Recent issues in open and hidden charm spectroscopy
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Abstract. I present a brief review of results obtained both in open and hidden charm spectroscopy, discussing the interpretation of $D_{sJ}(2860)$, $D_{sJ}(2700)$ and $X(3872)$.

Keywords: Charm spectroscopy, charmed mesons, quarkonium, exotic states, HQET

INTRODUCTION

Many new states have been recently observed in the open and hidden charm sector: $D^*_s(2317)$, $D_{sJ}(2460)$, $D_{sJ}(2700)$, $D_{sJ}(2860)$, $D'_0(2308)$, $D'_1(2440)$, together with $h_c$, $\eta_c$, $X(3872)$, $X(3940)$, $Y(3940)$, $Z(3930)$, $Y(4260)$... [1]. The need for theoretical interpretation of this states comes not only from the request of organizing the particle “zoo-ology”, but also from the interesting possibility of identifying new “exotic” structures. This is what we would like to briefly discuss in the next section devoted to the $c\bar{s}$ sector, with particular attention to the $D_{sJ}(2860)$ and a few words on $D_{sJ}(2700)$, and in the third section devoted to the hidden charm sector and, in particular, to the interpretation of $X(3872)$.

CHARMED-STRANGE MESONS AND $D_{sJ}(2860)$

The classification of the $c\bar{s}$ states is easier in the heavy-quark limit $m_c \rightarrow \infty$. In this limit the spin $s_Q$ of the heavy quark and the angular momentum $s_\ell$ of the light degrees of freedom: $s_\ell = s_{\bar{q}} + \ell$ ($s_{\bar{q}}$ light antiquark spin, $\ell$ orbital angular momentum of the light degrees of freedom relative to the heavy quark) are decoupled, and the spin-parity $s_\ell^P$ is conserved in strong interactions [2]. This makes possible to classify mesons into doublets labeled by $s_\ell^P$ (where $P$ is the parity), each containing a couple of meson of spin-parity $J^P = (s_\ell^P - 1/2, s_\ell^P + 1/2)$ and degenerate in mass. Mass differences between members of the same doublet are of order $O(1/m_c)$. The standard classification of known $c\bar{s}$ states in this scheme is given in Table[1][3]. The states labeled by $P^*_{s2}$ and $P^*_{s1}$ are still to be discovered; we discuss here a possible identification of $P_{s3}$ and $P'_{s1}$.

In the above classification the $D_{sJ}(2860)$, observed by BaBar in the $DK$ invariant mass distribution [4], can be either a $J^P = 1^-$ state, or a $J^P = 3^-$ state. Another possibility
mesons, represented by strong interaction. The interaction of these particles with the octet of light pseudoscalar

In order to evaluate them we define the fields representing the various doublets: $H_a$, for $s^P_\ell = \frac{1}{2}$, $S_a$ and $T_{\mu}$ for $s^P_\ell = \frac{1}{2}$, and $s^P_\ell = \frac{3}{2}$, respectively, and $X_a$ and $X'_{\mu\nu}$ for the doublets corresponding to $\ell = 2$, $s^P_\ell = \frac{3}{2}$, and $s^P_\ell = \frac{5}{2}$, respectively:

\[
H_a = \frac{1 + \gamma_5}{2} \left[ P^\mu_{a\gamma} \gamma^\mu - P_{a\gamma} \right], \quad S_a = \frac{1 + \gamma_5}{2} \left[ P^\mu_{1a\gamma} \gamma_5 - P_{1a\gamma} \right],
\]

\[
T_{\mu} = \frac{1 + \gamma_5}{2} \left( P^{\mu\nu}_{2a\gamma} \gamma_\nu - P_{1a\mu} \sqrt{\frac{3}{2}} \gamma_5 \left[ g_{\mu\nu} - \frac{1}{3} \gamma_\nu \gamma^\mu \right] \right),
\]

