Puzzles in Charm Spectroscopy

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We briefly analyze aspects of open and hidden charm resonances, discussing in particular the mesons \( D_{sJ}(2860) \) and \( X(3872) \).

§1. Prologue

The word puzzle means a problem, a mystery deserving explanation. It also indicates a game designed for testing ingenuity, where pieces of information have to be put together to reassemble a known picture. It is worth asking if recent results in charm spectroscopy\(^1\) represent problems or information fitting into a known theoretical scheme. The answer is different in case of open and hidden charm mesons.

§2. \( c\bar{s} \) system and \( D_{sJ}(2860) \)

An example of new experimental information fitting in an established theoretical scheme is the meson \( D_{sJ}(2860) \) recently observed by BaBar Collaboration\(^2\) in the \( DK \) system inclusively produced in \( e^+e^- \rightarrow DKX \), with \( M(D_{sJ}(2860)) = 2856.6 \pm 1.5 \pm 5.0 \) MeV and \( \Gamma(D_{sJ}(2860) \rightarrow DK) = 47 \pm 7 \pm 10 \) MeV \( (DK = D^0K^+ + D^+K^0) \).

Together with this state, a broad structure was noticed with \( M = 2688 \pm 4 \pm 3 \) MeV and \( \Gamma = 112 \pm 7 \pm 36 \) MeV; indeed, Belle Collaboration\(^3\) reported the evidence of \( D_{sJ}(2715) \) in \( B^+ \rightarrow \bar{D}^0D^+K^+ \) decays, with \( M(D_{sJ}(2715)) = 2715 \pm 11_{14}^{11} \) MeV,

\( \Gamma(D_{sJ}(2715)) = 115 \pm 20_{36}^{20} \) MeV and \( J^P = 1^- \).

The interpretation of these charmed resonances is easier in the heavy quark limit \( m_Q \rightarrow \infty \). In such a limit the spin \( s_Q \) of the heavy quark and the angular momentum \( s_\ell \) of the meson 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 interaction processes.\(^5\)

Mesons can be classified as doublets of \( s_\ell^P \). Two states \((P, P^*)\) with \( J^P = (0^-, 1^-) \) correspond to \( \ell = 0 \). The four states corresponding to \( \ell = 1 \) can be collected in two doublets, one \((P_0^*, P_1)\) with \( s_\ell^P = \frac{1}{2}^+ \) and \( J^P = (0^+, 1^+) \), another one \((P_1, P_2)\) with \( s_\ell^P = \frac{3}{2}^+ \) and \( J^P = (1^+, 2^+) \). For \( \ell = 2 \) the doublets have \( s_\ell^P = \frac{3}{2}^- ((P_1', P_2') \) with \( J^P = (1^-, 2^-) \)) and \( s_\ell^P = \frac{5}{2}^- ((P_2', P_3) \) with \( J^P = (2^-, 3^-) \).

In case of charm, \( m_c \) is greater than the strong interaction scale \( \Lambda_{QCD} \) but it is not very large; therefore, corrections can be expected compared to the infinite limit. \( O(\frac{1}{m_c}) \) effects are the hyperfine splitting between mesons belonging to the same \( s_\ell^P \) doublet, and the mixing of states with same \( J^P \) and different \( s_\ell^P \), namely the two axial vector states with \( s_\ell^P = \frac{1}{2}^+ \) and \( \frac{3}{2}^+ \).

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The six $c\bar{s}$ states reported by PDG 2006\textsuperscript{4)\textsuperscript{)} can be classified according to this scheme. $D_s$ and $D_s^*$ belong to the $s_P^\ell = \frac{1}{2}^-$ doublet. There are four candidates for the four $\ell = 1$ states: $D_{sJ}^*(2317)$ ($J^P = 0^+$), $D_{sJ}(2460)$ and $D_{s1}(2536)$ ($J^P = 1^+$), and $D_{s2}(2573)$ ($J^P = 2^+$). The natural assignment is $D_{sJ}^*(2317)$ to the $s_P^\ell = \frac{1}{2}^+$ doublet and $D_{s2}(2573)$ to the $s_P^\ell = \frac{3}{2}^+$ doublet. As for $D_{sJ}(2460)$ and $D_{s1}(2536)$, they can be a mixing of the $1^+$ $s_P^\ell = \frac{1}{2}^+$ and $\frac{3}{2}^+$ $c\bar{s}$ states. However, in case of non strange axial-vector $c\bar{q}$ mesons the measured mixing angle is small,\textsuperscript{6)} a result confirmed by an analysis of $O(\frac{1}{m_c})$ effects breaking the heavy quark spin symmetry.\textsuperscript{7)}

