $D\overline{D}$, the mass spectrum of charmonia deviates considerably from the quark model prediction [12]. The method we employ here can also be applied to investigate such states.

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