

$X(3915)$ as a tensor $D^*\bar{D}^*$ molecule

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Abstract. Two-photon decays of a tensor $D^*\bar{D}^*$ molecule are studied and the suggested approach is applied to the $X(3915)$ charmonium-like state under the assumption of the latter being a 2^{++} molecule — a spin partner of the $X(3872)$. It is argued that the existing experimental data disfavour such an identification of this state. Therefore, it is suggested that either the $X(3915)$ has a different exotic nature or it has to be identified as a scalar.

1 Introduction

Spectroscopy of the so-called exotic hadronic states keeps on bringing new puzzles for phenomenologists — for reviews see, for example, [1–6]. One of such states, the $X(3915)$, was observed by the Belle Collaboration in the two-photon annihilation to the $\omega J/\psi$ final state [7], and the variety of options for the J^{PC} quantum numbers of this state was limited to just 0^{++} and 2^{++} . Later, the BaBar Collaboration found the angular distributions in the given final state to favour the 0^{++} option [8], so that this state is often identified as the $\chi_{c0}(2P)$ charmonium [9, 10]. It has to be noticed, however, that this assignment was questioned in [11, 12]. It should also be stressed that the experimental analysis by BaBar relies on the assumption of a helicity-2 dominance for the tensor state. Indeed, it was found long ago that in the two-photon decays of the 2^{++} positronium and quarkonium the helicity-0 amplitude provides only a small relativistic correction to the dominating helicity-2 amplitude [14–16]. However, it was pointed out in [13] that the helicity-2 dominance constraint may be relaxed in the data analysis if one assumes the $X(3915)$ to be an exotic state. The authors concluded that, for the helicity-0 amplitude comparable in magnitude with the helicity-2 one, the measured angular distributions are compatible with the 2^{++} quantum numbers for the $X(3915)$. In our recent work [17] we investigated whether or not a prominent helicity-0 component was compatible with the $X(3915)$ being a $2^{++} D^*\bar{D}^*$ molecular state predicted to exist as tensor spin partner of the $X(3872)$ treated as a $D\bar{D}^*$ bound state [18]. The results obtained are discussed in this contribution.

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2 The amplitude $\gamma\gamma \rightarrow X_2 \rightarrow$ final state

We start from the amplitude of the two-photon fusion process $\gamma\gamma \rightarrow X_2$ which, irrespective of a particular nature of the tensor state X_2 , takes the form

$$M(\gamma\gamma \rightarrow X_2) = M^{\mu\nu\rho\sigma} \varepsilon_\mu(k_1) \varepsilon_\nu(k_2) \varepsilon_{\rho\sigma}(p), \quad p = k_1 + k_2, \quad (1)$$

where $\varepsilon_\mu(k_1)$, $\varepsilon_\nu(k_2)$ are the first and the second photon polarisation vector, respectively, and $\varepsilon_{\rho\sigma}$ is the X_2 polarisation tensor which obey the standard constraints,

$$k_1 \cdot \varepsilon(k_1) = k_2 \cdot \varepsilon(k_2) = 0, \quad p^\rho \varepsilon_{\rho\sigma}(p) = p^\sigma \varepsilon_{\rho\sigma}(p) = g^{\rho\sigma} \varepsilon_{\rho\sigma}(p) = 0. \quad (2)$$

Since there exist in total four independent, gauge invariant two-photon structures,

$$S_{\rho\sigma}^{(1)} \propto g_{\rho\sigma} (\partial_\alpha F_{\mu\nu}^{(1)}) (\partial^\alpha F^{(2)\mu\nu}), \quad (3)$$

$$S_{\rho\sigma}^{(2)} \propto (\partial_\rho F_{\mu\nu}^{(1)}) (\partial_\sigma F^{(2)\mu\nu}) + (\partial_\sigma F_{\mu\nu}^{(1)}) (\partial_\rho F^{(2)\mu\nu}) - \frac{1}{2} g_{\rho\sigma} (\partial_\alpha F_{\mu\nu}^{(1)}) (\partial^\alpha F^{(2)\mu\nu}), \quad (4)$$

