International Journal of Modern Physics A
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Understanding open-charm mesons

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We present a theoretical framework that accounts for the new $D_J$ and $D_{sJ}$ mesons measured in the open-charm sector. These resonances are properly described if considered as a mixture of conventional $P$–wave quark-antiquark states and four-quark components. The narrowest states are basically $P$–wave quark-antiquark mesons, while the dominantly four-quark states are shifted above the corresponding two-meson threshold. We study the electromagnetic decay widths as basic tools to scrutinize their nature.

During the last few years, heavy meson spectroscopy is living a continuous excitation due to the discovery of several new charmed mesons. Three years ago BABAR Collaboration reported the observation of a charm-strange state, the $D_{sJ}^{*}(2317)$¹, that was later on confirmed by CLEO² and Belle Collaboration³. Besides, BABAR had also pointed out to the existence of another charm-strange meson, the $D_{sJ}(2460)$¹. This resonance was measured by CLEO² and confirmed by Belle³. Belle results are consistent with the assignments of $J^P = 0^+$ for the $D_{sJ}^{*}(2317)$ and $J^P = 1^+$ for the $D_{sJ}(2460)$. However, although these states are well established, they present unexpected properties quite different from those predicted by quark potential models. If they would correspond to standard $P$–wave mesons made of a charm quark, $c$, and a strange antiquark, $\bar{s}$, their masses would be larger, around 2.48 GeV for the $D_{sJ}^{*}(2317)$ and 2.55 GeV for the $D_{sJ}(2460)$. They would be therefore above the $DK$ and $D^*K$ thresholds, respectively, being broad resonances. However the states observed by BABAR and CLEO are very narrow, $\Gamma < 4.6$ MeV for the $D_{sJ}^{*}(2317)$ and $\Gamma < 5.5$ MeV for the $D_{sJ}(2460)$.

The intriguing situation of the charm-strange mesons has been translated to the nonstrange sector with the Belle observation of a nonstrange broad scalar resonance, $D_{0}^{*}(2308)$, of a nonstrange broad scalar resonance, $D_{0}^{*}(2308)$, with a mass of 2308 ± 17 ± 15 ± 28 MeV/c² and a width $\Gamma = 276 \pm 21 \pm 18 \pm 60$ MeV. A state with similar properties has been suggested by FOCUS Collaboration at Fermilab during the measurement of masses and widths of excited charm mesons $D_{sJ}^{*}(2317)$. This state generates for the open-charm nonstrange mesons a very similar problem to the one arising in the strange sector with the $D_{sJ}^{*}(2317)$. If the $D_0^{*}(2308)$ would correspond to a standard $P$–wave meson made of a charm

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Table 1. $c\pi$ and $c\pi$ masses (QM), in MeV. Experimental data (Exp.) are taken from Ref.9, except for the state denoted by a dagger that has been taken from Ref. 4.

| $nJ^P$ | State | QM ($c\pi$) | Exp. | State | QM ($c\pi$) | Exp. |
|--------|-------|-------------|------|-------|-------------|------|
| $1S\ 0^-$ | $D_s$ | 1981 | 1968.5±0.6 | $D$ | 1883 | 1867.7±0.5 |
| $1S\ 1^-$ | $D_s^*$ | 2112 | 2112.4±0.7 | $D^*$ | 2010 | 2008.9±0.5 |
| $1P\ 0^+$ | $D_{sJ}^*(2317)$ | 2489 | 2317.4±0.9 | $D_{sJ}^0(2308)$ | 2465 | 2308±17±15±28$^1$ |
| $1P\ 1^+$ | $D_{sJ}(2460)$ | 2578 | 2459.3±1.3 | $D_1(2420)$ | 2450 | 2422.2±1.8 |
| $1P\ 2^+$ | $D_{s2}(2573)$ | 2543 | 2535.3±0.6 | $D_{sJ}^0(2430)$ | 2546 | 2427 ± 26 ± 25 |
| $1P\ 3^+$ | $D_{s3}(2615)$ | 2582 | 2572.4±1.5 | $D_{sJ}^0(2460)$ | 2496 | 2459±4 |

quark, $c$, and a light antiquark, $\pi$, its mass would have to be larger, around 2.46 GeV. In this case, the quark potential models prediction and the measured resonance are both above the $D\pi$ threshold, the large width observed being expected although not its low mass.

