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The $X(3872) \to J/\psi\gamma$, $J/\psi\pi\pi$ and $J/\psi\pi\pi\pi$ decays in the $D\bar{D}^*$ molecular picture.

F. Aceti[∗a], **R. Molina**[b] **and E. Oset**[a]

[a]*Instituto de Física Corpuscular, Universidad de Valencia (Spain)*

[b]*Research Center for Nuclear Physics, Osaka University (Japan)*

E-mail: aceti@ific.uv.es, molina@rcnp.osaka-u.ac.jp, oset@ific.uv.es

We start from a picture of the $X(3872)$ which appears as a bound state of $\bar{D}D^* - c.c.$ and we evaluate the decay width into the $J/\psi\gamma$, $J/\psi\pi\pi$ and $J/\psi\pi\pi\pi$ channels.
For this purpose we evaluate the loops through which the $X(3872)$ decays into its components. The J/ψ and the photon, as well as a ρ or a ω meson, are radiated from these components. We use the local hidden gauge approach extrapolated to $SU(4)$ with a particular $SU(4)$ breaking. The decays involve anomalous couplings and we obtain acceptable values for the total rates and their ratios which compare favorably with experiment.

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[∗]Speaker.

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1. Introduction

The first observation of the $X(3872)$ decay into $J/\psi\gamma$ was reported by the BELLE collaboration in [1]. After that, this decay mode was confirmed by the BABAR collaboration in [2] and more recently again in BELLE in [3].

A consistent dynamical picture of the $X(3872)$ in the coupled channels of $D\bar{D}^* - c.c.$ was elaborated in [4] using an extrapolations to SU(4) of chiral Lagrangians used in the study of pseudoscalar meson interaction with vector mesons [5]. This implies extending to $SU(4)$ the local hidden gauge approach of [6, 7, 8, 9] with a particular $SU(4)$ breaking.

We report here on the recent work of [10] which is done following the approach of [11, 12] where all the couplings are accurately determined from the unitary coupled channel approach and are tied to the binding of the $X(3872)$, which is generated dynamically as a composite state of $D\bar{D}^*$ in this picture. The mechanisms for radiative decay are then basically the same as in [13], except that we also have contribution from the $D_s\bar{D}_s^*$ components and have slightly different couplings of the resonance to the neutral and charged $D\bar{D}^*$ components. The work is also technically different. Our approach has not ambiguities about the regularization of the loops, and most of the terms are shown to be convergent. Some terms are formally divergent, but we can isolate the divergence into a term proportional to the same loop function G which appears in scattering. This function G is regularized in the scattering problem in order to fit the position of the resonance, such that when it comes to evaluate the radiative decay it is already fixed. This makes the scheme internally consistent and predictive, since one does not have to rely upon unknown parameters that have proved to have a strong repercussion in the numerical results from other studies.

2. Formalism

Within the formalism of [4, 11], the $X(3872)$ is a dynamically generated resonance from the interaction of $D\bar{D}^*$, having an eigenstate of positive C-parity with isospin $I = 0$. It also has some component of $D_s\bar{D}_s^*$.

The $X(3872)$ has couplings to the charged and neutral components of DD^* that are very close to each other, implying an approximate $I = 0$ character for the state. The couplings, assuming the present binding of 0.2 MeV of the $X(3872)$ with respect to the $D^0\bar{D}^{*0} - c.c$ component, are shown in table 1. From thE table we can also see the couplings to the $K^-K^{*+} - c.c.$ and $K^0\bar{K}^{*0} - c.c.$

Channel	$\lvert g_{R\to PV}\rvert$ [MeV]
$(K^-K^{*+} - c.c.)/\sqrt{2}$	-53
$(K^0\bar{K}^{*0} - c.c.)/\sqrt{2}$	-49
$(D^-D^{*+} - c.c.)/\sqrt{2}$	3638
$(D^0\bar{D}^{*0} - c.c.)/\sqrt{2}$	3663
$(D_s^-D_s^{*+} - c.c.)/\sqrt{2}$	3395

Table 1: Couplings g_R of the pole at $(3871.6 - i0.001)$ MeV to the channels ($\alpha_H = -1.27$ here).

channels, which represent less than the 1% of the contributions from the other channels. Therefore, we will treat the $X(3872)$ as if it were dynamically generated from only the last three channels in Table 1.