Invoking $SU(3)_F$, also the mixing angle in the case of $c\bar{s}$ is expected to be small, so that $D_{s1}(2536)$ and $D_{sJ}(2460)$ essentially coincide with the $s_P^\ell = \frac{3}{2}^+$ and $\frac{5}{2}^+$ states.

In the above classification $D_{sJ}(2860)$, which decays in two pseudoscalar mesons, can be either a $J^P = 1^− s_P^\ell = \frac{5}{2}^−$ state, or a $J^P = 3^− s_P^\ell = \frac{5}{2}^−$ state, i.e. a state with $\ell = 2$ and lowest radial quantum number. Another possibility is that $D_{sJ}(2860)$ is a radial excitation of the $J^P = 1^− s_P^\ell = \frac{1}{2}^−$ state ($D_{sJ}'$), of the $J^P = 0^+ s_P^\ell = \frac{1}{2}^+$ state (first radial excitation of $D_{sJ}^*(2317)$) or of the $J^P = 2^+ s_P^\ell = \frac{3}{2}^+$ state ($D_{s2}'$).

The $J^P$ assignment can be done considering the decay modes and width.

It was suggested\textsuperscript{8)} that a few high mass and high spin charm states could be narrow enough to be observed and, in particular, that the $3^−$ state belonging to the $s_P^\ell = \frac{5}{2}^− c\bar{q}$ $(c\bar{s})$ doublet is not too broad since it decays to $D\pi$ $(DK)$ in $f$-wave. An analysis\textsuperscript{9)} based on the heavy quark limit\textsuperscript{10)} supports the assignment. We define the fields representing the various heavy-light meson doublets: $H_α$ for $s_P^\ell = \frac{1}{2}^−$ (a light flavour index), $S_α$ and $T_α$ for $s_P^\ell = \frac{1}{2}^+$ and $s_P^\ell = \frac{3}{2}^+$, respectively, and $X_α$ and $X'_α$ for the doublets corresponding to $\ell = 2$, $s_P^\ell = \frac{3}{2}^−$ and $s_P^\ell = \frac{5}{2}^−$, respectively:

\begin{align}
H_α &= \frac{1 + \gamma_5}{2} [P_{αμ}^*γ_μ − P_αγ_5] , \quad S_α = \frac{1 + \gamma_5}{2} [P_{1α}μγ_μγ_5 − P_{0α}^*] , \\
T_α &= \frac{1 + \gamma_5}{2} \left\{ P_{2αμ}^*γ_ν − P_{1αν} \sqrt{\frac{3}{2}γ_5} \left[ g_{μν} − \frac{1}{3}γ_ν(γ_μ − ςμ) \right] \right\} , \\
X_α &= \frac{1 + \gamma_5}{2} \left\{ P_{2αμν}^*γ_γ − P_{1αμν} \sqrt{\frac{3}{2}} \left[ g_{μν} − \frac{1}{3}γ_γ(γ_μ − ςμ) \right] \right\} , \\
X'_α &= \frac{1 + \gamma_5}{2} \left\{ P_{3αμνγ}^*γ_σ − P_{2αμν}^*γ_β \sqrt{\frac{3}{2}} \left[ g_{μνγ} − \frac{1}{5}γ_γg_β^*(γ_μ − ςμ) − \frac{1}{5}γ_βg_α^*(γ_ν − ςν) \right] \right\} .
\end{align}

