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Coupled channel description for X(3872) and other XYZ mesons

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We have performed a coupled channel calculation of the 1^{++} $c\bar{c}$ sector including $q\bar{q}$ and $q\bar{q}q\bar{q}$ configurations. The calculation was done within a constituent quark model which successfully describes the meson spectrum, in particular the $c\bar{c}$ 1^{--} sector. Two and four quark configurations are coupled using the $^3P_0$ model.
The elusive $X(3872)$ meson appears as a mixture of $2P$ $c\bar{c}$ states and DD^* molecule with a high probability for the molecular component. When the mass difference between neutral and charged states is included a large D^0D^{*0} component is found which dominates for large distances and breaks isospin symmetry in the physical state. The original $c\bar{c}(2^3P_1)$ state also acquires a sizable DD^* component and can be identified with the $X(3940)$.

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1. Introduction

In the last years a number of exciting discoveries of new hadron states have challenged our description of the hadron spectroscopy. One of the most mysterious states is the well established $X(3872)$. It was first discovered by the Belle Collaboration in the $J/\psi\pi\pi$ invariant mass spectrum of the decay $B \to K^+\pi^+\pi^- J/\psi$ [1]. Its existence was soon confirmed by BaBar [2], CDF [3] and D0 [4] Collaborations. The world average mass is $M_X = 3871.2 \pm 0.5 MeV$ and its width $\Gamma_X < 2.3 MeV$. A later angular analysis by CDF Collaboration [5] concludes from the dipion mass spectrum that the most likely quantum numbers should be $J^{PC} = 1^{++}$ but cannot totally exclude the $J^{PC} = 2^{-+}$ combination. However the small phase space available for the decay $X(3872) \to D^0\bar{D}^0\pi^0$ observed by Belle [6] rules out the $J = 2$ leaving the 1^{++} assignment as the most likely option.

The relative decay rates outlines a puzzling structure for the $X(3872)$. The $\gamma J/\psi$ and $\gamma\psi'$ decay rates [7] suggest a $c\bar{c}$ structure whereas the $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$ decay mode

$$R = \frac{X(3872) \to \pi^+\pi^-\pi^0 J/\psi}{X(3872) \to \pi^+\pi^- J/\psi} = 1.0 \pm 0.4 \pm 0.3 \tag{1.1}$$

indicates a very different one [8]. The ratio $R \sim 1$ indicates that there should be a large isospin violation incompatible with a traditional charmonium assumption.

The $X(3872)$ is difficult to reproduce by the standard quark models (see Ref. [9] for a review). The proximity of the D^0D^{*0} threshold made the $X(3872)$ a natural candidate to a $C = +$ D^0D^{*0} molecule. This structure will also explain the large isospin violation because is an equal superposition of $I = 0$ and $I = 1$. However the molecular interpretation runs in trouble when it tries to explain the high $\gamma\psi'$ decay rate. For a molecular state this can be only proceed through annihilation diagrams and hence is very small.

This puzzling situation suggests for the $X(3872)$ state a combination of a $2P$ $c\bar{c}$ state and a weakly-bound D^0D^{*0} molecule.

2. The Model

To clarify these ideas we have performed a coupled channel calculation of the P-waves charmonium states including both $c\bar{c}$ and DD^* configurations. The calculation was done in the framework of the constituent quark model of Ref. [10]. The model has been succesfully applied to the description of the 1^{--} sector [11].

In Table 1 we show the results for the first two multiplets of $c\bar{c}$ P-waves. The $X(3872)$ is too heavy to be assigned to the 1^3P_1 $J^{PC} = 1^{++}$ state and too light to be the 2^3P_1 state. The rest of the multiplet members agree with the experimental value of the PDG including the recent $Z(3930)$ $J^{PC} = 2^{++}$. The 2^3P_0 state would correspond with the recent reported $X(3915)$ [12].

