NEW OPEN AND HIDDEN CHARM SPECTROSCOPY

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Many new results on open and hidden charm spectroscopy have been obtained recently. We present a short review of the experimental findings in the meson sector, of the theoretical interpretations and of the open problems, with a discussion on the possibility that some mesons are not quark-antiquark states.

Keywords: charmed mesons, quarkonium, nonstandard quark/gluon states

1. Introduction

Observation of a long list of new hadrons has been recently reported by experiments at $e^+e^-$ and $p\bar{p}$ colliders, by fixed target experiments and by reanalyses of old data. We can use Leporello’s words in Mozart’s Don Giovanni: Madamina, il catalogo è questo: \(^a\)

$D_{sJ}^*(2317), \ D_{sJ}(2460), \ D_{sJ}(2632), \ D_{sJ}(2860), \ D_0^*(2308), \ D'_1(2440), \ h_c, \ \eta_c, \ X(3872), \ X(3940), \ Y(3940), \ Z(3930), \ Y(4260), \ \Upsilon(1D), \ B_1, \ B_2, \ B_{s2}, \ \Theta(1540)^+, \ \Theta_c(3099), \ \Xi_{cc}(3518), \ldots$

Not all the states in the list have been confirmed ($D_{sJ}(2632), \Theta(1540)^+, \Theta_c(3099)$) and therefore we can ignore them. Other states ($\Xi_{cc}(3518)$) are baryons, deserving a dedicated analysis, and mesons with open ($B_1, B_2, B_{s2}$) or hidden beauty ($\Upsilon(1D)$), that we do not discuss here.

We only consider mesons with open and hidden charm. The wealth of information collected in recent years is impressive: not only the number of known states has nearly doubled, but a few experimental observations seem to challenge the current picture of mesons as simple quark-antiquark configurations. Therefore, it is important to search the signatures allowing us to assign a given state to a particular multiplet, so that the hints of exotic structures can be clearly interpreted. The next Sections are devoted to such

\(^a\)My lady, this is the list:
a discussion, considering separately the case of open charm mesons, which at present can be classified according to known rules, and that of hidden charm states where a couple of mesons seem to escape simple classification schemes. b

2. Mesons with open charm

In QCD, for hadrons containing a single heavy quark Q and in the limit \( m_Q \to \infty \), there is a spin-flavour symmetry due to the decoupling of the heavy quark from the dynamics of the light degrees of freedom (light quarks and gluons). Therefore, it is possible to classify states containing the heavy quark Q according to the total angular momentum \( s_\ell \) of the light degrees of freedom. For mesons, states belonging to doublets with the same \( s_\ell = s_q + \ell \), with \( s_q \) the spin of the light antiquark and \( \ell \) the orbital angular momentum relative to the heavy quark, are degenerate in mass in the large \( m_Q \) limit.

In case of charm, \( D^0, D^* \), \( D_s \) and \( D^*_s \) are the states in the \( s_\ell P = \frac{1}{2}^- \) \( c\bar{u}(\bar{d}, \bar{s}) \) doublet, corresponding to \( \ell = 0 \). The mass difference between the members of the doublet is \( O(\frac{1}{m_c}) \), and vanishes when \( m_c \to \infty \).

For \( \ell = 1 \) there are two doublets with \( s_\ell^P = \frac{1}{2}^+ \) and \( s_\ell^P = \frac{3}{2}^+ \), for \( \ell = 2 \) two other doublets with \( s_\ell^P = \frac{3}{2}^- \) and \( s_\ell^P = \frac{5}{2}^- \), and so on. The spin-flavour symmetry is important not only for spectroscopy, but also for the classification of strong decay modes and for evaluating the rates, since decays involving heavy mesons belonging to the same doublets are related. For example, the decays of mesons belonging to the \( s_\ell^P = \frac{3}{2}^- \) doublet in one light pseudoscalar and one heavy \( s_\ell^P = \frac{1}{2}^- \) meson occur in \( d^- \) wave, so that these states are expected, ceteris paribus, to be narrower than the states belonging to the doublet \( s_\ell^P = \frac{5}{2}^- \), which decay to the same final states by \( s^- \) wave transitions. These observations are at the basis of the analyses of the new mesons observed in \( c\bar{q} \) and in \( c\bar{s} \) systems. They must be used together with the consideration that \( \frac{1}{m_Q} \) effects can be important in case of charm: for example, the two \( 1^+ \) states belonging to \( s_\ell^P = \frac{1}{2}^+ \) and \( \frac{3}{2}^+ \) doublets, due to the finite charm quark mass, could mix with a mixing angle \( \theta_c \) to provide the physical axial vector mesons. Such effects must be investigated on the basis of the experimental observation.