\[
X_a = \frac{1 + \gamma_5}{2} \left( P^{\mu}_{2a\gamma} \gamma_5 \gamma_\nu - P_{1a\mu} \sqrt{\frac{3}{2}} \left[ g_{\mu\nu} - \frac{1}{3} \gamma_\nu \gamma^\mu \right] \right),
\]

\[
X'_{\mu\nu} = \frac{1 + \gamma_5}{2} \left( P^{\mu\nu}_{3a\gamma} \gamma_\sigma - P_{2a\mu} \sqrt{\frac{5}{3}} \gamma_5 \left[ g_{\alpha\beta} - \frac{1}{5} \gamma_\beta \gamma^\alpha \gamma^\mu - \frac{1}{5} \gamma_\beta \gamma^\alpha \gamma^\mu \right] \right)
\]

with the various operators annihilating mesons of four-velocity $v$ which is conserved in strong interaction. The interaction of these particles with the octet of light pseudoscalar mesons, represented by $\xi = e^{i\mathcal{M}/f_\pi}$, $\Sigma = \xi^2$ and the matrix $\mathcal{M}$ containing $\pi, K$ and $\eta$ fields:

\[
\mathcal{M} = \begin{pmatrix}
\sqrt{\frac{1}{2}} \pi^0 + \sqrt{\frac{1}{6}} \eta & \pi^+ & K^+
\pi^- & -\sqrt{\frac{1}{2}} \pi^0 + \sqrt{\frac{1}{6}} \eta & K^0
K^- & K^0 & -\sqrt{\frac{1}{3}} \eta
\end{pmatrix}
\]

($f_\pi = 132$ MeV) can be described by the interaction lagrangians:

\[
\mathcal{L}_H = g \text{Tr} \left[ H_a H_b \gamma_\mu \gamma_5 A^\mu_{ba} \right]
\]

\[
\mathcal{L}_S = i h \text{Tr} \left[ H_a S_b \gamma_5 \gamma_\mu A^\mu_{ba} \right] + h.c.,
\]

\[
\mathcal{L}_T = \frac{h'}{\Lambda^1_\chi} \text{Tr} \left[ H_a T^\mu_{ba} (i D_\mu A + i D_\mu A_\mu) \gamma_5 \right] + h.c.
\]

\[
\mathcal{L}_X = \frac{k'}{\Lambda^1_\chi} \text{Tr} \left[ H_a X^\mu_{ba} (i D_\mu A + i D_\mu A_\mu) \gamma_5 \right] + h.c.
\]

\[
\mathcal{L}_X' = \frac{1}{\Lambda^2_\chi} \text{Tr} \left[ H_a X'^{\mu\nu}_{ba} \left[ k_1 (D_\mu D_\nu A_\lambda + k_2 (D_\mu D_\nu A_\lambda + D_\nu D_\lambda A_\mu)] \gamma_\lambda \gamma_5 \right] + h.c.
\]

| $J^P = s^P_\ell - \frac{1}{2}$ | $\frac{1}{2}^-$ | $\frac{1}{2}^+$ | $\frac{3}{2}^+$ | $\frac{3}{2}^-$ | $\frac{5}{2}^-$ |
|-----------------------------|--------------|--------------|--------------|--------------|--------------|
| $D_s(1965)$ (0$^-$)         | $D_s^\prime(2317)$ (0$^+$) | $D_s(2536)$ (1$^+$) | (1$^-$)     | (2$^-$)     | (3$^-)$     |
| $D_s(2112)$ (1$^-$)         | $D_s^\prime(2460)$ (1$^+$) | $D_s(2573)$ (2$^+$) | (2$^-$)     | (2$^-$)     | (3$^-)$     |
where $\Lambda_\chi$ is the chiral symmetry-breaking scale ($\Lambda_\chi = 1$ GeV). $\mathcal{L}_S$ and $\mathcal{L}_T$ describe transitions of positive parity heavy mesons with the emission of light mesons in $s-$ and $d-$ wave, respectively, $g, h$ and $h'$ being effective coupling constants, while $\mathcal{L}_X$ and $\mathcal{L}_X'$ describe the transitions of higher mass mesons of negative parity with the emission of light mesons in $p-$ and $f-$ wave with coupling constants $k', k_1$ and $k_2$.