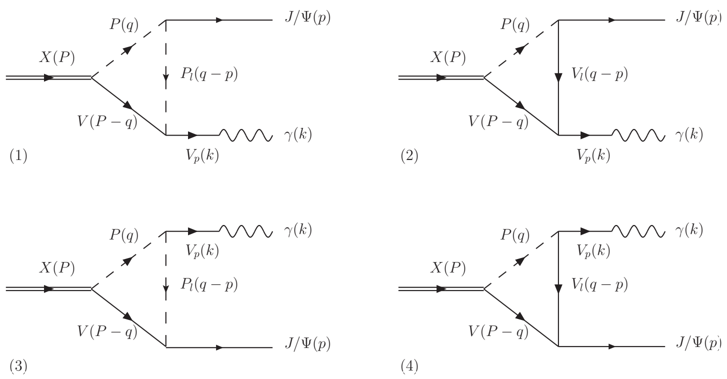

Figure 1: Different types of Feynmann diagrams for the decay of the $X(3872)$ into $J/\psi\gamma$.

In this picture, the $X(3872)$ decays into $J/\psi\gamma$ through the diagrams shown in Fig. 1. From this figure we observe that there are four kinds of different Feynman diagrams, all of them with an anomalous vertex coupling two vectors and a pseudoscalar (VVP), depending on whether the diagram contains a PPV or a 3V vertex, or the photon emerges from the anomalous vertex. There are three different channels: $D^0\bar{D}^{*0}$, D^+D^{*-} and $D_s^+D_s^{*-}$, which lead to 12, plus another 12 for the complex congujate, Feynman diagrams to evaluate.

The VPP, 3V and Vγ vertices are evaluated using the local hidden gauge approach [6, 7, 8, 9] which automatically incorporates vector meson dominance, by means of which the photon couples to other hadrons converting itself into ρ^0, ω, ϕ and J/ψ. As a consequence of this, we are also able to evaluate the rates of the $X(3872)$ decay into $J/\psi\rho$, $J/\psi\omega$, that account for the observed $J/\psi\pi\pi$ and $J/\psi\pi\pi\pi$ decay modes respectively, and the ratios of the decay rates, which can be compared to existing data.

The Lagrangians we need in order to evaluate the amplitude are listed below:

$$\mathscr{L}_{VVP} = \frac{G'}{\sqrt{2}}\epsilon^{\mu\nu\alpha\beta}\langle\partial_\mu V_\nu \partial_\alpha V_\alpha P\rangle \tag{2.1}$$

$$\mathscr{L}_{V\gamma} = -M_V^2\frac{e}{g}A_\mu\langle V^\mu Q\rangle \tag{2.2}$$

$$\mathscr{L}_{PPV} = -ig\langle V^\mu[P,\partial_\mu P]\rangle \tag{2.3}$$

$$\mathscr{L}_{3V} = ig\langle(V^\mu\partial_\nu V_\mu - \partial_\nu V_\mu V^\mu)V^\nu)\rangle\ , \tag{2.4}$$

with e the electron mass ($e^2/4\pi = \alpha$), $G' = 3g'^2/(4\pi^2 f)$, $g' = -G_V M_\rho/(\sqrt{2}f^2)$, $G_V = f/\sqrt{2}$ and $g = M_V/2f$. The constant f is the pion decay constant $f_\pi = 93\ MeV$, $Q = diag(2,-1,-1,1)/3$ and M_V is the mass of the vector meson, for which we take M_ρ. The P and V matrices contain the 15-plet of the pseudoscalars and the 15-plet of vectors respectively.

By means of these Lagrangians, we can derive the decay amplitudes for every diagram and every channel.

The diagrams of Fig. 1 that contribute to the total decay amplitude are all divergent, but we have been able to regularize them by means of the same loop function that appears in the scattering problem, which is already regularized. In the final expression of the amplitudes, the divergence is always isolated in a term proportional to this loop function, and hence there is no ambiguity in the regularization of the loops.