bFor other recent reviews on this subject see Refs. 1, 2.
2.1. \( c\overline{q} \) mesons: \( D_0^* (2308) \) and \( D_1^* (2440) \).

Information about broad \( c\overline{q} \) mesons, one scalar and one axial vector charmed meson that can be interpreted as the states belonging to the \( s_{P\ell}^P = \frac{1}{2}^+ c\overline{u}, c\overline{d} \) doublets, comes from Cleo\(^3\), Belle\(^4\) and Focus\(^5\) Collaborations. The resonance parameters are reported in Table 1; they are obtained observing that the \( D_{\pi} \) and \( D_{\pi^*} \) mass distributions, produced for example in \( B \rightarrow D^{**}\pi \) with a \( D^{**} \) a generic \( \ell = 1 \) meson, require contributions with scalar or axial vector quantum numbers. Improved determinations of mass and width of the two other positive parity charmed states \( D_1 \ (J^P = 1^+) \) and \( D_2 \ (J^P = 2^+) \) have been obtained, together with a measurement of the mixing angle between the two \( 1^+ \) states. It is small:

\[
\theta_c = -0.10 \pm 0.03 \pm 0.02 \pm 0.02 \text{ rad} \ (\simeq -6^0) \ .
\]

| State            | Mass (MeV)       | Width (MeV)     |
|------------------|------------------|-----------------|
| \( D_0^* \)      | 2308 ± 17 ± 15 ± 28 | 2407 ± 21 ± 35  |
| \( D_0^* \)      | 276 ± 21 ± 18 ± 60 | 240 ± 55 ± 59   |
| \( D_1^* \)      | 2403 ± 14 ± 35    | 283 ± 24 ± 34   |

2.2. \( c\overline{s} \) mesons: \( D_{sJ}^* (2317), D_{sJ} (2460) \) and \( D_{sJ} (2860) \).

\( D_{sJ}^* (2317) \) and \( D_{sJ} (2460) \) were found at the \( B \) factories in \( D_s\pi^0 \) and \( D_s^0\pi^0, D_s^*\gamma \) distributions, respectively, in \( e^+e^- \) continuum and in \( B \) decays\(^6\). Their widths are unresolved, and this has arisen doubts about their identification as the scalar and axial vector \( s_{\pi\ell}^P = \frac{1}{2}^+ c\overline{s} \) mesons (\( D_{s0} \) and \( D_{s1}^* \)), forming, together with \( D_{s1} (2536) \) and \( D_{s2} (2573) \), the set of four low-lying \( \ell = 1 \) states. However, the masses of \( D_{sJ}^* (2317) \) and \( D_{sJ} (2460) \) are below their respective thresholds for strong decays, \( DK \) and \( D^*K \), therefore the small width is natural. Moreover, analyses of radiative transitions, that probe the structure of hadrons, support the \( c\overline{s} \) interpretation of the two states\(^7\). For example, by Light-Cone QCD sum rules one can compute the hadronic parameters \( d, g_1, g_2 \) and \( g_3 \) governing the \( D_{sJ}^* (2317) \rightarrow D_{sJ}^* \gamma \) and
\[ D_s J(2460) \rightarrow D_s^{(*)} \gamma, \ D_s^*(2317) \gamma \] decay amplitudes:\n\[ \langle \gamma(q, \lambda) D_s^*(p, \lambda') D_{s0}(p + q) \rangle = e^d \left[ (\varepsilon^* \cdot \eta) (p \cdot q) - (\varepsilon^* \cdot p)(\eta^* \cdot q) \right] \]
\[ \langle \gamma(q, \lambda) D_s(p) D_{s1}^*(p + q, \lambda'') \rangle = e^g_1 \left[ (\varepsilon^* \cdot \eta)(p \cdot q) - (\varepsilon^* \cdot p)(\eta \cdot q) \right] \]
\[ \langle \gamma(q, \lambda) D_s^*(p, \lambda') D_{s1}^*(p + q, \lambda'') \rangle = i e g_2 \varepsilon_{\alpha \beta \sigma \tau} \eta^\alpha \tilde{\eta}^\beta \varepsilon^* \sigma q^\tau \]

