Latest Developments in Heavy Meson Spectroscopy

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I discuss developments in heavy meson spectroscopy. In particular, I consider the system of $c\bar{s}$ mesons and the puzzling state X(3872), with focus on the strategies for their classification.

1 Introduction

In the last decade, many new charm and beauty hadrons have been discovered. Some of them fit the quark model scheme, others still need to be properly classified. Here I focus on $c\bar{s}$ mesons and, to introduce the topic, I describe the properties of mesons with a single heavy quark in the infinite heavy quark mass limit. Then, I turn to the state X(3872) observed in the hidden charm spectrum.

Before the B-factory era, the $c\bar{s}$ spectrum consisted of the pseudoscalar $D_s(1968)$ and vector $D_s^*(2112)$ mesons, s-wave states of the quark model, and of the axial-vector $D_{s1}(2536)$ and tensor $D_{s2}(2573)$ mesons, p-wave states. In 2003, two narrow resonances were discovered: $D_{sJ}(2317)$ and $D_{sJ}^*(2460)$ with $J^P = 0^+, 1^+$ [1, 2]. Their identification as $c\bar{s}$ states was debated [3]; however, they have the right quantum numbers to complete the p-wave multiplet, and their radiative decays occur accordingly, so that their interpretation as ordinary $c\bar{s}$ mesons seems natural and now widely accepted [3–5]. Afterwards, two other $c\bar{s}$ mesons decaying to DK were observed: $D_{sJ}(2860)$ [6] and $D_{sJ}(2700)$ [7], the latter with $J^P = 1^-$. Later, in [8] it was found that $D_{sJ}(2700)$ is likely the first radial excitation of D_s^*. In [8] also another state was observed: $D_{sJ}(3040)$. As discussed in Section 3, the predictions for the decays of $D_{sJ}(2860)$, $D_{sJ}(2700)$ and $D_{sJ}(3040)$ following from different identifications can be used for the classification [9, 10].

In Section 4, after briefly recalling some of the latest news in the spectroscopy of hidden charm and beauty mesons, I survey the properties of X(3872) and study a few radiative decay modes which are useful to shed light on its structure.

2 Hadrons containing a single heavy quark Q

The description of mesons with a single heavy quark Q is simplified in QCD in the heavy quark $m_Q \to \infty$ limit, when the spin s_Q of the heavy quark and the angular momentum

s_ℓ of the light degrees of freedom: $s_\ell = s_{\bar q} + \ell$ ($s_{\bar q}$ being the light antiquark spin and ℓ the orbital angular momentum of the light degrees of freedom relative to Q) are decoupled. Hence spin-parity s_ℓ^P of the light degrees of freedom is conserved in strong interactions [11] and mesons can be classified as doublets of s_ℓ^P. Two states with $J^P = (0^-, 1^-)$, denoted as (P, P^*), correspond to $\ell = 0$ (the *fundamental* doublet). The four states corresponding to $\ell = 1$ can be collected in two doublets, (P_0^*, P_1') with $s_\ell^P = \frac{1}{2}^+$ and $J^P = (0^+, 1^+)$, (P_1, P_2) with $s_\ell^P = \frac{3}{2}^+$ and $J^P = (1^+, 2^+)$. For $\ell = 2$ the doublets have $s_\ell^P = \frac{3}{2}^-$, consisting of states with $J^P = (1^-, 2^-)$, or $s_\ell^P = \frac{5}{2}^-$ with $J^P = (2^-, 3^-)$ states. And so on. For each doublet, one can consider a tower of similar states corresponding to their radial excitations.

One can predict whether these states are narrow or broad. For example, strong decays of the members of the $J^P_{s_\ell} = (1^+, 2^+)_{3/2}$ doublet to the fundamental doublet plus a light pseudoscalar meson occur in d-wave. Since the rate for this process is proportional to $|\vec{p}|^5$ (in general, to $|\vec{p}|^{2\ell+1}$, p being the light pseudoscalar momentum and ℓ the angular momentum transferred in the decay), these states are expected to be narrow. On the contrary, the members of the $J^P_{s_\ell} = (0^+, 1^+)_{1/2}$ doublet decay in s-wave, hence they should be broad.

$D_s(1968)$, $D_s^*(2112)$ belong to the lowest $s_\ell^P = \frac{1}{2}^-$ doublet. $D_{s1}(2536)$, $D_{s2}(2573)$ correspond to the doublet with $J^P_{s_\ell} = (1^+, 2^+)_{3/2}$, $D_{sJ}(2317)$, $D_{sJ}^*(2460)$, to that with $J^P_{s_\ell} = (0^+, 1^+)_{1/2}$. Mixing between the two 1^+ states is allowed at $O(1/m_Q)$; however, for non-strange charm mesons such a mixing was found to be small [12, 13].