In Table 2, the ratios $\frac{\Gamma(D_{sJ}(2860) \to D^+ K)}{\Gamma(D_{sJ}(2860) \to D K)}$ and $\frac{\Gamma(D_{sJ}(2860) \to D_s \eta)}{\Gamma(D_{sJ}(2860) \to D K)}$ obtained in this framework for various quantum number assignments to $D_{sJ}(2860)$ [5] are shown. These ratios can be used to exclude some assignments. Indeed, since a $D^* K$ signal has not been observed in the $D_{sJ}(2860)$ mass range, the production of $D^* K$ is not favoured and therefore $D_{sJ}(2860)$ is not a radial excitation of $D_s^*$ or $D_2$. The assignment $s^p_\ell = \frac{3}{2}^+, J^P = 1^-$ can also be excluded: the width $\Gamma(D_{sJ}(2860) \to D K)$ obtained using $s_\ell$ would be too big using $k' \simeq h' \simeq 0.45 \pm 0.05$ [6], and there is no reason to presume that the coupling constant $k'$ is sensibly smaller.

In the case of the assignment $s^p_\ell = \frac{1}{2}^-, J^P = 0^+$, proposed in [7], the decay $D_{sJ}(2860) \to D^* K$ is forbidden and the transition into $D K$ occurs in $s-$wave. The coupling constant for the lowest radial quantum number is $h \simeq -0.55$ [8]; using this value for $h$ we would obtain $\Gamma(D_{sJ}(2860) \to D K) \simeq 1$ GeV. It is reasonable to suppose that $|h| < |h|$, although no information is available about couplings of radially excited heavy-light mesons to low-lying states: the experimental width corresponds to $\tilde{h} = 0.1$. A large signal in the $D_s \eta$ channel would also be expected. A problem is that, if $D_{sJ}(2860)$ is a $0^+$ radial excitation, its partner with $J^P = 1^+$ would decay to $D^* K$ with a width of the order of 40 MeV. Since both the lowest lying states with $J^P = 0^+$ and $1^+$, $D_s^*(2317)$ and $D_{sJ}(2460)$, are produced in charm continuum at $B$ factories, one must invoke an exotic mechanism to explain the absence of the $D^* K$ signal at energy around 2860 MeV.

In the last case $s^p_\ell = \frac{5}{2}^-, J^P = 3^-$ the narrow $D K$ width is due to the kaon momentum suppression: $\Gamma(D_{sJ}(2860) \to D K) \approx q_k^2$. A smaller but non negligible signal in the $D^* K$ mode is predicted, and a small signal in the $D_s \eta$ mode is also expected. Moreover, a fact that supports this assignment is that $D_{sJ}(2860)$ with $J^P = 3^-$ is not expected to be produced in non leptonic $B$ decays such as $B^0 \to D^- D_{sJ}(2860)^+$ and $B^+ \to \bar{D}^0 D_{sJ}(2860)^+$ and indeed in the Dalitz plot analysis of $B^+ \to \bar{D}^0 D^0 K^+$ Belle found no signal of $D_{sJ}(2860)$ [9].

The conclusion of our study is that $D_{sJ}(2860)$ is likely a $J^P = 3^-$ state, a predicted high mass, high spin and relatively narrow $c \bar{c}$ state [11]. This conclusion is confirmed