(2.1)

with the various operators annihilating mesons of four-velocity $ν$. The interaction of these particles with the octet of light pseudoscalar mesons, introduced using $ξ = e \frac{f_π}{m_π} M$, $Σ = ξ^2$, the matrix $M$ containing the octet of $π, K$ and $η$ fields, and $f_π = 132$ MeV, is described by an effective Lagrangian invariant under chiral and heavy-quark spin-flavour transformations. At the leading order in the $1/m_Q$ and light meson momentum expansion, the decays $F → HM$ ($F = H, S, T, X, X'$ and $M$ a light
pseudoscalar meson) are described by the Lagrangian terms:11)

\[
\mathcal{L}_H = g \text{Tr}[\bar{H}_a H_b \gamma_\mu \gamma_5 A^\mu_{ba}], \\
\mathcal{L}_S = h \text{Tr}[\bar{H}_a S_b \gamma_\mu \gamma_5 A^\mu_{ba}] + \text{h.c.}, \\
\mathcal{L}_T = \frac{h'}{\Lambda} \text{Tr}[H_a T^\mu_b (iD_\mu A + iD A_\mu)_{ba} \gamma_5] + \text{h.c.}, \\
\mathcal{L}_X = \frac{k'}{\Lambda} \text{Tr}[H_a X^\mu_b (iD_\mu A + iD A_\mu)_{ba} \gamma_5] + \text{h.c.}, \\
\mathcal{L}_{X'} = \frac{1}{\Lambda^2} \text{Tr}[\bar{H}_a X'^{\mu\nu}_{ba}[k_1(D_\mu D_\nu A_\lambda + D_\nu D_\lambda A_\mu)]_{ba} \gamma^\lambda \gamma_5] + \text{h.c.},
\]

(2.2)

where \(\Lambda\) is the chiral symmetry-breaking scale (\(\Lambda = 1\) GeV), \(D_{ba} = -\delta_{ba} \partial_\mu + \frac{1}{2} (\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger)_{ba}\) and \(A_{ba} = \frac{1}{2} (\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger)_{ba}\). \(\mathcal{L}_S\) and \(\mathcal{L}_T\) describe transitions of positive parity heavy mesons with the emission of light pseudoscalar mesons in \(s\)- and \(d\)-wave, respectively, with \(g, h\) and \(h'\) effective coupling constants. \(\mathcal{L}_X\) and \(\mathcal{L}_{X'}\) describe the transitions of higher mass mesons of negative parity with the emission of light pseudoscalar mesons in \(p\)- and \(f\)-wave with couplings \(k', k_1\) and \(k_2\).

At the same order in the expansion in the light meson momentum, the structure of the Lagrangian terms for radial excitations of \(H, S\) and \(T\) doublets does not change, but the coupling constants \(g, h\) and \(h'\) are substituted by \(\tilde{g}, \tilde{h}\) and \(\tilde{h}'\).

In Table I we collect the ratios \(\frac{\Gamma(D_{sJ}(2860) \rightarrow D^{*}K)}{\Gamma(D_{sJ}(2860) \rightarrow DK)}\) and \(\frac{\Gamma(D_{sJ}(2860) \rightarrow D_{sJ}(2860) \rightarrow D_{sJ}(2860) \rightarrow DK)}{\Gamma(D_{sJ}(2860) \rightarrow DK)}\) obtained for various quantum number assignments to \(D_{sJ}(2860)\).9) These ratios can be used to exclude some assignments. Indeed, since a \(D^{*}K\) signal has not been observed (so far) 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 \(D^{*}\) or \(D_{s2}\). The assignment \(s^{p}_{\xi} = \frac{3}{2}^{-}, J^{P} = 1^{-}\) can also be excluded: the width \(\Gamma(D_{sJ}(2860) \rightarrow DK)\) obtained using (2.2) would be \(\Gamma(D_{sJ}(2860) \rightarrow DK) \geq 1\) GeV using \(k' \simeq h' \simeq 0.45 \pm 0.05\),7) and there is no reason to presume that the coupling constant \(k'\) is sensibly smaller.