In the heavy quark limit, the various doublets are represented by effective fields: H_a for $s_\ell^P = \frac{1}{2}^-$ ($a = u, d, s$ is a light flavour index), S_a and T_a for $s_\ell^P = \frac{1}{2}^+$ and $s_\ell^P = \frac{3}{2}^+$, respectively; X_a and X'_a for $s_\ell^P = \frac{3}{2}^-$ and $s_\ell^P = \frac{5}{2}^-$, respectively:

$$
\begin{aligned}
H_a &= \frac{1+\not v}{2}[P^*_{a\mu}\gamma^\mu - P_a\gamma_5] \\
S_a &= \frac{1+\not v}{2}\left[P'^{\mu}_{1a}\gamma_\mu\gamma_5 - P^*_{0a}\right] \\
T^\mu_a &= \frac{1+\not v}{2}\left\{P^{\mu\nu}_{2a}\gamma_\nu - P_{1a\nu}\sqrt{\frac{3}{2}}\gamma_5\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\} \\
X^\mu_a &= \frac{1+\not v}{2}\left\{P^{*\mu\nu}_{2a}\gamma_5\gamma_\nu - P^{*\prime}_{1a\nu}\sqrt{\frac{3}{2}}\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\} \\
X'^{\mu\nu}_a &= \frac{1+\not v}{2}\left\{P^{\mu\nu\sigma}_{3a}\gamma_\sigma - P^{*'\alpha\beta}_{2a}\sqrt{\frac{5}{3}}\gamma_5\left[g^\mu_\alpha g^\nu_\beta - \frac{1}{5}\gamma_\alpha g^\nu_\beta(\gamma^\mu - v^\mu) - \frac{1}{5}\gamma_\beta g^\mu_\alpha(\gamma^\nu - v^\nu)\right]\right\} ;
\end{aligned}
\tag{1}
$$

the various operators annihilate mesons of four-velocity v (conserved in strong interactions) and contain a factor $\sqrt{m_P}$. At the leading order in the heavy quark mass and light meson momentum expansion the decays $F \to HM$ ($F = H, S, T, X, X'$ and M a light pseudoscalar meson) can be described by the Lagrangian interaction terms (invariant under chiral and heavy-quark spin-flavour transformations) [14,15]:

$$
\begin{aligned}
\mathcal{L}_H &= g\, Tr[\overline{H}_a H_b \gamma_\mu \gamma_5 \mathcal{A}^\mu_{ba}] \\
\mathcal{L}_S &= h\, Tr[\overline{H}_a S_b \gamma_\mu \gamma_5 \mathcal{A}^\mu_{ba}] \,+\, h.c.\,, \\
\mathcal{L}_T &= \frac{h'}{\Lambda_\chi} Tr[\overline{H}_a T^\mu_b (iD_\mu \not{\mathcal{A}} + i \not{D} \mathcal{A}_\mu)_{ba} \gamma_5] + h.c. \qquad (2)\\
\mathcal{L}_X &= \frac{k'}{\Lambda_\chi} Tr[\overline{H}_a X^\mu_b (iD_\mu \not{\mathcal{A}} + i \not{D} \mathcal{A}_\mu)_{ba} \gamma_5] + h.c. \\
\mathcal{L}_{X'} &= \frac{1}{{\Lambda_\chi}^2} Tr[\overline{H}_a X'^{\mu\nu}_b [k_1 \{D_\mu, D_\nu\} \mathcal{A}_\lambda + k_2 (D_\mu D_\nu \mathcal{A}_\lambda + D_\nu D_\lambda \mathcal{A}_\mu)]_{ba} \gamma^\lambda \gamma_5] + h.c.
\end{aligned}
$$

where $D_{\mu ba} = -\delta_{ba}\partial_\mu + \frac{1}{2}\left(\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger\right)_{ba}$, $\mathcal{A}_{\mu ba} = \frac{i}{2}\left(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger\right)_{ba}$ and $\xi = e^{\frac{i\mathcal{M}}{f_\pi}}$. $\mathcal{M}$ is a matrix containing the light pseudoscalar meson fields ($f_\pi = 132$ MeV), $\Lambda_\chi \simeq 1$ GeV the chiral symmetry-breaking scale. $\mathcal{L}_S$, $\mathcal{L}_T$ describe decays of positive parity heavy mesons with the emission of light pseudoscalar mesons in s- and d- wave, respectively, g, h and h' representing effective coupling constants. $\mathcal{L}_X$, $\mathcal{L}_{X'}$ describe the decays of negative parity mesons with the emission of light pseudoscalar mesons in p- and f- wave with couplings k', k_1 and k_2. The structure of the Lagrangian terms for radial excitations of the doublets is the same, but the couplings $g, h, \ldots$ have to be substituted by $\tilde{g}, \tilde{h}, \ldots$.