To model the 1^{++} system we assume that the hadronic state is

$$|\Psi\rangle = \sum_\alpha c_\alpha |\psi_\alpha\rangle + \sum_\beta \chi_\beta(P)|\phi_{M_1}\phi_{M_2}\beta\rangle \tag{2.1}$$

where $|\psi_\alpha\rangle$ are $c\bar{c}$ eigenstates of the two body Hamiltonian, ϕ_{M_i} are $c\bar{n}$ ($\bar{c}n$) eigenstates describing the D ($\bar{D}$) mesons, $|\phi_{M_1}\phi_{M_2}\beta\rangle$ is the two meson state with β quantum numbers coupled to total

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	$c\bar{c}(1^3P_0)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(1^3P_2)$	$c\bar{c}(2^3P_0)$	$c\bar{c}(2^3P_1)$	$c\bar{c}(2^3P_2)$
Theory	3451	3503	3531	3909	3947	3968
Exp.	3414.75 ± 0.31	3510.66 ± 0.07	3556.20 ± 0.09	-	-	3929 ± 5

Table 1: Theoretical and experimental masses for the n^3P_J $c\bar{c}$ multiplet ($n=1,2$).

J^{PC} quantum numbers and $\chi_\beta(P)$ is the relative wave function between the two mesons in the molecule [1].

The simplest way to couple the two sectors is the so called $^3P_0$ model [13] that assume that the pair creation Hamiltonian is

$$\mathscr{H} = g\int d^3x\, \bar{\psi}(x)\psi(x) \tag{2.2}$$

which in the nonrelativistic reduction is equivalent to the transition operator [14]

$$T = -3\gamma\sum_\mu \int d^3p d^3p'\, \delta^{(3)}(p+p')\left[\mathscr{Y}_1\left(\frac{p-p'}{2}\right) b^\dagger_\mu(p) d^\dagger_\nu(p')\right]^{C=1,I=0,S=1,J=0} \tag{2.3}$$

where μ ($\nu=\bar{\mu}$) are the quark (antiquark) quantum numbers and $\gamma = 2^{5/2}\pi^{1/2}\frac{g}{2m}$ is a dimensionless constant that gives the strength of the $q\bar{q}$ pair creation from the vacuum.

The two body eigenstates are solved using the Gaussian Expansion Method [15]. In this method the wave function solution of the Schrödinger equation is expanded in terms of basis functions whose range are in geometrical progression. This basis function helps to evaluate the transition potential within the $^3P_0$ model

$$\langle \phi_{M_1}\phi_{M_2}\beta|T|\psi_\alpha\rangle = P\,V_{\beta\alpha}(P)\,\delta^{(3)}(\vec{P}_{\rm cm}) \tag{2.4}$$

where P is the relative momentum of the two meson state.

Solving the coupling with $c\bar{c}$ states we finally end up with an Schrödinger type equation for the relative wave function of the two meson state

$$\sum_\beta \int \left(H^{M_1M_2}_{\beta'\beta}(P',P) + V^{eff}_{\beta'\beta}(P',P)\right)\chi_\beta(P)\,P^2\,dP = E\,\chi_{\beta'}(P') \tag{2.5}$$

where $H^{M_1M_2}_{\beta'\beta}$ is the RGM Hamiltonian for the two meson state obtained from the $q\bar{q}$ interaction and

$$V^{eff}_{\beta'\beta}(P',P) = \sum_\alpha \frac{V_{\beta'\alpha}(P')V_{\alpha\beta}(P)}{E-M_\alpha} \tag{2.6}$$

is an effective interaction between the two mesons due to the coupling to intermediate $c\bar{c}$ states.

The normalization condition is $1=\sum_\alpha |c_\alpha|^2 + \langle\chi|\chi\rangle$, where we take into account the $c\bar{c}$ amplitudes c_α.