$$S_{\rho\sigma}^{(3)} \propto (\partial_\rho \partial_\sigma F_{\mu\nu}^{(1)}) F^{(2)\mu\nu} + F_{\mu\nu}^{(1)} (\partial_\rho \partial_\sigma F^{(2)\mu\nu}), \quad (5)$$

$$S_{\rho\sigma}^{(4)} \propto F_{\rho\beta}^{(1)} F_\sigma^{(2)\beta} + F_{\sigma\beta}^{(1)} F_\rho^{(2)\beta} - \frac{1}{2} g_{\rho\sigma} F_{\mu\nu}^{(1)} F^{(2)\mu\nu}, \quad (6)$$

the amplitude $M^{\mu\nu\rho\sigma}$ from (1) can be expanded as

$$M^{\mu\nu\rho\sigma} = g_{X_2 D^* \bar{D}^*} e^2 \sum_{n=1}^4 C_n e_n^{\mu\nu\rho\sigma} \quad (7)$$

in a complete set of four tensors $\{e_n^{\mu\nu\rho\sigma}\}$ ($n = 1..4$) which are defined by the structures (3)-(6) and which can be chosen to be mutually orthogonal, normalised, symmetric and transversal,

$$e_m^{\mu\nu\rho\sigma} e_n^{\mu\nu\rho\sigma} = \delta_{mn}, \quad e_n^{\mu\nu\rho\sigma} = e_n^{\mu\nu\sigma\rho}, \quad k_{1\mu} e_n^{\mu\nu\rho\sigma} = k_{2\nu} e_n^{\mu\nu\rho\sigma} = 0, \quad m, n = \overline{1, 4}. \quad (8)$$

In particular, for real photons, a possible choice of such tensors is given by [17]

$$e_1^{\mu\nu\rho\sigma} = \frac{1}{2\sqrt{2}} g^{\rho\sigma} \left(g^{\mu\nu} - \frac{k_1^\mu k_2^\nu}{(k_1 \cdot k_2)} \right), \quad (9)$$

$$e_2^{\mu\nu\rho\sigma} = \frac{1}{\sqrt{2}} \left(\frac{k_1^\rho k_2^\sigma + k_1^\sigma k_2^\rho}{(k_1 \cdot k_2)} - \frac{1}{2} g^{\rho\sigma} \right) \left(g^{\mu\nu} - \frac{k_1^\mu k_2^\nu}{(k_1 \cdot k_2)} \right), \quad (10)$$

$$e_3^{\mu\nu\rho\sigma} = \frac{(k_1^\rho k_1^\sigma + k_2^\rho k_2^\sigma)}{2(k_1 \cdot k_2)} \left(g^{\mu\nu} - \frac{k_1^\mu k_2^\nu}{(k_1 \cdot k_2)} \right), \quad (11)$$

$$e_4^{\mu\nu\rho\sigma} = \frac{1}{2\sqrt{2}} \left(\frac{k_{1\sigma} k_{2\mu} g_{\nu\rho} + k_{1\rho} k_{2\mu} g_{\nu\sigma} - (k_{1\sigma} k_{2\rho} + k_{1\rho} k_{2\sigma}) g_{\mu\nu}}{(k_1 \cdot k_2)} - g_{\mu\sigma} \left(g^{\nu\rho} - \frac{k_1^\nu k_2^\rho}{(k_1 \cdot k_2)} \right) - g_{\mu\rho} \left(g^{\nu\sigma} - \frac{k_1^\nu k_2^\sigma}{(k_1 \cdot k_2)} \right) + g_{\rho\sigma} \left(g^{\mu\nu} - \frac{k_1^\mu k_2^\nu}{(k_1 \cdot k_2)} \right) \right). \quad (12)$$