| $D_{sJ}(2860)$ | $D_{sJ}(2860) \to D K$ | $\frac{\Gamma(D_{sJ} \to D^+ K)}{\Gamma(D_{sJ} \to D K)}$ | $\frac{\Gamma(D_{sJ} \to D_s \eta)}{\Gamma(D_{sJ} \to D K)}$ |
|---------------|----------------|-----------------|-----------------|
| $s^p_\ell = \frac{1}{2}^-, J^P = 1^-$, rad. excit. | p-wave | 1.23 | 0.27 |
| $s^p_\ell = \frac{1}{2}^+, J^P = 0^+$, " | s-wave | 0 | 0.34 |
| $s^p_\ell = \frac{3}{2}^+, J^P = 2^+$, " | d-wave | 0.63 | 0.19 |
| $s^p_\ell = \frac{3}{2}^-, J^P = 1^-$ | p-wave | 0.06 | 0.23 |
| $s^p_\ell = \frac{5}{2}^-, J^P = 3^-$ | f-wave | 0.39 | 0.13 |
by a recent lattice QCD analysis \[10\]. Its non-strange partner \(D_3\), if the mass splitting \(M_{D_s(2860)} - M_{D_3}\) is of the order of the strange quark mass, is also expected to be narrow: \(\Gamma(D_3^+ \to D^0 \pi^+) \simeq 37\) MeV. It can be produced in semileptonic and in non leptonic \(B\) decays, such as \(B^0 \to D_3^- \ell^+ \nu_\ell\) and \(B^0 \to D_3^+ \pi^+ [11]\): its observation could be used to confirm the quantum number assignment to the resonance \(D_{sJ}(2860)\) found by BaBar.

An analogous study for \(D_{sJ}(2700) (J^P = 1^-)\) discussing how to distinguish between the two possible quantum number assignments \(s_\ell^0 = 1/2^-, n = 1\) or \(s_\ell^0 = 3/2^-, n = 1\) \[12\], shows that the ratio \(\frac{\Gamma(D_{sJ} \to D^+ K)}{\Gamma(D_{sJ} \to K^+)}\) is different in the two scenarios and so it may be useful to understand the right identification. Other investigations of \(D_{sJ}(2700)\) and \(D_{sJ}(2860)\) involving potential models can be found in \[13\].

**HIDDEN CHARM SECTOR AND \(X(3872)\)**

One of the most interesting mesons in the hidden charm sector is the \(X(3872)\), discovered in the \(J/\psi \pi^+ \pi^-\) invariant mass distribution in \(B\) decays and in \(p\bar{p}\) collisions \[14\], with \(M(X) = 3871.2 \pm 0.5\) MeV and \(\Gamma(X) < 2.3\) MeV (90\% C.L.) \[15\]. The \(\pi^+ \pi^-\) spectrum is peaked for large invariant mass \[15\]. \(X(3872)\) was not observed in \(e^+ e^-\) annihilation and in \(\gamma \gamma\) fusion, and there is also no evidence of the existence of charged partners. The observation of the \(X \to J/\psi \gamma\) mode \[17\] indicates that the charge conjugation of the state is \(C=+1\); angular distribution studies show that the most likely quantum number assignment is \(J^{PC} = 1^{++} [16]\).

Since another hadronic decay mode was observed for \(X(3872)\): \(X \to J/\psi \pi^+ \pi^- \pi^0\) with \(\frac{B(X \to J/\psi \pi^+ \pi^- \pi^0)}{B(X \to J/\psi \pi^+ \pi^-)} = 1.0 \pm 0.4 \pm 0.3\) \[17, 18\], there are G-parity violating \(X\) transitions: this suggested the conjecture that \(X(3872)\) is not a charmonium \(c\bar{c}\) state. Indeed, the coincidence between the \(X\) mass as averaged by PDG and the \(D^{*0} \bar{D}^0\) mass inspired the proposal that \(X(3872)\) could be a molecular quarkonium \[19\], a \(D^{*0}\) and \(\bar{D}^0\) bound state with small binding energy due to a single pion exchange \[20\]. Such an interpretation would allow to account for a few properties of \(X(3872)\). For example, describing the wave function of \(X(3872)\) through various hadronic components \[21\]:

\[
|X(3872)\rangle = a |D^{*0} \bar{D}^0 + \bar{D}^{*0} D^0\rangle + b |D^{*+} D^- + D^{*-} D^+\rangle + \ldots
\]