[1] As we always work with eigenstates of the C-parity operator we use the usual notation in which DD^* is the right combination of $D\bar{D}^*$ and $D^*\bar{D}$:

$$DD^* \equiv \frac{1}{\sqrt{2}}\left(|D\bar{D}^*\rangle + |D^*\bar{D}\rangle\right)$$

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	$M\,(MeV)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^{\pm}D^{*\mp}$
	3936	0 %	79 %	10.5 %	10.5 %
A	3865	1 %	32 %	33.5 %	33.5 %
	3467	95 %	0 %	2.5 %	2.5 %
	3937	0 %	79 %	7 %	14 %
B	3863	1 %	30 %	46 %	23 %
	3467	95 %	0 %	2.5 %	2.5 %
	3942	0 %	88 %	4 %	8 %
C	3871	0 %	7 %	83 %	10 %
	3484	97 %	0 %	1.5 %	1.5 %

Table 2: Masses and channel probabilities for the three states in three different calculations.

All the parameters are taken from the previous calculation in the $c\bar{c}$ sector [11] including the γ parameter in Eq. (2.3) which was fitted to the reaction $\psi(3770) \to DD$ which is the only well established charmonium strong decay, so the calculation is parameter free. This way to determine the value of γ might overestimate it since the $\psi(3770)$ is very close to the DD threshold and FSI effects, which were not included, might be relevant [16].

3. Results

We first perform an isospin symmetric calculation including $^3S_1$ and $^3D_1$ DD^* partial waves and taking the D and D^* masses as average of the experimental values between charged states. If we neglect the coupling to $c\bar{c}$ states we don't get a bound state for the DD^* molecule in the 1^{++} channel, neither in the $I=0$ nor in the $I=1$ channels. The interaction coming from OPE is attractive in the $I=0$ channel but not enough to bind the system, even allowing for distortion in the meson states.

Now we include the coupling to the 1^3P_1 and 2^3P_1 $c\bar{c}$ states. The results of this calculation are shown in part A of Table 2. We find an almost pure $c\bar{c}(1^3P_1)$ state with mass $3467\,MeV$ which we identify with the $\chi_{c_1}(1P)$ and two states with significant molecular admixture. One of them with mass $3865\,MeV$ is almost a DD^* molecule bound by the coupling to the $c\bar{c}$ states. The second one, with mass $3936\,MeV$, is a $c\bar{c}(2^3P_1)$ with sizable DD^* component. We assign the first state to the $X(3872)$, being the second one a candidate to the $X(3940)$. We have also analyze the effect of higher bare $c\bar{c}$ states finding a negligible effect on the mass and probabilities that will not change the above numbers.

To introduce the isospin breaking we turn to the charge basis instead of the isospin symmetric basis writing our isospin symmetric interaction on the charged basis. We now explicitly break isospin symmetry taking the experimental threshold difference into account in our equations and solving for the charged components. Now we get again three states being the main difference in the DD^* molecular component. The masses and channel probabilities are shown in part B of Table 2. We now get a higher probability for the D^0D^{*0} component although the isospin 0 component still dominates with a 66 % probability and a 3 % for isospin 1.

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Having in mind that the $^3P_0$ model is probably too naive and we might be overestimating the value of γ we can vary the $X(3872)$ mass with it. We can see that it is possible to get the experimental binding energy with a fine tune of this parameter. Using $0.6MeV$ as the binding energy we get a value of $\gamma = 0.19$, 25 % smaller than the original. The results are shown in part C of Table 2. Now the D^0D^{*0} clearly dominates with a 83 % probability giving a 70 % for the isospin 0 component and 23 % for isospin 1.

As a summary, we have shown that the $X(3872)$ emerges in a constituent quark model calculation as a mixed state of a DD^* molecule and $\chi_{c_1}(2P)$ state. This dual structure may explain simultaneously the isospin violation showed by the experimental data and the radiative decay rates. Moreover, the $X(3940)$ can be interpreted as the $\chi_{c1}(2P)$ with a significant DD^* component. This assignment together with the 2^3P_0 and 2^3P_2 to the $X(3915)$ and $Z(3940)$ complete the description of the 2^3P_J $c\bar{c}$ multiplet.

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