It can be demonstrated that, due to the properties of the polarisation tensor $\varepsilon_{\rho\sigma}(p)$, only the coefficient C_4 and the linear combination $(C_2 \sqrt{2} - C_3)$ contribute to the helicity-2 and helicity-0 amplitude, respectively, of the two-photon annihilation process which is assumed to proceed through the formation of the tensor state X_2 [17]. Then, for any final state f , the angular distribution takes a universal form,

$$\frac{d\sigma(\gamma\gamma \rightarrow X_2 \rightarrow f)}{d \cos \theta} = \text{const}_f \left[|A_0|^2 f_0^{(f)}(\cos \theta) + 2|A_{\pm 2}|^2 f_2^{(f)}(\cos \theta) \right], \quad (13)$$

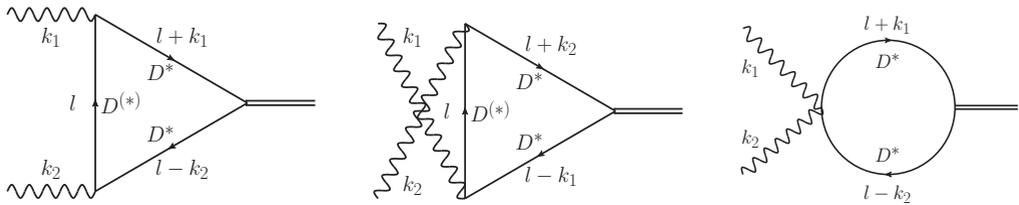


Figure 1. Diagrams contributing to amplitude (1) in the molecule picture of the $X(3915)$.

where the functions $f_0^{(f)}$ and $f_2^{(f)}$ depend on the particular final state and are given by the normalised helicity-0 and helicity-2 distribution, respectively — see, for example, the distributions derived in [13, 17, 19]. The dynamics of the reaction is encoded in the helicity amplitudes A_0 and $A_{\pm 2}$ trivially related to the aforementioned combinations of the coefficients C_n ,

$$A_0 = C_2 \sqrt{2} - C_3, \quad A_{\pm 2} = \sqrt{\frac{3}{2}} C_4. \quad (14)$$

It also proves convenient to introduce a ratio of the amplitudes,

$$R \equiv \frac{2|A_{\pm 2}|^2}{|A_0|^2}, \quad (15)$$

which defines the relative strength of the helicity-0 and helicity-2 contributions to the probability. In particular, the total cross section can be presented in the form

$$\sigma(\gamma\gamma \rightarrow X_2 \rightarrow \text{final state}) = \sigma_0(1 + R), \quad (16)$$

where σ_0 corresponds to the total cross section evaluated solely for the helicity-0 amplitude. If the helicity-2 component is dominant, like for the genuine tensor quarkonium [16], $R \gg 1$.

3 Ratio of the helicity amplitudes from data

If one assumes the $X(3915)$ to be an S -wave molecular state with the quantum numbers 2^{++} then the only plausible candidate for such a resonance is the $D^* \bar{D}^*$ molecule. Then, its dominating production/decay mechanism proceeds through the S -wave $X_2 \rightarrow D^* \bar{D}^*$ vertex preceded/followed by $D^{(*)}$ -meson loops, as depicted in Fig. 1. It is important to note that, while each individual coefficient C_n defined in (7) and given by a loop integral diverges, the combination $C_2 \sqrt{2} - C_3$ (and, therefore, the helicity-0 contribution to the two-photon width of the $X(3915)$) appears to be finite [17], so that one needs only one observable to completely fix the model.