(\varepsilon(\lambda) \text{ is the photon polarization vector and } \tilde{\eta}(\lambda'), \eta(\lambda'') \text{ the } D_s^* \text{ and } D_{s1}^* \text{ polarization vectors}).

Considering the correlation functions\textsuperscript{10,11}
\[ F(p, q) = i \int d^4x \ e^{ip \cdot x} \langle \gamma(q, \lambda) | T[J_A(x) J_B(0)] | 0 \rangle \]

of quark-antiquark currents \( J_{A,B} \) having the same quantum number of the decaying and of the produced charmed mesons, and an external photon state of momentum \( q \) and helicity \( \lambda \), and expanding on the light-cone, it is possible to express \( F \) in terms of the perturbative photon coupling to the strange and charm quarks, together with the contributions of the photon emission from the soft \( s \) quark, expressed as photon matrix elements of increasing twist\textsuperscript{12}, see fig.1. The hadronic representation of the correlation function involves the contribution of the lowest-lying resonances, the current-vacuum matrix elements of which are computed by the same method\textsuperscript{13}, and a continuum of states treated invoking global quark-hadron duality. A Borel transformation introduces an external parameter \( M^2 \), the hadronic quantities being independent of it (fig. 2).
Looking at the results, collected in Table 2, one sees that the rate of $D_{sJ}(2460) \rightarrow D_s\gamma$ is the largest one among the radiative $D_{sJ}(2460)$ rates, and this is confirmed by experiment, as reported in Table 3. Quantitative understanding of the ratios in Table 3 requires a precise knowledge of the widths of the isospin violating transitions $D_{s0} \rightarrow D_s\pi^0$ and $D_{s1}' \rightarrow D_s^*\pi^0$. In the description of these transitions based on the mechanism of $\eta - \pi^0$ mixing\textsuperscript{7,8}, the accurate determination of the strong $D_{s0}D_s\eta$ and $D_{s0}D_s^*\eta$ couplings for finite heavy quark mass and including $SU(3)$ corrections is required.

If there are no reasons to consider $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ as exotic mesons, the same conclusion seems mandatory for $D_{sJ}(2860)$, a state recently observed by BaBar\textsuperscript{15} in the $DK$ system inclusively produced in $e^+e^- \rightarrow DKX$. The parameters of the resonance are: $M(D_{sJ}(2860)) = 2856.6 \pm 1.5 \pm 5.0$ MeV and $\Gamma(D_{sJ}(2860) \rightarrow DK) = 48 \pm 7 \pm 10$ MeV, (where $DK = D^0K^+$ and $D^+K_S$). In the same set of data and range of

Table 2. Radiative decay widths (in keV) of $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ obtained by Light-Cone sum rules (LCSR), Vector Meson Dominance (VMD) and constituent quark model (QM).

| Initial state | Final state | LCSR $^a$ | VMD $^b$ | QM $^c$ | QM $^d$ |
|---------------|-------------|-----------|----------|---------|---------|
| $D_{sJ}^*(2317)$ | $D_s^*\gamma$ | 4-6 | 0.85 | 1.9 | 1.74 |
| $D_{sJ}(2460)$ | $D_s\gamma$ | 19-29 | 3.3 | 6.2 | 5.08 |
| $D_{sJ}^*(2317)$ | $D_s^*\gamma$ | 0.6-1.1 | 1.5 | 5.5 | 4.66 |
| $D_{sJ}(2460)$ | $D_s\gamma$ | 0.5-0.8 | — | 0.012 | 2.74 |
Table 3. Measurements and 90% CL limits of ratios of $\Gamma(D_{sJ}(2317))$ and $D_{sJ}(2460)$ decay widths.