The difficulties to identify the $D_J$ and $D_{sJ}$ states with conventional $c\pi$ mesons are rather similar to those appearing in the light-scalar meson sector$^6$ and may be indicating that other configurations are playing a role. $q\bar{q}$ states are more easily identified with physical hadrons when virtual quark loops are not important. This is the case of the pseudoscalar and vector mesons, mainly due to the $P$–wave nature of this hadronic dressing. On the contrary, in the scalar sector is the $q\bar{q}$ pair the one in a $P$–wave state, whereas quark loops may be in a $S$–wave. In this case the intermediate hadronic states that are created may play a crucial role in the composition of the resonance, in other words unquenching is important. This has been shown to be relevant for the proper description of the low-lying scalar mesons$^7$.

In this work we have explored the same ideas for the understanding of the properties of the $D_J$ and $D_{sJ}$ meson states. In non-relativistic quark models the wave function of a zero baryon number ($B=0$) hadron may be written as $|B=0\rangle = \Omega_1 |qq\rangle + \Omega_2 |qqq\rangle + \ldots$ where $q$ stands for quark degrees of freedom and the coefficients $\Omega_i$ take into account the mixing of four- and two-quark states. The hamiltonian considering the mixing between both configurations could be described using the $^3P_0$ model, however, since this model depends on the vertex parameter, we prefer in a first approximation to parametrize this coefficient by looking to the quark pair that is annihilated and not to the spectator quarks that will form the final $q\bar{q}$ state. Therefore we have taken $V_{q\bar{q}\rightarrow qqqq} = \gamma$. Further details about the formalism and the constituent quark model used are given in Refs. 7$^7$, 8$^8$.

A thoroughly study of the full meson spectra has been presented in Ref. 8$^3$. The results for the open-charm mesons are resumed in Table 1$^3$. It can be seen how the open-charm states are easily identified with standard $c\pi$ mesons except for the cases of the $D_{sJ}^*(2317)$, the $D_{sJ}(2460)$, and the $D_{sJ}^0(2308)$. This is a common behavior of almost all quark potential model calculation$^{10}$. In a similar manner, quenched lattice NRQCD predicts for the $D_{sJ}^*(2317)$ a mass of 2.44 GeV$^{11}$, while using relativistic charm quarks the mass obtained is 2.47 GeV$^{12}$. Unquenched lattice QCD calculations of $c\pi$ states do not find a window for the $D_{sJ}^*(2317)$, supporting the difficulty of a $P$–wave $c\pi$ interpretation.
Table 2. Probabilities (P), in %, of the wave function components and masses (QM), in MeV, of the open-charm mesons once the mixing between $q\bar{q}$ and $qq\bar{q}$ configurations is considered. Experimental data are taken from Ref. 9 except for the state denoted by a dagger that has been taken from Ref. 4.

| J$^P$ | I = 0 | J$^P$ | I = 1/2 | J$^P$ = 0$^+$ |
|-------|-------|-------|----------|----------------|
|       | QM    | Exp.  | QM       | Exp.          |
|       | 2339  | ±0.9  | 2421     | ±1.3          | 2555          |
| P(cn$n$) | 28    | P(cn$n$) | 25  | ~ 1             | P(cn$n$) | 46 |
| P(c$n$1$p$) | 71    | P(c$n$1$p$) | 74  | ~ 1             | P(c$n$1$p$) | 53 |
| P(c$2$p) | ~ 1   | P(c$2$p) | ~ 1         | 98             | P(c$2$p) | ~ 1 |

Using for the $qq$ interaction the parametrization of Ref. 7, the results obtained for the $cn$n configuration are 2731 and 2699 MeV for the $J^P = 0^+$ with $I = 0$ and $I = 1$, and 2841 and 2793 MeV for the $J^P = 1^+$ with $I = 0$ and $I = 1$. For the $cn$n configuration with $I = 1/2$ the energy is 2505 MeV. The $I = 1$ and $I = 0$ states are far above the corresponding strong decaying thresholds and therefore should be broad, what rules out a pure four-quark interpretation of the new open-charm mesons.