3 $c\bar{s}$ mesons: The case of $D_{sJ}(2860)$, $D_{sJ}(2700)$ and $D_{sJ}(3040)$

In 2006, BaBar observed a heavy $c\bar{s}$ meson, $D_{sJ}(2860)$, decaying to D^0K^+ and D^+K_S, with mass $M = 2856.6 \pm 1.5 \pm 5.0$ MeV and width $\Gamma = 47 \pm 7 \pm 10$ [6]. Shortly after, analysing the D^0K^+ invariant mass distribution in $B^+ \to \overline{D}^0 D^0 K^+$ Belle Collaboration [7] found a $J^P = 1^-$ resonance, $D_{sJ}(2710)$, with $M = 2708 \pm 9^{+11}_{-10}$ MeV and $\Gamma = 108 \pm 23^{+36}_{-31}$ MeV.

In order to classify $D_{sJ}(2860)$ and $D_{sJ}(2710)$, their strong decays were studied in [9], comparing the predictions which follow from different quantum number assignments. I summarize here the main results, starting with $D_{sJ}(2860)$. A new $c\bar{s}$ meson decaying to DK can be either the $J^P = 1^-$ state of the $s_\ell^P = \frac{3}{2}^-$ doublet, or the $J^P = 3^-$ state of the $s_\ell^P = \frac{5}{2}^-$ one, in both cases with lowest radial quantum number. Otherwise $D_{sJ}(2860)$ could be a radial excitation of already observed $c\bar{s}$ mesons: the first radial excitation of D_s^* ($J^P = 1^-$ $s_\ell^P = \frac{1}{2}^-$) or of $D_{sJ}(2317)$ ($J^P = 0^+$ $s_\ell^P = \frac{1}{2}^+$) or of $D^*_{s2}(2573)$ ($J^P = 2^+$ $s_\ell^P = \frac{3}{2}^+$). As for $D_{sJ}(2710)$, having $J^P = 1^-$, it could be either the first radial excitation belonging to the $s_\ell^P = \frac{1}{2}^-$ doublet ($D_s^{*\prime}$) or the low lying state with $s_\ell^P = \frac{3}{2}^-$ (D^*_{s1}).

For both mesons the ratios of decay rates $R_1 = \frac{\Gamma(D_{sJ} \to D^* K)}{\Gamma(D_{sJ} \to DK)}$ $R_2 = \frac{\Gamma(D_{sJ} \to D_s \eta)}{\Gamma(D_{sJ} \to DK)}$ ($D^{(*)}K = D^{(*)+}K_S + D^{(*)0}K^+$), obtained using eqs. (1) and (2), are useful to discriminate among the various assignments [9]. Table 1 reports such ratios in the various cases; it is interesting that they do not depend on the coupling constants, but only on the quantum numbers.

$D_{sJ}(2860)$	R_1	R_2
$s_\ell^p = \frac{1}{2}^-, J^P = 1^-, n = 2$	1.23	0.27
$s_\ell^p = \frac{1}{2}^+, J^P = 0^+, n = 2$	0	0.34
$s_\ell^p = \frac{3}{2}^+, J^P = 2^+, n = 2$	0.63	0.19
$s_\ell^p = \frac{3}{2}^-, J^P = 1^-, n = 1$	0.06	0.23
$s_\ell^p = \frac{5}{2}^-, J^P = 3^-, n = 1$	0.39	0.13
$D_{sJ}(2710)$	R_1	R_2
$s_\ell^p = \frac{1}{2}^-, J^P = 1^-, n = 2$	0.91	0.20
$s_\ell^p = \frac{3}{2}^-, J^P = 1^-, n = 1$	0.043	0.163

Table 1: Predicted ratios R_1 and R_2 (see text for definitions) for the various assignment of quantum numbers to $D_{sJ}(2860)$ and $D_{sJ}(2710)$.

I first consider $D_{sJ}(2860)$. The case $s_\ell^p = \frac{3}{2}^-, J^P = 1^-, n = 1$ can be excluded since, using $k' \simeq h' \simeq 0.45 \pm 0.05$ [13], would give a width incompatible with the measurement. In the assignment $s_\ell^p = \frac{1}{2}^+, J^P = 0^+, n = 2$ the decay to D^*K is forbidden. However, in this case $D_{sJ}(2860)$ should have a spin partner with $J^P = 1^+$ decaying to D^*K with a small width and mass around 2860 MeV. To explain the absence of such a signal one should invoke a mechanism favoring the production of the 0^+ $n = 2$ state and inhibiting that of 1^+ $n = 2$ state, which is difficult to imagine.