|                  | Belle | BaBar | CLEO |
|------------------|-------|-------|------|
| $\Gamma(D_{sJ}(2317) \to D_s^0\gamma)/\Gamma(D_{sJ}(2317) \to D_s\pi^0)$ | < 0.18 | < 0.069 |
| $\Gamma(D_{sJ}(2460) \to D_s\gamma)/\Gamma(D_{sJ}(2460) \to D_s^0\pi^0)$ | 0.45 ± 0.09 | 0.30 ± 0.04 | < 0.40 |
| $\Gamma(D_{sJ}(2460) \to D_s^*\gamma)/\Gamma(D_{sJ}(2460) \to D_s^*\pi^0)$ | < 0.31 | — | < 0.16 |
| $\Gamma(D_{sJ}(2460) \to D_{sJ}^*(2317)\gamma)/\Gamma(D_{sJ}(2460) \to D_{sJ}^*\pi^0)$ | — | < 0.23 | < 0.58 |

mass no structures seem to appear in the $D^*K$ distribution, while a broad contribution seems to be present in the $DK$ distribution at smaller mass.

It is interesting to discuss this new meson in some detail. A possible quantum number assignment for a $c\bar{s}$ meson decaying to $DK$ is either $s^P_\ell = \frac{3}{2}^-$, $J^P = 1^-$, or $s^P_\ell = \frac{5}{2}^-$, $J^P = 3^-$, in both cases corresponding to $\ell = 2$ and lowest radial quantum number ($n = 0$). Another possibility is that $D_{sJ}(2860)$ is a radial excitation ($n = 1$) of already observed $c\bar{s}$ mesons: the $J^P = 1^-$, $s^P_\ell = \frac{1}{2}^-$ state (the first radial excitation of $D_{sJ}$), the $J^P = 0^+$, $s^P_\ell = \frac{1}{2}^+$ state (radial excitation of $D_{sJ}(2317)$) or the $J^P = 2^+$, $s^P_\ell = \frac{3}{2}^+$ state (radial excitation of $D_{sJ}(2573)$). In the absence of the helicity distribution of the final state, arguments can be provided to support a particular assignment of $J^P$ considering the observed mass, the decay modes and width.

A piece of information comes from the $DK$ width. Using an effective QCD Lagrangian incorporating spin-flavour heavy quark symmetry and light quark chiral symmetry, an estimate is possible of the ratios $\Gamma(D_{sJ}(2860) \to D^*K)$ and $\Gamma(D_{sJ}(2860) \to D_s\eta)$ for various quantum number assignments to $D_{sJ}(2860)$ (Table 4). Non observation (at present) of a $D^*K$ signal implies that the production of $D^*K$ is not favoured, and therefore the assignments $s^P_\ell = \frac{1}{2}^-$, $J^P = 1^-$, $n = 1$, and $s^P_\ell = \frac{3}{2}^+$, $J^P = 2^+$, $n = 0$ are disfavoured.

Table 4. Predicted $\Gamma(D_{sJ} \to D^*K)$ and $\Gamma(D_{sJ} \to D_s\eta)$ for various assignment of quantum numbers to $D_{sJ}(2860)$. The sum $DK = D^0K^+ + D^+K_S$ is understood.

| $s^P_\ell$, $J^P$, $n$ | $D_{sJ}(2860) \to DK$ | $\Gamma(D_{sJ} \to D^*K)$ | $\Gamma(D_{sJ} \to D_s\eta)$ |
|------------------------|------------------------|------------------------|------------------------|
| $\frac{1}{2}^-$, 1      | 1.23                   | 0.27                   |
| $\frac{1}{2}^+$, 0+     | 0                     | 0.34                   |
| $\frac{3}{2}^-$, 2+     | 0.63                   | 0.19                   |
| $\frac{3}{2}^-$, 1      | 0.06                   | 0.23                   |
| $\frac{3}{2}^-$, 0      | 0.39                   | 0.13                   |
\[ J^P = 2^+, \ n = 1 \] can be excluded. The assignment \[ s_P^{\ell} = \frac{3}{2}^-, \ J^P = 1^-, \ n = 0 \] can also be excluded, since the width \[ \Gamma(D_{sJ} \to DK) \] would be naturally large for a \( p^- \)-wave \( D_{sJ} \to DK \) transition. \(^c\)