As outlined above, for $P-$wave mesons the hadronic dressing is in a $S-$wave, thus physical states may correspond to a mixing of two- and four-body configurations. In the isoscalar sector, the $cn$n and $c\bar{s}$ states get mixed, as it happens with $cn$n and $c\bar{n}$ for the $I = 1/2$ case. The parameter $\gamma$ has been fixed to reproduce the mass of the $D_{sJ}(2317)$ meson, $\gamma = 240$ MeV. The results obtained are shown in Table 2. Let us first analyze the nonstrange sector. The $^3P_0$ $c\bar{n}$ pair and the $cn$n have a mass of 2465 MeV and 2505 MeV, respectively. Once the mixing is considered one obtains a state at 2241 MeV with 46% of four-quark component and 53% of $c\bar{n}$ pair. The lowest state, representing the $D_0^+(2308)$, is above the isospin preserving threshold $D\pi$, being broad as observed experimentally. The mixed configuration compares much better with the experimental data than the pure $c\bar{n}$ state. The orthogonal state appears higher in energy, at 2713 MeV, with and important four-quark component.

Concerning the strange sector, the $D_{sJ}^+(2317)$ and the $D_{sJ}(2460)$ are dominantly $c\bar{s}$ $J = 0^+$ and $J = 1^+$ states, respectively, with almost 30% of four-quark component. Such component is responsible for the shift of the mass of the unmixed states to the experimental values below the $DK$ and $D^*K$ thresholds. Being both states below their isospin-preserving two-meson threshold, the only allowed strong decays to $D_{sJ}^0\pi$ would violate isospin and are expected to have small widths $O(10) \text{ keV}$. As a consequence, they should be narrower than the $D_{s2}(2573)$ and $D_{s1}(2536)$, opposite to what is expected from heavy quark symmetry. The second isoscalar $J^P = 1^+$ state, with an energy of 2555 MeV and 98% of $c\bar{s}$ component, corresponds to the $D_{s1}(2536)$. Regarding the $D_{sJ}^+(2317)$, it has been argued that a possible $DK$ molecule would be preferred with respect to an $I = 0$ $cn$n tetraquark, what would anticipate an $I = 1$ $cn$n partner nearby in mass. Our results confirm the last argument, the vicinity of the isoscalar and isovector tetraquarks, however, the re-
Electromagnetic decay widths, in keV, for the \( D^*_s J^+ (2317) \) and \( D^*_s J^+ (2460) \) (QM), compared to the results of two different quark models based only on \( q \bar{q} \) states. To compare with the experimental data by CLEO and Belle we have assumed for \( \Gamma(D^{*+}_s \pi^0) \approx \Gamma(D^{*+}_s \pi^0) \approx 10 \text{ keV} \) as estimated in Ref. [14].

| Transition                  | Quark models QM | Ref. 13 | Ref. 14 | Experiments CLEO 2 | Belle 3 |
|-----------------------------|------------------|---------|---------|---------------------|---------|
| \( D^*_s J^+ (2317) \rightarrow D^{*+}_s \gamma \) | 1.6              | 1.74    | 1.9     | < 0.59              | > 1.8   |
| \( D^*_s J^+ (2460) \rightarrow D^{*+}_s \gamma \) | 0.06             | 4.66    | 5.5     | < 1.6               | < 3.1   |
| \( D^*_s J^+ (2460) \rightarrow D^{*+}_s \gamma \) | 6.7              | 5.08    | 6.2     | < 4.9               | 5.5 ± 1.3 ± 0.8 |

Apart from the masses, the structure of the \( D^*_s J^+ (2317) \) and the \( D^*_s J^+ (2460) \) mesons could be scrutinized also through the study of their electromagnetic decay widths. We compare in Table 3 our results with different theoretical approaches and the experimental limits reported by Belle and CLEO. The main difference is noticed in the suppression predicted for the \( D^*_s J^+ (2460) \rightarrow D^{*+}_s \gamma \) decay as compared to the \( D^*_s J^+ (2460) \rightarrow D^{*+}_s \gamma \). A ratio \( D^*_s J^+ (2460) \rightarrow D^{*+}_s \gamma / D^*_s J^+ (2460) \rightarrow D^{*+}_s \gamma \approx 1 - 2 \) has been obtained assuming a \( q \bar{q} \) structure for both states (what seems incompatible with their properties). We find a larger value, \( D^*_s J^+ (2460) \rightarrow D^{*+}_s \gamma / D^*_s J^+ (2460) \rightarrow D^{*+}_s \gamma \approx 100 \), due to the small \( 1^3 P_1 \) probability of the \( D^*_s J^+ (2460) \). A similar enhancement has been obtained in Ref. [11] in the framework of light-cone QCD sum rules.

This work has been partially funded by Ministerio de Ciencia y Tecnología under Contract No. FPA2004-05616, by Junta de Castilla y León under Contract No. SA-104/04, and by Generalitat Valenciana under Contract No. GV05/276.

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