However, before we proceed to the full calculation, we make an instructive exercise and study the dependence of the helicity-0 contribution to the two-photon width on the mass of the resonance. To make things even more transparent, we evaluate the ratio $\Gamma_0(M_{X_2})/\Gamma_0^{\text{ph}}$, where $\Gamma_0^{\text{ph}} \equiv \Gamma_0(M_{X_2}^{\text{ph}})$ with $M_{X_2}^{\text{ph}} = 3915$ MeV. In this ratio, the coupling constant $g_{X_2 D^* \bar{D}^*}$ drops out since it scales both helicity components and, therefore, the result is insensitive to the details of the molecule coupling to its constituents and as such is a prediction of the model, although it is known to carry a significant mass dependence itself, $g_{X_2 D^* \bar{D}^*}^2 \propto \sqrt{M_{\text{th}} - M_{X_2}}$, for near threshold states [20, 21].

The result of the calculations is depicted in Fig. 2 and demonstrates that, near the threshold, the helicity-0 part to the width vanishes as a result of strong cancellations between different contributions to the amplitude. In other words, near the threshold, helicity-2 dominance holds also for the $D^*\bar{D}^*$ molecule, in analogy to regular charmonia. However, since the mass of the $X(3915)$ is significantly below the $D^*\bar{D}^*$ threshold, further considerations appear to be necessary.

In order to proceed to the calculation of the two-photon width of the $X(3915)$ one needs to estimate the coupling $g_{X_2 D^* \bar{D}^*}$. Typically, as was mentioned above, the coupling constant of a molecule to its constituents can be evaluated through its binding energy [20, 21], however, in case of the $X(3915)$ as a $D^*\bar{D}^*$ molecule, the binding energy appears to be as large as about 100 MeV that entails uncontrolled finite-range corrections to the coupling obtained this way. We choose to bypass this problem by employing an additional assumption that the $X(3915)$ is a spin-2 partner of the $X(3872)$ treated as the $D\bar{D}^*$ molecule. Under this assumption, the couplings $g_{X_1 D\bar{D}^*}$ and $g_{X_2 D^* \bar{D}^*}$ are related by the Heavy-Quark Spin Symmetry (HQSS) which is expected to be accurate up to the corrections¹ governed by a fairly small parameter $\Lambda_{\text{QCD}}/m_c \simeq 1/5$. Since the binding energy of the $X(3872)$ is tiny [10],

$$E_B = m_0 + m_{*0} - M_{X_1} = 0.01 \pm 0.20 \text{ MeV}, \quad (17)$$

where m_0 and m_{*0} are the masses of the neutral D and D^* mesons, respectively, the finite-range corrections to the result for the coupling $g_{X_1 D\bar{D}^*}$ derived from value (17) [22] are also tiny, and the main uncertainty comes from the accuracy of the binding energy extraction from the data — see the error in (17). For the reasons explained below we choose the maximal value $E_B = 0.21$ MeV consistent with the experimental result (17). This allows us to arrive at the following theoretical prediction for the two-photon decay width of the $X(3915)$:

$$\Gamma_{\text{th}}(X_2 \rightarrow \gamma\gamma) = \Gamma_0(X_2 \rightarrow \gamma\gamma) [1 + R], \quad (18)$$

where, as before, $\Gamma_0(X_2 \rightarrow \gamma\gamma)$ denotes the width evaluated solely for the helicity-0 amplitude [17],

$$\Gamma_0(X_2 \rightarrow \gamma\gamma) \lesssim 0.015 \text{ keV}. \quad (19)$$

We may now employ the result from (18) to extract the ratio R from the data on $\Gamma(X(3915) \rightarrow \gamma\gamma)$ for which we take the value

$$\Gamma_{\text{exp}}(X(3915) \rightarrow \gamma\gamma) \simeq 0.18 \text{ keV} \quad (20)$$

consistent with various measurements performed by Belle and BaBar [10] — see a detailed discussion of the issue in [17].

Therefore, in order to reconcile the theoretical result from (18) with the experimental one contained in (20) one needs as large ratios R as

$$R \gtrsim 11 \gg 1, \quad (21)$$

and it is important to notice that smaller values of the $X(3872)$ binding E_B would result in even larger values of R in (21) that justifies our above-mentioned choice of the maximal E_B consistent with the data.