In the case of the assignment \[ s_P^{\ell} = \frac{1}{2}^+, \ J^P = 0^+, \ n = 1 \] the decay \( D_{sJ} \to D^*K \) is forbidden; this is the assignment proposed in Refs. 19 and 18. However, \( D_{sJ} \to DK \) occurs in \( s^- \)-wave, therefore it should be rather broad: for the state with the lowest radial quantum number \( n = 0 \) the computed coupling constant \( g_{D_{sJ}DK} \) is in agreement with observation\(^{13,1} \), and using it one would obtain \( \Gamma(D_{sJ} \to DK) \approx 1.4 \text{ GeV} \). Although it is reasonable to suppose that the coupling of radial excitation is smaller, the suppression should be substantial to reproduce the observed width. Moreover, a large signal would be expected in the \( D_s \eta \) channel. Another remark is that the spin partner with \( J^P = 0^+ \) \( (s_P^{\ell} = \frac{1}{2}^+, \ n = 1) \) would decay to \( D^*K \) with a small width, \( \approx 40 \text{ MeV} \), a rather easy signal to observe; therefore, to explain the absence of the \( D^*K \) signal one must invoke a mechanism favouring the production of the \( 0^+ \) state and inhibiting that of \( 1^+ \) state in \( e^+e^- \to DKX \), a mechanism discriminating the first radial excitation from the case \( n = 0 \).

For \( s_P^{\ell} = \frac{5}{2}^- \), \( J^P = 3^- \), \( n = 0 \) the small \( DK \) width is mainly due to kinematics (\( \Gamma \propto q_K^7 \)). 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 coupling constant is similar to the couplings of the other doublets to light pseudoscalars. If \( D_{sJ}(2860) \) has \( J^P = 3^- \), it is not expected to be produced in non leptonic \( B \) decays such as \( \bar{B}^0 \to D_{sJ}(2860)^-D^+ \) and \( B^- \to \bar{D}_{sJ}(2860)^-D^0 \), so that the quantum number assignment can be confirmed by studies of \( D_{sJ} \) production in \( B \) transitions. \( D_{sJ}(2860) \) can be one of the predicted high mass, high spin and relatively narrow \( c\bar{s} \) states \(^{21,16} \); its non-strange partner \( D_3 \) is also expected to be narrow: \( \Gamma(D_3^+ \to D^0\pi^+ ) \approx 37 \text{ MeV} \), and can be produced in semileptonic and non leptonic \( B \) decays, such as \( \bar{B}^0 \to D_3^+ \ell^-\bar{\nu}_\ell \) and \( \bar{B}^0 \to D_3^0 \pi^- \).

We conclude this Section showing in fig. 3 a tentative classification of the known \( c\bar{s} \) mesons. Confirmation of this classification and the search for the missing states is a task for current and future investigations.

\(^c\)A candidate for this assignment is the resonance \( D_{sJ}(2715) \) observed very recently by Belle\(^7 \) in \( B^+ \to \bar{D}^0D^0K^+ \) decays with \( M = 2715 \pm 11_{-14}^{+11} \text{ MeV} \), \( \Gamma = 115 \pm 20_{-32}^{+36} \text{ MeV} \) and \( J^P = 1^- \), a state that could also be interpreted as the first radial recurrence of \( D^*_s \), as discussed in Refs. 18, 20.
3. Hidden charm mesons

While the results in the open charm sector can be organized in a well-established scheme, the situation in the hidden charm sector is more complex. A few new results, in particular those concerning $\eta_c'$ and $h_c$, essentially agree with the expectations, although some particular aspects deserve investigations. Others, namely those concerning $X(3940)$, $Y(3940)$ and $Z(3930)$, could be organized according to generally accepted schemes with some caveat. The observations concerning $Y(4260)$ and $X(3872)$ have puzzling aspects: in particular, these states present features that could be expected for non standard quark-antiquark mesons, as we briefly discuss below.