In the case of the assignment \(s^{p}_{\xi} = \frac{1}{2}^{+}, J^{P} = 0^{+}\), proposed in some analyses,12) the decay \(D_{sJ}(2860) \rightarrow D^{*}K\) is forbidden and the transition into \(DK\) occurs in \(s\)-wave. The coupling constant for the lowest radial quantum number was computed: \(h \simeq -0.55;13)\) using this value for \(\tilde{h}\) we would obtain \(\Gamma(D_{sJ}(2860) \rightarrow DK) \geq 1\) GeV. It is reasonable to suppose that \(|\tilde{h}| < |h|\), although no information is available about

| \(D_{sJ}(2860)\) | \(D_{sJ}(2860) \rightarrow DK\) | \(\frac{\Gamma(D_{sJ}(2860) \rightarrow D^{*}K)}{\Gamma(D_{sJ}(2860) \rightarrow DK)}\) | \(\frac{\Gamma(D_{sJ}(2860) \rightarrow D_{sJ}(2860) \rightarrow D_{sJ}(2860) \rightarrow DK)}{\Gamma(D_{sJ}(2860) \rightarrow DK)}\) |
|---|---|---|---|
| \(s^{p}_{\xi} = \frac{1}{2}^{+}, J^{P} = 1^{-}\), rad. excit. | \(p\)-wave | 1.23 | 0.27 |
| \(s^{p}_{\xi} = \frac{1}{2}^{+}, J^{P} = 0^{+}\), \(n\) | \(s\)-wave | 0 | 0.34 |
| \(s^{p}_{\xi} = \frac{3}{2}^{+}, J^{P} = 2^{+}\), \(n\) | \(d\)-wave | 0.63 | 0.19 |
| \(s^{p}_{\xi} = \frac{3}{2}^{-}, J^{P} = 1^{-}\) | \(p\)-wave | 0.06 | 0.23 |
| \(s^{p}_{\xi} = \frac{3}{2}^{-}, J^{P} = 3^{-}\) | \(f\)-wave | 0.39 | 0.13 |
couplings of radially excited heavy-light mesons to low-lying states: the experimental width corresponds to $\hbar = 0.1$. A large signal in the $D_s \eta$ channel would 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 $J^P = 0^+ \ and \ 1^+$, $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$, are produced in charm continuum at $B$ factories, to explain the absence of the $D^*K$ signal at energy around 2860 MeV one must invoke a mechanism favouring the production of the $0^+$ first radial excitation and inhibiting the production of the $1^+$ radial excitation.

In the last case $s^P_\ell = \frac{5}{2}^-$, $J^P = 3^-$ the narrow $DK$ width is due to the kaon momentum suppression: $\Gamma(D_{sJ}(2860) \rightarrow DK) \propto q_K^7$. 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. The state of spin two $D_{s2}^{*'}$ belonging to the $s^P_\ell = \frac{5}{2}^-$ doublet, which can decay to $D^*K$ and not to $DK$, would be narrow: $\Gamma(D_{s2}^{*'} \rightarrow D^*K) \approx 50$ MeV for $m_Q \rightarrow \infty$: as an effect of $1/m_Q$ corrections, $D_{s2}^{*'} \rightarrow D^*K$ can occur in $p$-wave, in which case $\Gamma(D_{s2}^{*'})$ could be broader.

$D_{sJ}(2860)$ with $J^P = 3^-$ is not expected to be produced in non leptonic $B$ decays such as $B^0 \rightarrow D^-D_{sJ}(2860)^+$ and $B^+ \rightarrow \bar{D}^0D_{sJ}(2860)^+$: indeed in the Dalitz plot analysis of $B^+ \rightarrow \bar{D}^0D^0K^+$ Belle found no signal of $D_{sJ}(2860)$. The non-strange partner $D_3$ of a $J^P = 3^-$ $D_{sJ}(2860)$ state, if the mass splitting $M_{D_{sJ}(2860)} - M_{D_3}$ is of the order of the strange quark mass, is also expected to be narrow: $\Gamma(D_3^+ \rightarrow D^0\pi^+) \approx 37$ MeV. It can be produced in semileptonic as well as in non leptonic $B$ decays, such as $B^0 \rightarrow D_3^-\ell^+\bar{\nu}_\ell$ and $B^0 \rightarrow D_3^-\pi^+$.\(^{9)}\)

The analysis of $D_{sJ}(2715)$ can be done analogously and is in progress. A proposal for the $c\bar{s}$ spectrum is shown in Fig. 1.