Among the remaining possibilities, the assignment $s_\ell^p = \frac{5}{2}^-, J^P = 3^-, n = 1$ seems the most likely one. In this case the small DK width is due to the kaon momentum suppression factor: $\Gamma(D_{sJ} \to DK) \propto q_K^7$. The spin partner, D_{s2}^*, has $s_\ell^p = \frac{5}{2}^-, J^P = 2^-$, decaying to D^*K and not to DK. It would also be narrow in the $m_Q \to \infty$ limit, where the transition $D_{s2}^* \to D^*K$ occurs in f-wave. As an effect of $1/m_Q$ corrections this decay can occur in p-wave, so that D_{s2}^* could be broader; hence, it is not necessary to invoke a mechanism inhibiting the production of this state with respect to $J^P = 3^-$. If $D_{sJ}(2860)$ has $J^P = 3^-$, it is not expected to be produced in non leptonic B decays such as $B \to DD_{sJ}(2860)$. Actually, in the Dalitz plot analysis of $B^+ \to \overline{D}^0 D^0 K^+$ no signal of $D_{sJ}(2860)$ was found [7].

In the latest BaBar analysis [8] $D_{sJ}(2860)$ has been observed decaying to DK and D^*K final states, hence excluding the assignment $J^P = 0^+$. However, the measurement [8]

$$\frac{BR(D_{sJ}(2860) \to D^*K)}{BR(D_{sJ}(2860) \to DK)} = 1.10 \pm 0.15_{stat} \pm 0.19_{syst}$$

leaves the identification of $D_{sJ}(2860)$ still an open issue. A confirmation that $D_{sJ}(2860)$ is a $J^P = 3^-$ state could be the detection of its non-strange partner D_3, also expected to be narrow, that can be produced in semileptonic and in non leptonic B decays [16].

Let us now look at $D_{sJ}(2710)$. As Table 1 shows, R_1 is very different if $D_{sJ}(2710)$ is $D_s^{*\prime}$ or

D^*_{s1}. Comparing the results in that Table with the BaBar measurement [8]:

$$\frac{BR(D_{sJ}(2710) \to D^*K)}{BR(D_{sJ}(2710) \to DK)} = 0.91 \pm 0.13_{stat} \pm 0.12_{syst}$$

allows to conclude that $D_{sJ}(2710)$ is most likely $D_s^{*\prime}$, the first radial excitation of $D_s^*(2112)$.

From the computed widths, assuming that $\Gamma(D_{sJ}(2710))$ is saturated by the considered modes and identifying $D_{sJ}(2710)$ with $D_s^{*\prime}$, the coupling $\tilde{g}$, analogous to g in (2) when H is the doublet of the $n = 2$ radial excitations, can be determined $\tilde{g} = 0.26 \pm 0.05$, a value similar to those obtained for analogous effective couplings [17]. This result for $\tilde{g}$ can provide information about D_s', the spin partner of $D_{sJ}(2710)$ having $J^P = 0^-$; it is the first radial excitation of D_s and can decay to $D^{*0}K^+$, $D^{*+}K^0_{S(L)}$, $D_s^*\eta$. In the heavy quark limit, these partners are degenerate. Using the result for $\tilde{g}$ one predicts $\Gamma(D_s') = (70 \pm 30)$ MeV.

Identifying $D_{sJ}(2700)$ with $D_s^{*\prime}$, its charmed non strange partners are $D^{*\prime +}$ and $D^{*\prime 0}$, the radial excitations of $D^{*+,0}$. Their masses can be fixed to 2600 ± 50 MeV assuming that $D_{sJ}(2700)$ is heavier by an amount of the size of the strange quark mass. $D^{*\prime}$ can decay to $D^{*\prime} \to D\pi$, D_sK, $D\eta$, $D^*\pi$, $D^*\eta$ so that the previous result for $\tilde{g}$ gives $\Gamma(D^{*\prime +(0)}) = (128 \pm 61)$ MeV. Noticeably, studying $D^+\pi^-$, $D^0\pi^+$, $D^{*+}\pi^-$ systems, BaBar found four new charmed non strange mesons [18] and, among these, the state $D^*(2600)$ likely to be identified with $D^{*\prime}$ (the non strange partner of $D_{sJ}(2700)$), and the state $D(2550)^0$ likely to be the spin partner of $D^*(2600)$, corresponding to the first radial excitation of the D meson. Comparison of the measured widths $\Gamma(D^*(2600)) = 93 \pm 6 \pm 13$ MeV, $\Gamma(D(2550)) = 130 \pm 12 \pm 13$ MeV with the prediction for $\Gamma(D^{*\prime +(0)})$ supports the proposed identification.