3.1. $h_c$ and $\eta_c'$

The observation of $h_c$ ($J^{PC} = 1^{++}$) by Cleo$^{22}$ in $\psi' \to \pi^0 h_c$, with $h_c$ decaying to $\eta_c \gamma$, completes the set of four low-lying charmonium states with $\ell = 1$. The mass: $M(h_c) = 3524.4 \pm 0.6 \pm 0.4$ MeV deviates by less than 1 MeV from the center of gravity of the $\chi_{cJ}$ states. The strategy of searching
\(h_c\) in \(B\) decays\(^\text{23}\) has not been successful, yet, since the branching fraction of \(B \rightarrow K h_c\) is smaller than estimated by the methods that reproduce the measured \(B(B \rightarrow K \chi_{c0})\) \(^\text{24}\).

Also the observation of \(\eta'_c\), made by Belle, Cleo and BaBar in \(B\) decays: \(B \rightarrow K \eta'_c\), in \(e^+e^- \rightarrow J/\psi \eta'_c\) and in \(\gamma \gamma \rightarrow \eta'_c \rightarrow K_S K^{\pm} \pi^\mp\) \(^\text{25}\) completes the doublet of the first radial excitations of \((\eta_c, J/\psi)\). The parameters of the resonance are: \(M(\eta'_c) = 3638 \pm 4\) MeV (thus the hyperfine splitting is 48 MeV) and \(\Gamma(\eta'_c) = 14 \pm 7\) MeV. The observations are in agreement with the expectations, with some difficulty with the \(\gamma \gamma\) rate of \(\eta'_c\) which is smaller than estimated\(^\text{26}\). The \(c \bar{c}\) spectrum below the open charm threshold can be reproduced by a one-glue-exchange short-distance potential, a scalar linearly confining potential and spin-spin and spin-orbit interactions\(^\text{27}\). However, when the energy increases, the theoretical determination of the meson properties, in particular of the spectrum, cannot ignore the open charm thresholds, starting from \(D^0 \bar{D}^0\), an old problem for which there is no model-independent solution, yet. Mass shifts of \(20 - 40\) MeV have been estimated for states close to the thresholds\(^\text{28}\). These effects must be considered in the discussion of \(X(3940), Y(3940)\) and \(Z(3930)\).

### 3.2. \(X(3940), Y(3940)\) and \(Z(3930)\).

For \(X(3940)\), found by Belle\(^\text{29}\) in the hadronic system recoiling against \(J/\psi\) in \(e^+e^-\) annihilation, with \(M = 3943 \pm 6 \pm 6\) MeV, \(\Gamma < 52\) MeV and decays into \(D^+ \bar{D}\), two interpretations are possible: i) the \(3^1S_0\) partner of \(3^3S_1\) (\(\psi(4040)\)), an assignment that could be confirmed by observation of the state in \(\gamma \gamma\); ii) the first radial excitation of \(\chi_{c1}\), with the difficulty that \(\chi_{c1}\) has not been found in the same set of data; moreover, another candidate, \(Y(3940)\), is available for the same assignment.

Indeed, \(Y(3940)\) was also found by Belle\(^\text{30}\) in the \(J/\psi \omega\) system produced in \(B \rightarrow K J/\psi \omega\). Its parameters are: \(M = 3943 \pm 11 \pm 13\) MeV and \(\Gamma = 85 \pm 22 \pm 26\) MeV; decays to open charm mesons have not been found, so far. The possible assignment as \(2^3P_1\) (\(\chi'_{c1}\)) implies that it should be observed in \(DD^*\), even though the phase space for such a mode is small.

\(Z(3930)\) is the last state in this region of mass found by Belle\(^\text{31}\) in \(\gamma \gamma \rightarrow DD\), with \(M = 3941 \pm 4 \pm 2\) MeV and \(\Gamma = 20 \pm 8 \pm 3\) MeV. The helicity distribution in the final state is consistent with a \(J = 2\) state, therefore it can be identified as the \(2^3P_2\) (\(\chi'_{c2}\)) meson.