4 Conclusions

In conclusion, let us summarise the results obtained in this work and give an outlook.

¹The role of HQSS violating effects for the molecular partners in the c - and b -quark sectors is discussed, for example, in [23, 24].

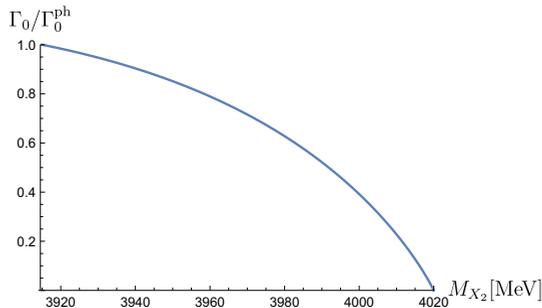


Figure 2. The helicity-0 contribution to the width, $\Gamma_0(X_2 \rightarrow \gamma\gamma)$, in units of its physical value (that is, its value at the mass 3915 MeV) as a function of the mass of the X_2 state. In this ratio, the binding energy E_B is cancelled.

Motivated by the claim made in [13], we investigate the possibility that the $X(3915)$ charmonium-like state may be identified as a tensor $D^*\bar{D}^*$ molecule and as such may have a prominent helicity-0 component in its wave function which would allow one to treat the $X(3915)$ as a helicity-0 realisation of the $\chi_{c2}(3930)$ state.² Thus, we study the two-photon annihilation processes proceeding through the $X(3915)$ and, in particular, evaluate the two-photon decay width of this state. We find that, for the tensor $D^*\bar{D}^*$ molecule, the helicity-0 component vanishes as the binding energy tends to zero while the helicity-2 piece (which contains an unknown counter term) is expected to be finite, unless the $X(3915)$ completely decouples from the $\gamma\gamma$ channel in this limit. Thus, it appears natural that the $X(3915)$, as a shallow bound state, shares the feature of a helicity-2 dominance with regular charmonia.

As a next step, we employ the Occam’s razor principle to identify the tensor $X(3915)$ state with the hypothetical spin-2 partner of the $X(3872)$ treated as an axial-vector $D\bar{D}^*$ molecule. This allows us to use the HQSS constraints to relate the coupling constant of the $X(3915)$ to the $D^*\bar{D}^*$ pair with the experimentally measured binding energy of the $X(3872)$. Then we evaluate the contribution of the helicity-0 amplitude to the two-photon decay width of the $X(3915)$, which is finite and comes out as a prediction of the model, and argue that the experimental data presently available favour a scenario in which the contribution of the helicity-2 amplitude dominates over the helicity-0 one, similarly to the case of the genuine 2^{++} charmonium. Therefore, if the $X(3915)$ is indeed dominated by the helicity-0 contribution of a nearby tensor state, as suggested in [13], its nature would require some exotic interpretation related neither with regular quarkonia nor with the $D^*\bar{D}^*$ spin partner of the $X(3872)$. However, an important disclaimer for the results and conclusions obtained in this work is that the analysis performed is subject to several uncertainties which are difficult to quantify, given the present status of the experimental data as well as our theoretical understanding of the charmonium spectrum above the open-flavour thresholds. We expect that these uncertainties could be reduced in future studies.

An alternative scenario for the $X(3915)$ would be to assign it the quantum numbers 0^{++} but, to avoid the criticisms contained in [11, 12], to treat it as an exotic scalar. For example, in [25], the $X(3915)$ was proposed to be a scalar $D_s\bar{D}_s$ molecule. The scalar $D^*\bar{D}^*$ molecule option also looks plausible for the $X(3915)$, however, it requires an additional experimental input to fix the model. This work is in progress and will be reported elsewhere.

²We adopt the naming scheme defined in the RPP [10], so that calling the state $\chi_{c2}(3930)$ only refers to its quantum numbers and does not imply a $\bar{c}c$ assignment for this state.

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