In [8] another broad structure was observed, $D_{sJ}(3040)$, with $M = 3044 \pm 8_{stat}(^{+30}_{-5})_{syst}$ MeV and $\Gamma = 239 \pm 35_{stat}(^{+46}_{-42})_{syst}$ MeV. $D_{sJ}(3040)$ decays to D^*K and not to DK, hence it has unnatural parity: $J^P = 1^+, 2^-, 3^+, \cdots$. The lightest not yet observed states with such quantum numbers are the two $J^P = 2^-$ states belonging to the doublets with $s_\ell = 3/2$ and $s_\ell = 5/2$ denoted as D_{s2} and D'^*_{s2}, respectively. The identification with the radial excitations with $n = 2$, $J^P = 1^+$, and $s_\ell = 1/2$ (the meson $\tilde{D}'_{s1}$) or $s_\ell = 3/2$ (the meson $\tilde{D}_{s1}$) is also possible. Notice that, if the identification of $D_{sJ}(2860)$ as the $J^P_{s_\ell} = 3^-_{5/2}$ meson were experimentally confirmed, this would disfavor the assignment of $D_{sJ}(3040)$ to its spin partner $D^{*\prime}_{s2}$ with $J^P_{s_\ell} = 2^-_{5/2}$, since a mass inversion in a spin doublet seems unlikely. For a similar reason, one would also disfavor the identification of $D_{sJ}(3040)$ with D_{s2}, although in that case the two mesons would belong to different doublets. The strong decays of $D_{sJ}(3040)$ to a charmed meson and a light pseudoscalar one can be evaluated using the effective Lagrangians in Eq.(2). In particular, one can compute the ratio $R_1 = \frac{\Gamma(D_{sJ}(3040) \to D_s^*\eta)}{\Gamma(D_{sJ}(3040) \to D^*K)}$ ($D^*K = D^{*0}K^+ + D^{*+}K^0_S$), with results collected in Table 2 [10]. The spread among them is useful to discriminate among the assignments, in particular between $\tilde{D}'_{s1}$ and $D^{*\prime}_{s2}$.

The mass of $D_{sJ}(3040)$ is large enough to allow decays to $(D_0^*, D_1')K$, $(D_1, D_2^*)K$ and $D^*_{s0}\eta$, with different features in the four cases. Other allowed modes are into DK^* or $D_s\phi$ which can be described using an approach based on effective Lagrangian terms [19]. The results

decay modes	$\tilde{D}'_{s1}$ (n=2) ($J^P_{s_\ell} = 1^+_{1/2}$)	$\tilde{D}_{s1}$ (n=2) ($J^P_{s_\ell} = 1^+_{3/2}$)	D_{s2} (n=1) ($J^P_{s_\ell} = 2^-_{3/2}$)	$D^{*\prime}_{s2}$ (n=1) ($J^P_{s_\ell} = 2^-_{5/2}$)
D^*K, $D^*_s\eta$	$s-$ wave	$d-$ wave	$p-$ wave	$f-$ wave
R_1	0.34	0.20	0.245	0.143
D^*_0K, $D^*_{s0}\eta$, D'_1K	$p-$ wave	$p-$ wave	$d-$ wave	$d-$ wave
D_1K	$p-$ wave	$p-$ wave	-	$d-$ wave
D^*_2K	$p-$ wave	$p-$ wave	$s-$ wave	$d-$ wave
DK^*, $D_s\phi$	$s-$ wave	$s-$ wave	$p-$ wave	$p-$ wave
	$\Gamma \simeq 140$ MeV	$\Gamma \simeq 20$ MeV	negligible	negligible

Table 2: Features of the decay modes of $D_{sJ}(3040)$ for the four proposed assignments.

obtained in the four possible identifications are collected in Table 2 [10], from which some conclusions can be drawn. The determination of the wave in which a particular decay proceeds is useful to predict a hierarchy among the widths of the states in the four cases. Consequently, the two $J^P = 1^+$ are expected to be broader than the two $J^P = 2^+$ states, hence it is likely that $D_{sJ}(3040)$ should be identified with one of such two axial-vector mesons. These can be distinguished since the widths to the DK^* and $D_s\phi$ decay modes are larger for $\tilde{D}'_{s1}$ than for $\tilde{D}_{s1}$. Finally, although less probable, the identification with D_{s2} can be discarded/confirmed studying the D^*_2K $s-$wave final state.

4 Heavy quarkonium and the intriguing case of X(3872)

Besides the new charmed mesons, new heavy quarkonium or quarkonium-like states were observed. Some have been classified as standard quarkonia: the charmonia h_c [20], $\eta_c(2S)$ [21], $\chi_{c2}(2P)$ [22], and, in the beauty case, the $\eta_b(1S)$ [23], $h_b(1P)$ [24,25] and $h_b(2P)$ [25]. Others are still awaiting for the right interpretation, since not only their quantum numbers are not established, but even their $Q\overline{Q}$ structure is questioned [26]. Among these, the charged $Z(4430)^-$ state seen by Belle Collaboration in $B \to Z^-K$, decaying to $\psi(2S)\pi^-$, $\chi_{c1}\pi^-$ [27]. The minimal quark content of this state would be $c\bar{c}u\bar{d}$, identifying it necessarily as an exotic state. Search for Z^- was performed by BaBar, but no signal was found [28]. Later on, Belle found other charmonium-like charged Z states [29] and, more recently, also bottomonium-like $Z_b(10610)$ and $Z_b(10650)$ states decaying to $\Upsilon(nS)\pi^\pm$ (n=1,2,3) and $h_b(mP)\pi^\pm$ (m=1,2) [30]. These states require confirmation, too.