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Fig. 1. $c\bar{s}$ spectrum with a possible assignment of $D_{sJ}(2860)$ and $D_{sJ}(2715)$. 
§3. Hidden charm mesons and $X(3872)$

A puzzle in the hidden charm sector is the meson $X(3872)$ discovered in the $J/\psi\pi^+\pi^-$ invariant mass distribution in $B$ decays and in $pp$ collisions,\(^{14}\) with $M(X) = 3871.2 \pm 0.5 \text{ MeV}$ and $\Gamma(X) < 2.3 \text{ MeV} \ (90\% \text{ C.L.}).$\(^{4}\) The $\pi^+\pi^-$ spectrum is peaked for large invariant mass.\(^{15}\) $X(3872)$ was not observed in $e^+e^-$ annihilation, in $\gamma\gamma$ fusion; searches of charged partners also produced negative results. The charge conjugation of the state is $C = +1$ since the mode $X \to J/\psi\gamma$ was observed;\(^{16}\) angular distribution studies show that the most likely quantum number assignment is $J^{PC}=1^{++}.\(^{17}\)$

Furthermore, a near-threshold $D^0\bar{D}^0\pi^0$ enhancement in $B \to D^0\bar{D}^0\pi^0K$ decay was recently reported, with the peak at $M = 3875.4 \pm 0.7^{+1.2}_{-2.0} \text{ MeV}$ and $B(B \to KX \to KD^0\bar{D}^0\pi^0) = (1.27 \pm 0.31^{+0.22}_{-0.39}) \times 10^{-4}.\(^{18}\)$ If the enhancement is only due to $X(3872)$ one finds $B(X \to D^0\bar{D}^0\pi^0) / B(X \to J/\psi\pi^+\pi^-) = 9 \pm 4$, hence $X$ mainly decays into final states with open charm mesons. Notice that the central value of the mass measured in $D^0\bar{D}^0\pi^0$ is 4 MeV higher than the PDG value (with a large systematic error).

Since another hadronic decay mode was observed for $X(3872)$: $X \to J/\psi\pi^+\pi^-\pi^0$ with $B(X \to J/\psi\pi^+\pi^-\pi^0) / B(X \to J/\psi\pi^+\pi^-) = 1.0 \pm 0.4 \pm 0.3,\(^{16}\)\(^{19}\)$ there are G-parity violating $X$ transitions or, if the two modes are considered as induced by $\rho^0$ and $\omega$ intermediate states, isospin violation: this suggested the conjecture that $X(3872)$ is not a charmonium $cc$ state. In the search of the right interpretation, the coincidence between the $X$ mass as averaged by PDG and the $D^*\bar{D}^0$ mass: $M(D^*\bar{D}^0) = 3871.2 \pm 1.0 \text{ MeV}$, inspired the proposal that $X(3872)$ could be a realization of the molecular quarkonium,\(^{20}\) a $D^*\bar{D}^0$ bound state with small binding energy,\(^{21}\) an interpretation that would allow to account for a few properties of $X(3872)$. For example, describing the wave function of $X(3872)$ through various hadronic components:\(^{22}\)

$$|X(3872) >= a |D^*0\bar{D}^0 + \bar{D}^*0D^0 > + b |D^+D^- + D^*D^+ > + \ldots$$ (3.1)

(with $|b| \ll |a|$) 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 provided by a single pion exchange, there are no $D\bar{D}$ molecular states. It has also been suggested that the molecular interpretation implies 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.\(^{22}\)$