In spite of the uncertainties in the quantum number assignment, the three states can be arranged in the \(c \bar{c}\) spectrum, as shown in fig. 4. The case of \(Y(4260)\) and \(X(3872)\) is more difficult.
Fig. 4. Spectrum of $c\bar{c}$ states together with the thresholds for decays to open charm mesons. Possible positions of $X(3872)$ and $Y(4260)$ are shown.

### 3.3. $Y(4260)$

$Y(4260)$ is the first meson in the list of states seeming to escape ordinary classifications. It was found by BaBar$^{32}$ in $B^{-} \rightarrow K^{-}\pi\pi J/\psi$ and in radiative return analyses $e^{+}e^{-} \rightarrow \gamma_{ISR}\pi\pi J/\psi$, and confirmed by Cleo$^{33}$ in $e^{+}e^{-} \rightarrow \gamma_{ISR}Y$, with $Y$ observed in $\pi^{+}\pi^{-} J/\psi$, $\pi^{0}\pi^{0} J/\psi$ and $K^{+}K^{-} J/\psi$. The properties of the resonance are: $M = 4259 \pm 8 \pm 4$ MeV, $\Gamma = 88 \pm 23 \pm 5$ MeV and $J^{PC} = 1^{--}$. Moreover, the dipion mass distribution is consistent with a $s$-wave structure, so that a decay through $f_{0}(980)$ can be supposed.

The problem with a $c\bar{c}$ interpretation is that a $1^{--}$ meson can be either a $\ell = 0$ state, a radial excitation between $\psi(4040)$ ($\psi(3S)$) and $\psi(4415)$ (at present interpreted as $\psi(4S)$), or a $\ell = 2$ state above $\psi(4159)$ (interpreted as $\psi(2D)$), with mass not predicted by any theoretical determination. Therefore, the meson looks as an extra state with respect to the $1^{--}$ levels, a state with a large coupling to $\pi\pi J/\psi$ and without observed (so far) decays in open charm mesons. Its mass is just above the $D_{s}^{*}D_{s}^{*}$ threshold and below the $DD_{1}$ threshold, $D_{1}(2420)$ being the narrow $c\bar{c}$ axial vector state.

Among various interpretations$^{34}$, the one suggesting that $Y(4260)$ is a $\bar{c}Gc$ $1^{--}$ hybrid$^{35}$ emphasizes the agreement of the observation with some expectations. Indeed, charmed hybrids in this range of mass are conjectured,
namely on the basis of lattice QCD simulations, with large couplings to $J/\psi$ and light ($\eta, \eta'$) mesons and with decays in open charm mesons with different orbital angular momentum (a decay in $DD'_1(2440)$ is possible, due to the broad width of $D'_1$). Noticeably, other hybrids with different quantum numbers are expected in the same range of mass; their observation would open a new chapter of the hadron spectroscopy.

3.4. $X(3872)$

We have left $X(3872)$ as the last meson to discuss, since it presents the most puzzling aspects. The observations can be summarized as follows:

(i) the $X$ resonance has been found in $J/\psi \pi^+ \pi^-$ distribution by four experiments, both in $B$ decays ($B^{-}(0) \rightarrow K^{-}(0) X$), both in $p\bar{p}$ annihilation\textsuperscript{36}. The mass is $M = 3871.9 \pm 0.6$ MeV while the width remains unresolved: $\Gamma < 2.3$ MeV (90 % CL);

(ii) there is no evidence of resonances in the charged mode $J/\psi \pi^\pm$ or in $J/\psi \eta$\textsuperscript{37};

(iii) the state is not observed in $e^+e^-$ annihilation;

(iv) for $X$ produced in $B$ decays the ratio $B(B^0 \rightarrow K^0 X)/B(B^+ \rightarrow K^+ X)$ is obtained\textsuperscript{37};

(v) the dipion spectrum in $J/\psi \pi^+ \pi^-$ is peaked at large mass;

(vi) the decay in $J/\psi \pi^+ \pi^- 0$ is observed\textsuperscript{38} with $B(X \rightarrow J/\psi \pi^+ \pi^- 0)/B(X \rightarrow J/\psi \pi^+ \pi^-) = 1.0 \pm 0.4 \pm 0.3$: this implies G-parity violation;