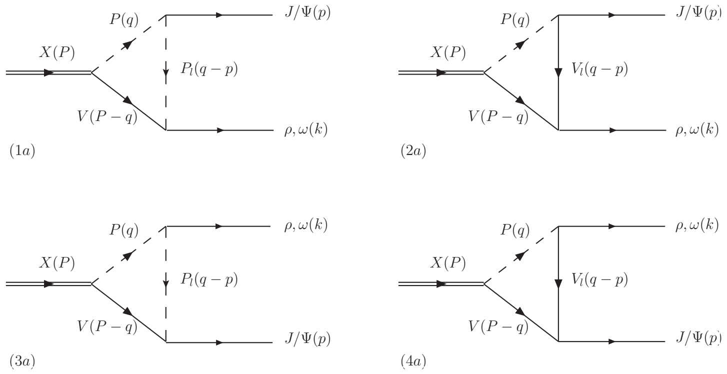

Figure 2: Different types of Feynmann diagrams for the decay of the $X(3872)$ into $J/\psi\rho$ and $J/\psi\omega$.

This formalism also allows us to evaluate the amplitudes for the decays $X \to J/\psi\rho$ and $X \to J/\psi\omega$ (Fig. 2). We can proceed in analogy with the radiative decay to determine these amplitudes, simply removing the final photon and leaving the vector meson in the final state, the ρ^0 or the ω. Moreover, we must take into account that the ρ^0 and the ω do not couple to the strange D mesons, so that we also have four different kinds of diagrams, but only two channels plus their complex conjugate, that is 16 Feynman diagrams to evaluate.

3. Results

The total decay amplitude for the radiative decay of the X meson can now be calculated and we can evaluate the correspondent decay width for this channel by means of

$$\Gamma = \frac{|\vec{k}|^2}{8\pi M_X^2} \bar{\sum}\sum |t|^2 \ , \tag{3.1}$$

where we must sum over the polarizations of the final states and average over the X meson polarizations.

To evaluate the amplitude we use the dimensional regularization for the loop function. The subtraction constants used are $\alpha = \alpha_S = -1.27$, where the subscript S identifies the strange channel. These parameters are chosen to fit the mass of the $X(3872)$ [11].

Applying Eq. (3.1), we obtain

$$\Gamma(X \to J/\psi\gamma) = 150\ keV \ . \tag{3.2}$$

In order to make an estimation of the theoretical uncertainty on this quantity we perform a suitable variation of the parameters used to compute the total amplitude: the coupling G' for the VVP vertex (Eq. (2.1)), the axial-vector-pseudoscalar couplings g_X for the three channels, and the two subtraction constants in the loop function, α and α_S.

We obtain the result

$$\Gamma(X \to J/\psi\gamma) = (117 \pm 40)\ keV \ . \tag{3.3}$$

We can also evaluate the branching ratios for the decays $X \to J/\psi\rho$ and $X \to J/\psi\omega$. These two decays, if we consider the ρ and the ω with fixed masses, are not allowed because of the phase space, but they can occur when their mass distributions are taken into account and they are observed in the decays $X \to J/\psi\pi\pi$ and $X \to J/\psi\pi\pi\pi$ respectively. The two and three pions states are produced in the decays of the ρ and the ω.

Thus, the decay widths, must be convoluted with the spectral functions and we find

$$\Gamma_\rho = 822\ keV\ , \qquad \Gamma_\omega = 1097\ keV\ , \tag{3.4}$$

and when the error anlysis that leads to Eq. (3.3) is done, the band of values becomes

$$\Gamma_\rho = (645 \pm 221)\ keV\ , \qquad \Gamma_\omega = (861 \pm 294)\ keV\ . \tag{3.5}$$

With the results of Eq. (3.4) we can evaluate the ratio

$$R = \frac{\mathscr{B}(X \to J/\psi\pi\pi\pi)}{\mathscr{B}(X \to J/\psi\pi\pi)} = \frac{\Gamma_\omega}{\Gamma_\rho} = 1.33\ . \tag{3.6}$$

However, the experiment gives the ratio

$$R^{exp} = \frac{\mathscr{B}(X \to J/\psi\pi^+\pi^-\pi^0)}{\mathscr{B}(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3_{(sys)} \tag{3.7}$$

and, to compare this with our result, we must take into account that the ω decays into $\pi^+\pi^-\pi^0$ with a branching ratio $B_{\omega,3\pi} = 0.892$.