Here I focus on the state $X(3872)$, discovered in 2003 by Belle Collaboration in $B^\pm \to K^\pm X \to K^\pm J/\psi\pi^+\pi^-$ decays [31] and confirmed by BaBar [32], CDF [33] and D0 [34] Collaborations. The PDG resonance parameters are: $M(X) = 3871.57 \pm 0.25$ MeV and $\Gamma(X) < 2.3$ MeV (90/% C.L.) [35]. Looking at the $J/\psi\pi^\pm\pi^0$ channel, no charged partners were found [36]. The mode $X \to J/\psi\gamma$ allows to fix charge conjugation of X to $C = +1$. Moreover, a $D^0\overline{D}^0\pi^0$

enhancement in $B \to D^0\overline{D}^0\pi^0 K$ decay was reported [37] with $\frac{B(X\to D^0\overline{D}^0\pi^0)}{B(X\to J/\psi\pi^+\pi^-)} = 9 \pm 4$, hence X mainly decays into final states with open charm mesons.

These measurements, though not fully consistent with the charmonium interpretation (as far as the mass of X is concerned), do not contradict it. However, the observation of $X \to J/\psi\pi^+\pi^-\pi^0$ with the measurement $\frac{B(X\to J/\psi\pi^+\pi^-\pi^0)}{B(X\to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$ [38] implies, considering the two modes as induced by ρ^0 and ω intermediate states, isospin violation.

The three pion decay is also important to fix the spin-parity of X. While the angular analysis in $X \to J/\psi\pi^+\pi^-$ favours $J^P = 1^+$, studies of the three pion distribution in $X \to J/\psi\omega \to J/\psi\pi\pi\pi$ are more favourable to $J^P = 2^-$ [39]. Hence, if X is a $c\bar{c}$ state it can be either the first radial excitation of χ_{c1}, χ'_{c1}, or the state η_{c2} having $J^{PC} = 2^{-+}$.

On the other hand, the peculiar features of X suggested the conjecture that it is not a charmonium state. In particular, the coincidence between its mass and the $D^{*0}\overline{D}^0$ mass: $M(D^{*0}\overline{D}^0) = 3871.2 \pm 1.0$ MeV, inspired the proposal that $X(3872)$ could be a molecule [40], a bound state of D^{*0} and $\overline{D}^0$ with small binding energy [41], an interpretation that would account for a few properties of $X(3872)$. For example, if the wave function of $X(3872)$ has various hadronic components [42] one could explain why this state seems not to have definite isospin. However, the molecular binding mechanism still needs to be clearly identified, while the description of X(3872) as a charmonium state presents alternative arguments to the molecular description [43, 44]. Concerning the isospin violation, to correctly interpret the large ratio $\frac{B(X\to J/\psi\pi^+\pi^-\pi^0)}{B(X\to J/\psi\pi^+\pi^-)}$ one has to consider that phase space effects in two and three pion modes are very different and it turns out that the isospin violating amplitude is 20% of the isospin conserving one [45]: $\frac{B(X\to J/\psi\rho^0)}{B(X\to J/\psi\omega)} \simeq 0.2$.

I focus on two studies of X decays. The first one [46] compares the charmonium versus the molecular interpretation, discussing the argument that, if X(3872) is a DD^* molecule the decay $X \to D^0\overline{D}^0\gamma$ should be dominant with respect to $X \to D^+D^-\gamma$, such decays being mainly due to the decays of its meson components [42]. In order to discuss whether this is true, in [46] the ratio $R = \frac{\Gamma(X\to D^+D^-\gamma)}{\Gamma(X\to D^0\overline{D}^0\gamma)}$ has been computed assuming that X(3872) is an ordinary $J^{PC} = 1^{++}$ charmonium state.

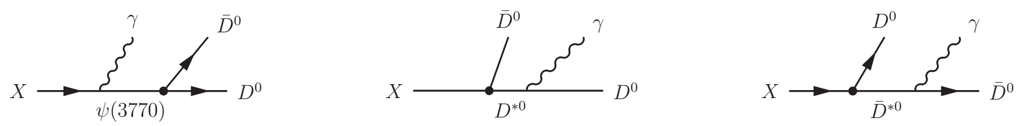

Figure 1: Diagrams describing the radiative modes $X \to D\overline{D}\gamma$.