(vii) the radiative mode $X \rightarrow J/\psi \gamma$ is found\textsuperscript{38,39} with $B(X \rightarrow J/\psi \gamma)/B(X \rightarrow J/\psi \pi^+ \pi^-) = 0.19 \pm 0.07$, therefore charge conjugation of the state is $C = +1$;

(viii) the angular distribution of the final state is compatible with the spin-parity assignment $J^P = 1^+ 40$;

(ix) there is a signal in $D^0\bar{D}^0\pi^0$ with $B(X \rightarrow B^0\bar{D}^0\pi^0)/B(X \rightarrow J/\psi \pi^+ \pi^-) = 9 \pm 4$\textsuperscript{41}.

All the measurements are thus compatible with the assignment $J^{PC} = 1^{++}$. If the $2^3P_2$ is identified with $Y(3940)$, there is overpopulation of $1^{++}$ $c\bar{c}$ mesons.

Noticeably, the mass of the resonance coincides with that of the $D^{*0}\bar{D}^0$ pair; this suggests that the state could be a realization of the molecular quarkonium\textsuperscript{42}, a bound state of two mesons, $D^{*0}$ and $\bar{D}^0$, with small binding energy\textsuperscript{43}. The absence of a $D^{*+}D^-$ molecule can be interpreted in this scheme observing that, being heavier by 7 MeV, such a state can rapidly de-
cay in $D^{*0}\bar{D}^0$. In this description, the wave function of $X(3872)$ has various components:

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

(3) allowing to explain a few observations and to make predictions:

(i) the state has no definite isospin;
(ii) the decay $X \rightarrow J/\psi\pi^0\pi^0$ is forbidden;
(iii) since the decays of the resonance are mainly due to the decays of its components, the radiative transition in neutral mesons $X \rightarrow D^0\bar{D}^0\gamma$ should be dominant with respect to $X \rightarrow D^+D^-\gamma$;
(iv) a resonance $X_b(10604)$ is expected as a bound state of $\bar{B}^0$ and $B^{*0}$;
(v) if the molecular binding mechanism is provided by a single pion exchange, this model explains the absence of $DD$ molecular states.

The description of $X(3872)$ in the simple charmonium scheme, leaving unsolved the issue of the overpopulation of $1^{++}$ states, presents alternative arguments to the molecular description. First, the molecular binding mechanism cannot be a single $\pi^0$ exchange, since this produces an attractive potential which is a delta function in space:

$$V(r) = -\frac{1}{3} g_{D^*D\pi} \epsilon' \cdot \epsilon \delta(r) + \ldots$$

($g_{D^*D\pi}$ is the coupling constant of the $D^*D\pi$ vertex, $\epsilon$ and $\epsilon'$ the $D^*$ polarization vectors) and therefore it does not give rise to a bound state in three spatial dimensions. Concerning the isospin (G-parity) violation, to correctly interpret the large value of the ratio $B(X \rightarrow J/\psi\pi^+\pi^-\pi^0)$ one has to consider that the phase space effects in two and three pion modes are very different. The amplitude ratio is rather small: $A(X \rightarrow J/\psi\rho^0) / A(X \rightarrow J/\psi\omega) \approx 0.2$, 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. Finally, also the eventual dominance of $X \rightarrow D^0\bar{D}^0\gamma$ with respect to $X \rightarrow D^+D^-\gamma$ could be interpreted invoking standard mechanisms. Notice that a prediction of the charmonium description is that the rates of $B^0 \rightarrow XK^0$ and $B^- \rightarrow XK^-$ are nearly equal; the measurements are not conclusive on this point.

Our conclusion is that, at present, there are no compelling arguments allowing to exclude an interpretation in favour of others. Further analyses are requested to solve the issue of $X(3872)$. 

4. Conclusions
In this short review of the new charm meson spectroscopy we have attempted to schematically describe the experimental observations, various interpretations and the main open problems. We do not want to emphasize how interesting the present situation is, and how much work is needed, both on the experimental, both on the theory side, to elaborate the information collected so far. We prefer to borrow the conclusion from another review on charm, written about 30 years ago: "It is easy to see the time when the charmed particles will be studied in detail... so that we look for new enjoyment and surprises." 46

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