Hence, the ratio to compare with R^{exp} is

$$R^{th} = \frac{\Gamma_\omega}{\Gamma_\rho} \times B_{\omega,3\pi} = 1.19\ , \tag{3.8}$$

which is well within the experimental error.

The result we obtain for the ratio

$$\frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\pi\pi)} = 0.18\ , \tag{3.9}$$

is also compatible with the two values known from the experiment (0.14 ± 0.05) [1] and (0.22 ± 0.06) [2].

We can also estimate the theoretical errors for the two ratios in Eqs. (3.8) and (3.9), by evaluating the γ, ρ and ω decays with the same set of parameters, and varying these parameters in the range used to evaluate $\Gamma(X \to J/\psi\gamma)$. We find

$$R^{th} = (0.92 \pm 0.13)\ , \qquad \frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\pi\pi)} = (0.17 \pm 0.02)\ . \tag{3.10}$$

The uncertainties in the ratios, of the order of 15%, are smaller than for the absolute values.

Finally, we do another exercise removing the $D^+D^{*-} - c.c$ and $D_S^+D_S^{*-} - c.c$ and letting only the $D^0\bar{D}^{*0} - c.c$ contribution. The results that we obtain are

$$\Gamma_\gamma = 0.46\ keV\ , \quad \Gamma_\rho = 9104.9\ keV\ , \quad \Gamma_\omega = 368.9\ keV\ , \tag{3.11}$$

$$R^{th} = 0.04\ , \qquad \frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\pi\pi)} = 5.05 \cdot 10^{-5}\ . \tag{3.12}$$

As we can see, the two ratios that we have to compare with experiment grossy differ from the experimental values, and Γ_ρ by itself becomes much bigger than the width of the $X(3872)$ ($\Gamma_X < 1.2\ MeV$).

4. Conclusions

In this paper we summarized the result of [10], where we have exploited the picture of the $X(3872)$ as a composite state of $D\bar{D}^* - c.c.$ dynamically generated by the interaction of the D and D^* states. The couplings of the state to the different $D\bar{D}^* - c.c.$ channels were taken from previous published papers. The coupling for the $D^0\bar{D}^{*0} - c.c$ is similar to the one that would be obtained using the compositeness condition of Weinberg, since the state is barely bound in the $D^0\bar{D}^{*0}$ component. However the dynamics of the model produces also couplings for the $D^+D^{*-} - c.c$ and $D_S^+D_S^{*-} - c.c$ states. Using an extension to SU(4) with an explictit breaking of this symmetry of the local hidden gauge approach, which was successfully used before in the study of related processes, one can determine the widths of the $X(3872)$ to $J/\psi\rho$, $J/\psi\omega$ and $J/\psi\gamma$ and compare with the ratios determined experimentally in recent works. We find a very good agreement with the experimental results. We see that the absolute rates obtained for the different widths are also reasonable and their sum within errors, $(1.6 \pm 0.6)\ MeV$, is compatible with the recent total X(3972) upper limit of the width, $\Gamma = 1.2\ MeV$.

We have also conducted a test neglecting the charged and strange components of the wave function, thus having only the $D^0\bar{D}^{0*} - c.c.$ component. The ratios obtained are in great disagreement with experiment and the absolute value for the $X(3872)$ partial width into $J/\psi\rho$ largely exceeds the experimental upper bound for the total width of the $X(3872)$. This exercise confirms the relevance of the charged channels and shows that the $X(3872)$ behaves as an approximate I=0 state. We also showed that in these processes it is the wave function at the origin what matters, or more concretely the couplings, which are related to it, and not the probability, which is bigger for the $D^0\bar{D}^{0*} - c.c.$ component, because of its small binding, but is irrelevant for processes that involve short range force, that only test small distances.

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