The transition $X(3872) \to D\overline{D}\gamma$ can be studied assuming that the radiative decay amplitude is dominated by polar diagrams with D^* and the $\psi(3770)$ mesons as intermediate states nearest to their mass shell (fig.1). These amplitudes can be expressed in terms of two unknown quantities: the coupling constant $\hat{g}_1$ governing the $X\overline{D}D^*(D\overline{D}^*)$ matrix elements, and the one appearing in the $X\psi(3770)\gamma$ matrix element. For the matrix element $X\overline{D}D^*(D\overline{D}^*)$ one can use a formalism suitable to describe the interaction of the heavy charmonium with the doublet H in (1) [47]. In the multiplet:

$$(3) \qquad P^{(Q\overline{Q})\mu} = \left(\frac{1+\not{v}}{2}\right)\left(\chi_2^{\mu\alpha}\gamma_\alpha + \frac{1}{\sqrt{2}}\epsilon^{\mu\alpha\beta\gamma}v_\alpha\gamma_\beta\chi_{1\gamma} + \frac{1}{\sqrt{3}}(\gamma^\mu - v^\mu)\chi_0 + h_1^\mu\gamma_5\right)\left(\frac{1-\not{v}}{2}\right)$$

the fields χ_2, χ_1, χ_0 correspond to the spin triplet with $J^{PC} = 2^{++}, 1^{++}, 0^{++}$, respectively, while the spin singlet h_1 has $J^{PC} = 1^{+-}$. If $X(3872) = \chi'_{c1}$, it is described by χ_1. The strong interaction with the D and D^* mesons can be described by the effective Lagrangian [48]

$$(4) \qquad \mathcal{L}_1 = ig_1 Tr\left[P^{(Q\overline{Q})\mu}\overline{H}_{1a}\gamma_\mu\overline{H}_{2a}\right] + h.c. \,.$$

Using (4) the couplings XDD^* which enter in the second and the third diagrams in fig.1, can be expressed in terms of the dimensionless coupling constant $\hat{g}_1 = g_1\sqrt{m_D}$. Notice that, due to isospin symmetry, the couplings of the meson X to charged and neutral D are equal, at odds with the molecular description where X mainly couples to neutral D.

The matrix element $< D(k_1)\gamma(k,\tilde{\epsilon})|D^*(p_1,\xi) >= i\,e\,c'\,\epsilon^{\alpha\beta\tau\theta}\,\tilde{\epsilon}^*_\alpha\,\xi_\beta\,p_{1\tau}\,k_\theta$ is also required. The parameter c' accounts for the coupling of the photon to both the charm and the light quark and can be fixed from data on radiative D^{*+} decays [35].

To compute the first diagram in fig.1 the matrix element $< \psi_{(3770)}(q,\eta)\gamma(k,\tilde{\epsilon})|X(p,\epsilon) >= i\,e\,c\,\epsilon^{\alpha\beta\mu\nu}\,\tilde{\epsilon}^*_\alpha\,\epsilon_\beta\,\eta^*_\mu\,k_\nu$ is needed; c is an unknown parameter. On the other hand, the coupling $\psi(3770)D\overline{D}$ can be fixed from experiment to $g_{\psi D\overline{D}} = 25.7 \pm 1.5$.

Putting all the ingredients together one obtains the ratio $R = \frac{\Gamma(X\to D^+D^-\gamma)}{\Gamma(X\to D^0\overline{D}^0\gamma)}$, plotted in fig.2 [46] versus $\frac{c}{\hat{g}_1}$, showing that the radiative X decay into charged D mesons is always suppressed with respect to the mode with neutral D and in any case $R < 0.7$. Moreover, for small values of $\frac{c}{\hat{g}_1}$ the ratio R is tiny, so that this is not peculiar of a molecular structure of $X(3872)$.

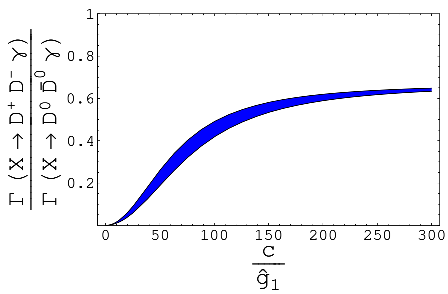

Figure 2: Ratio of $X \to D^+D^-\gamma$ to $X \to D^0\overline{D}^0\gamma$ decay widths versus the ratio of parameters $c/\hat{g}_1$.

$\hat{g}_1$ enters also in the mode $X(3872) \to D^0\overline{D}^0\pi^0$ that can be considered as induced by intermediate D^* states. The amplitude depends on the coupling constant $D^*D\pi$, proportional to the constant g in eq. (2). Using data on D^{*+} decays to $D\pi$ [35], one can derive $g = 0.64 \pm 0.07$. This allows to constrain $\hat{g}_1 < 4.5$ from the upper bound $\Gamma(X \to D^0\overline{D}^0\pi^0) < \Gamma(X(3872)) < 2.3$ MeV. Hence, a value of $\hat{g}_1$ of the typical size of the hadronic couplings can reproduce the small width of $X(3872)$.