The description of $X(3872)$ in a simple charmonium scheme, in which it would be identified as the first radial excitation of the $J^{PC}=1^{++}$ state, presents alternative arguments to the molecular description.\(^{23}\) For example, the molecular binding mechanism cannot be a single $\pi^0$ exchange, since this would produce an attractive potential which is a delta function in space and it does not give rise to a bound state.\(^{24}\) Concerning the large value of the ratio $B(X \to J/\psi\pi^+\pi^-\pi^0) / B(X \to J/\psi\pi^+\pi^-)$ one has to consider that phase space effects in two and three pion modes are very different. The ratio of the amplitudes is smaller: $A(X \to J/\psi\pi^0)$/$A(X \to J/\psi\omega) \simeq 0.2$, so that the isospin violating amplitude is 20% of the isospin conserving one, an effect that could be related to another
isospin violating effect, the mass difference between neutral and charged $D$ mesons, considering the contribution of $DD^*$ intermediate states to $X$ decays. The prediction $\Gamma(B^0 \to XK^0) \simeq \Gamma(B^- \to XK^-)$, based on the charmonium description, is neither confirmed nor excluded, since $\frac{\Gamma(B^0 \to K^0X)}{\Gamma(B^+ \to K^+X)} = 0.50 \pm 0.30 \pm 0.05$. The $\bar{c}c$ interpretation leaves unsolved the issue of the eventual overpopulation of the level corresponding to the first radial excitations of $1^{++}$ $\bar{c}c$ states resulting from the possible assignment of these quantum numbers to another structure observed by Belle Collaboration, $Y(3930)$,\(^1\) however, since this other resonance is still not confirmed and its properties not fully understood, the charmonium option for $X(3872)$ seems not excluded, yet. A warning comes from the $D^0\bar{D}^0\pi^0$ signal which can contribute to settle the question of the coincidence of the $X$ and $D^0\bar{D}^0$ mass: an $X$ mass above the $D^0\bar{D}^0$ threshold would be difficult to explain in the molecular scheme.

The suggestion that observation of the dominance of $X \to D^0\bar{D}^0\gamma$ with respect to $X \to D^+D^-\gamma$ can be interpreted as a signature of the molecular structure of $X(3872)$\(^2\) is also questionable.\(^3\) Assuming that $X(3872)$ is an ordinary $J^{PC} = 1^{++}$ charmonium state together with a standard mechanism for $X$ radiative transition into charmed mesons, the ratio $R = \frac{\Gamma(X \to D^+D^-\gamma)}{\Gamma(X \to D^0\bar{D}^0\gamma)}$ 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 $X(3872)$.\(^4\) This can be demonstrated describing the $X(3872) \to D\bar{D}\gamma$ amplitude by diagrams with intermediate particles nearest to their mass shell, as those depicted in Fig. 2 with $D^*$ and $\psi(3770)$ as intermediate states. The amplitude can be expressed in terms of two unknown quantities: a coupling $\hat{g}_1$ governing the $XDD^*(D\bar{D}^*)$ matrix elements, and a coupling $c$ appearing in the $X\psi(3770)\gamma$ matrix element, all the other quantities being fixed by experimental data.\(^5\) As shown in Fig. 3, the ratio $R$ is tiny for small values of $c/\hat{g}_1$.

The photon spectrum is different in case of a charmonium or a molecule. It is interesting to consider it in $X$ decays to neutral and charged $D$ meson pairs for two representative values: $c/\hat{g}_1 = 1$ and 300 (Fig. 4). For low value of $c/\hat{g}_1$, i.e. in the condition where 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 $E_\gamma \simeq 139$ MeV. The narrow peak is different from the line shape expected in a molecular description, which is related to the wave function of the two heavy mesons bounded in the $X(3872)$, in particular to the binding energy of the system, 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 $E_\gamma \simeq 125$ MeV, the total $X \to D^+D^-\gamma$ rate being severely suppressed with respect to $X \to D^0\bar{D}^0\gamma$.

At the opposite side of the $c/\hat{g}_1$ range, where $\psi(3770)$ gives a large contribution to the radiative amplitude, a peak at $E_\gamma \simeq 100$ MeV appears both in neutral and
charged $D$ meson modes, in the first case together with the structure at $E_\gamma \simeq 139$ MeV. This spectrum was previously described and the radiative decay was interpreted as due to the $\bar{c}c$ core of $X(3872)$.\textsuperscript{22} So, the measurement of the photon spectrum $\Gamma(X \to D\bar{D}\gamma)$ could be used to shed light on the structure of $X(3872)$.

§4. Conclusions

A few results in charm spectroscopy challenge our understanding. More than thirty years after the first observation, charm continues to be a surprise for us.

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