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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 scrutiny 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 CLEO[2] and Belle Collaborations[3]. Besides, BABAR had also pointed out to the existence of another charm-strange meson, the $D_{sJ}(2460)$[1]. This resonance was measured by CLEO[2] and confirmed by Belle[3]. 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[4] of a nonstrange broad scalar resonance, D^*_0, with a mass of $2308 \pm 17 \pm 15 \pm 28$ MeV/c^2 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[5] during the measurement of masses and widths of excited charm mesons D^*_2. 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. $c\bar{s}$ and $c\bar{n}$ 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].

$nL\ J^P$	State	QM ($c\bar{s}$)	Exp.	State	QM ($c\bar{n}$)	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	$D_0^*(2308)$	2465	2308±17±15±28†
$1P\ 1^+$	$D_{sJ}(2460)$	2578	2459.3±1.3	$D_1(2420)$	2450	2422.2±1.8
$1P\ 1^+$	$D_{s1}(2536)$	2543	2535.3±0.6	$D_1^0(2430)$	2546	2427 ± 26 ± 25
$1P\ 2^+$	$D_{s2}(2573)$	2582	2572.4±1.5	$D_2^*(2460)$	2496	2459±4

quark, c, and a light antiquark, $\bar{n}$, 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 $c\bar{n}$ 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 $|\mathrm{B}=0\rangle = \Omega_1\,|q\bar{q}\rangle + \Omega_2\,|qq\bar{q}\bar{q}\rangle + ...$ where q stands for quark degrees of freedom and the coefficients Ω_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 $V_{q\bar{q}\leftrightarrow qq\bar{q}\bar{q}} = \gamma$. Further details about the formalism and the constituent quark model used are given in Refs.[7,8].

A thoroughly study of the full meson spectra has been presented in Ref.[8]. The results for the open-charm mesons are resumed in Table 1. It can be seen how the open-charm states are easily identified with standard $c\bar{n}$ mesons except for the cases of the $D_{sJ}^*(2317)$, the $D_{sJ}(2460)$, and the $D_0^*(2308)$. This is a common behavior of almost all quark potential model calculations[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 $c\bar{s}$ states do not find a window for the $D_{sJ}^*(2317)$[6], supporting the difficulty of a $P-$wave $c\bar{s}$ 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 $qq\bar{q}\bar{q}$ 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].

$I=0$					$I=1/2$	
$J^P=0^+$		$J^P=1^+$			$J^P=0^+$	
QM	2339	QM	2421	2555	QM	2241
Exp.	2317.4±0.9	Exp.	2459.3±1.3	2535.3±0.6	Exp.	2308±17±15±28†
P($cn\bar{s}\bar{n}$)	28	P($cn\bar{s}\bar{n}$)	25	~ 1	P($cn\bar{n}\bar{n}$)	46
P($c\bar{s}_{1^3P}$)	71	P($c\bar{s}_{1^1P}$)	74	~ 1	P($c\bar{n}_{1P}$)	53
P($c\bar{s}_{2^3P}$)	~ 1	P($c\bar{s}_{1^3P}$)	~ 1	98	P($c\bar{n}_{2P}$)	~ 1

Using for the qq interaction the parametrization of Ref.[7], the results obtained for the $cn\bar{s}\bar{n}$ 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 $cn\bar{n}\bar{n}$ 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 $cn\bar{s}\bar{n}$ and $c\bar{s}$ states get mixed, as it happens with $cn\bar{n}\bar{n}$ and $c\bar{n}$ for the $I=1/2$ case. The parameter γ 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 $cn\bar{n}\bar{n}$ 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 $D^*_s\pi$ would violate isospin and are expected to have small widths $O(10)$ keV[13,14]. As a consequence, they should be narrower than the $D_{s2}(2573)$ and $D_{s1}(2536)$, opposite to what it 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 $I=0$ $cn\bar{s}\bar{n}$ tetraquark, what would anticipate an $I=1$ $cn\bar{s}\bar{n}$ partner nearby in mass[15]. Our results confirm the last argument, the vicinity of the isoscalar and isovector tetraquarks, however, the re-

Table 3. Electromagnetic decay widths, in keV, for the $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ (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 $\Gamma(D_s^{*+}\pi^0) \approx \Gamma(D_s^+\pi^0) \approx 10$ keV as estimated in Ref. [14].

	Quark models			Experiments	
Transition	QM	Ref.[13]	Ref.[14]	CLEO[2]	Belle[3]
$D_{sJ}^*(2317) \to D_s^{*+}\gamma$	1.6	1.74	1.9	< 0.59	< 1.8
$D_{sJ}(2460) \to D_s^{*+}\gamma$	0.06	4.66	5.5	< 1.6	< 3.1
$D_{sJ}(2460) \to D_s^{+}\gamma$	6.7	5.08	6.2	< 4.9	5.5±1.3±0.8

stricted coupling to the $c\bar{s}$ system allowed only for the $I = 0$ four-quark states opens the possibility of a mixed nature for the $D_{sJ}^*(2317)$ while the $I = 1$ $J = 0^+$ and $J = 1^+$ four-quark states appear above 2700 MeV and cannot be shifted to lower energies.

Apart from the masses, the structure of the $D_{sJ}^*(2317)$ and the $D_{sJ}(2460)$ mesons could be scrutinied 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 $D_{sJ}(2460) \to D_s^{*+}\gamma$ decay as compared to the $D_{sJ}(2460) \to D_s^+\gamma$. A ratio $D_{sJ}(2460) \to D_s^+\gamma / D_{sJ}(2460) \to D_s^{*+}\gamma \approx 1-2$ has been obtained assuming a $q\bar{q}$ structure for both states[13,14] (what seems incompatible with their properties). We find a larger value, $D_{sJ}(2460) \to D_s^+\gamma / D_{sJ}(2460) \to D_s^{*+}\gamma \approx 100$, due to the small 1^3P_1 $c\bar{s}$ probability of the $D_{sJ}(2460)$. A similar enhancement has been obtained in Ref.[16] in the framework of light-cone QCD sum rules.

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