The second analysis that I discuss also aims at shedding light on the structure of X(3872) through the calculation of its radiative decay rates to $J/\psi\gamma$ and $\psi(2S)\gamma$ assuming that it is the state χ'_{c1} [49] and using an effective Lagrangian approach which exploits spin symmetry for heavy $Q\overline{Q}$ states [50]. Unlike the heavy-light $Q\overline{q}$ mesons, in heavy quarkonia there is no heavy flavour symmetry [51], hence it would not be possible to exploit data on charmonium to obtain quantitative information on bottomonium or viceversa. However, at a qualitative level, bottomonium system can help in understanding charmonium.

A heavy $Q\overline{Q}$ state ($Q = c,\, b$) can be identified by $n^{2s+1}L_J$ as a meson with parity $P = (-1)^{L+1}$ and charge-conjugation $C = (-1)^{L+s}$: n is the radial quantum number, L the orbital angular momentum, s the spin and J the total angular momentum. Radiative transitions between states belonging to the same nL multiplet to states belonging to another $n'L'$ one are described in terms of a single coupling constant $\delta^{nLn'L'}$.

I introduce the effective fields for the states involved in the decays $X \to J/\psi\gamma$ and $X \to \psi(2S)\gamma$. Identifying X with the state χ'_{c1}, it belongs to the multiplet with $L = 1$ introduced in (3). J/ψ and $\psi(2S)$ are described by the $J^P = 1^-$ H_1 component of the doublet:

$$J = \frac{1+ \not{v}}{2}\left[H_1^\mu\gamma_\mu - H_0\gamma_5\right]\frac{1- \not{v}}{2}\ . \tag{5}$$

The effective Lagrangian describing radiative transitions among members of the P wave and of the S wave multiplets has been derived in [50]:

$$\mathcal{L}_{nP\leftrightarrow mS} = \delta_Q^{nPmS}\, Tr\left[\overline{J}(mS)J_\mu(nP)\right] v_\nu F^{\mu\nu} + \text{h.c.}\,. \tag{6}$$

$F^{\mu\nu}$ the electromagnetic field strength tensor. Hence, a single constant δ_Q^{nPmS} describes all the transitions among the members of the nP multiplet and those of the mS one.

I consider the ratios $R_J^{(b)} = \frac{\Gamma(\chi_{bJ}(2P)\to\Upsilon(2S)\,\gamma)}{\Gamma(\chi_{bJ}(2P)\to\Upsilon(1S)\,\gamma)}$, proportional to $R_\delta^{(b)} = \frac{\delta_b^{2P1S}}{\delta_b^{2P2S}}$ ($J = 0, 1, 2$). From the measured branching ratios of $\chi_{bJ}(2P) \to \Upsilon(1S)\,\gamma\,, \Upsilon(2S)\,\gamma$ [35], the average value can be obtained: $R_\delta^{(b)} = 8.8 \pm 0.7$. It is reasonable that, even though the couplings might be different in the beauty and the charm cases, their ratios stay stable. Therefore, using the result for $R_\delta^{(b)}$ in the case of χ'_{c1} decays, I get:

$$R_1^{(c)} = \frac{\Gamma(\chi_{c1}(2P) \to \psi(2S)\,\gamma)}{\Gamma(\chi_{c1}(2P) \to \psi(1S)\,\gamma)} = 1.64 \pm 0.25\,. \tag{7}$$

In [52] the following ratio has been measured [1]:

$$R_X = \frac{\Gamma(X(3872) \to \psi(2S)\,\gamma)}{\Gamma(X(3872) \to \psi(1S)\,\gamma)} = 3.5 \pm 1.4\,. \tag{8}$$

In view of the underlying approximation, one can conclude that the experimental value in (8) and the theoretical prediction (7) are close enough to consider plausible the identification $X(3872) = \chi_{c1}(2P)$, in contrast to the composite scenarios, in which the mode $X(3872) \to \psi(2S)\,\gamma$ is suppressed compared to $X(3872) \to \psi(1S)\,\gamma$ [43,54].

5 Conclusions

In the last decade, many predicted charm and beauty mesons have been discovered, along with many unexpected ones. In the case of D_{sJ} mesons, the analysis of their decay modes allows to classify them as ordinary $c\bar{s}$ states, although the identification of $D_{sJ}(2860)$ is still under scrutiny.

The case of hidden charm and beauty mesons is more complicated. As for $X(3872)$, two analyses of the radiative decays of X show that the charmonium interpretation seems to be a likely one, although experimentally it is still unclear whether its spin-parity is $J^P = 1^+$ or $J^P = 2^-$.

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