(with \(|b| < |a|\) one could explain why this state seems not to have definite isospin, why the mode \(X \to J/\psi \pi^0 \pi^0\) was not found, and why, if the molecular binding mechanism is truly provided by a single pion exchange (however, this is a controversial point), there are no \(D \bar{D}\) molecular states. Anyway, concerning the large value of the 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. The ratio of the amplitudes is smaller: \(\frac{A(X \to J/\psi \rho^0)}{A(X \to J/\psi \omega)} \simeq 0.2\), so that the isospin violating amplitude is 20\% of the isospin conserving one, an effect that could be related to the mass difference between neutral and charged \(D\) mesons, considering the contribution of \(DD^*\) intermediate states to \(X\) decays. It has also been suggested that the molecular interpretation would imply that the radiative decay in neutral \(D\) mesons: \(X \to D^0 \bar{D}^0 \gamma\) should be dominant with respect to \(X \to D^{+} D^- \gamma\) \[21\].
However, assuming that $X(3872)$ is an ordinary $J^{PC} = 1^{++}$ charmonium and describing the $X(3872) \rightarrow DD\gamma$ amplitude by diagrams with $D^*$ and $\psi(3770)$ as intermediate particles, the ratio $R = \frac{\Gamma(X\rightarrow D^+D^-\gamma)}{\Gamma(X\rightarrow D^0D^0\gamma)}$ is small, and it is tiny in a wide range of the hadronic parameters governing the decays, therefore $R \ll 1$ is not peculiar of a molecular quarkonium $X(3872)$, but it is mostly a phase space effect \cite{22}.

The photon spectrum is drawn in fig. 1 for extremal values of the hadronic parameters governing the transition. When the intermediate $D^*$ dominates the decay amplitude, the photon spectrum in the $D^0\bar{D}^0\gamma$ mode coincides with the line corresponding to the $D^*$ decay at $E_\gamma \approx 139$ MeV. The narrow peak is different from the line shape expected in a molecular description, being broader for larger binding energy. On the other hand, the photon spectrum in the charged $D^+D^-\gamma$ mode is broader, with a peak at $E_\gamma \approx 125$ MeV, the total $X \rightarrow D^+D^-\gamma$ rate being severely suppressed with respect to $X \rightarrow D^0\bar{D}^0\gamma$.

Instead, in the range where $\psi(3770)$ gives the main contribution, a peak at $E_\gamma \approx 100$ MeV appears in neutral and charged $D$ modes, in the first case together with the structure at $E_\gamma \approx 139$ MeV. This spectrum was previously described and the radiative decay was interpreted as due to the $cc$ core of $X(3872)$\cite{21}. We then suggest that its experimental investigation could be a better tool to shed light on the structure of this meson.

![Photon spectrum](image)

**Figure 1.** Photon spectrum (in arbitrary units) in $X \rightarrow D^0\bar{D}^0\gamma$ (top) and $X \rightarrow D^+D^-\gamma$ (bottom) decays for values of the hadronic parameter for which the intermediate $D^*$ dominates (left) or the intermediate $\psi(3770)$ dominates (right).

**CONCLUSIONS**

In the open charm sector, the $c\bar{s}$ meson, $D_{sJ}(2860)$ seems to be a $J^P = 3^-$, a member of the $s^P = 5/2^-$ doublet. We have also briefly discussed about the possible quantum number assignment of $D_{sJ}(2700)$. In both cases the analysis of the $D^*K$ mode is crucial.
In the hidden charm sector we have described the meson $X(3872)$, focusing our attention on its radiative decays and pointing out that the smallness of the ratio $R = \frac{\Gamma(X \rightarrow D^+ D^- \gamma)}{\Gamma(X \rightarrow D^0 D^0 \gamma)}$ is not a smoking gun for the molecular nature of this state. The experimental investigation of the photon spectrum could be useful to shed more light on this puzzling hadron.

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