Eur. Phys. J. A **31**, 722–724 (2007)
DOI 10.1140/epja/i2006-10199-0

THE EUROPEAN PHYSICAL JOURNAL A

Special Article – QNP 2006

The puzzle of the D and D_s mesons

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Received: 25 October 2006

Abstract. 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.

PACS. 14.40.Lb Charmed mesons – 14.40.Ev Other strange mesons

During the last few years, there has been a renewed interest in heavy-meson spectroscopy due to the discovery of several new charmed mesons. Three years ago the 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, $\overline{s}$, 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, becoming 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 extended to the nonstrange sector with the Belle observation [4] of a nonstrange broad scalar resonance, D^*_0, with a mass of $2308 \pm 17 \pm 15 \pm 28\,\mathrm{MeV}/c^2$ and a width $\Gamma = 276 \pm 21 \pm 18 \pm 60$ MeV. A state with similar properties has been suggested by the 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 quark, c, and a light antiquark, $\overline{n}$, 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 in identifying the D_J and D_{sJ} states with conventional $c\overline{q}$ 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. $q\overline{q}$ 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. In contrast, in the scalar sector the $q\overline{q}$ pair is the one in a P-wave state, whereas quark loops may be in an 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 nonrelativistic quark models the wave function of a hadron with baryon number equal to zero may be written as $|B=0\rangle = \Omega_1|q\bar{q}\rangle + \Omega_2|qq\bar{q}\bar{q}\rangle + \ldots$, 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

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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.
$1S\ 0^-$	D_s	1981	1968.5 ± 0.6
$1S\ 1^-$	D_s^*	2112	2112.4 ± 0.7
$1P\ 0^+$	$D_{sJ}^*(2317)$	2489	2317.4 ± 0.9
$1P\ 1^+$	$D_{sJ}(2460)$	2578	2459.3 ± 1.3
$1P\ 1^+$	$D_{s1}(2536)$	2543	2535.3 ± 0.6
$1P\ 2^+$	$D_{s2}(2573)$	2582	2572.4 ± 1.5
$1S\ 0^-$	D	1883	1867.7 ± 0.5
$1S\ 1^-$	D^*	2010	2008.9 ± 0.5
$1P\ 0^+$	$D_0^*(2308)$	2465	$2308 \pm 17 \pm 15 \pm 28^\dagger$
$1P\ 1^+$	$D_1(2420)$	2450	2422.2 ± 1.8
$1P\ 1^+$	$D_1^0(2430)$	2546	$2427 \pm 26 \pm 25$
$1P\ 2^+$	$D_2^*(2460)$	2496	2459 ± 4

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].

$I = 0\ J^P = 0^+$		
QM	2339	2847
Exp.	2317.4 ± 0.9	–
$P(cn\bar{s}\bar{n})$	28	55
$P(c\bar{s}_{1^3P})$	71	25
$P(c\bar{s}_{2^3P})$	~ 1	20
$I = 0\ J^P = 1^+$		
QM	2421	2555
Exp.	2459.3 ± 1.3	2535.3 ± 0.6
$P(cn\bar{s}\bar{n})$	25	~ 1
$P(c\bar{s}_{1^1P})$	74	~ 1
$P(c\bar{s}_{1^3P})$	~ 1	98
$I = 1/2\ J^P = 0^+$		
QM	2241	2713
Exp.	$2308 \pm 17 \pm 15 \pm 28^\dagger$	–
$P(cn\bar{n}\bar{n})$	46	49
$P(c\bar{n}_{1P})$	53	46
$P(c\bar{n}_{2P})$	~ 1	5

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 thorough study of the full meson spectrum in this model has been presented in ref. [8]. The results for the open-charm mesons are summarized in table 1. It can be seen how the open-charm states are easily identified with standard $c\bar{q}$ mesons except for the cases of the $D_{sJ}^*(2317)$, the $D_{sJ}(2460)$, and the $D_0^*(2308)$. This is a common feature 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.

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 decay 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 an 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 mix, 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 $D\pi$, becoming broad as it is 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 an 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 restricted 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 investigated also

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 $\Gamma(D_s^{*+}\pi^0) \approx \Gamma(D_s^+\pi^0) \approx 10\,\mathrm{keV}$ as estimated in ref. [14].

	Quark models		
Transition	QM	Ref. [13]	Ref. [14]
$D_{sJ}^*(2317) \to D_s^{*+}\gamma$	1.6	0.8	1.9
$D_{sJ}(2460) \to D_s^{*+}\gamma$	0.06	2.2	5.5
$D_{sJ}(2460) \to D_s^{+}\gamma$	6.7	2.4	6.2

	Experiments	
Transition	CLEO [2]	Belle [3]
$D_{sJ}^*(2317) \to D_s^{*+}\gamma$	< 0.59	< 1.8
$D_{sJ}(2460) \to D_s^{*+}\gamma$	< 1.6	< 3.1
$D_{sJ}(2460) \to D_s^{+}\gamma$	< 4.9	$5.5 \pm 1.3 \pm 0.8$

Table 4. Masses (QM), in MeV, of the recently measured charmonium and B_c states obtained within the model of ref. [8] used in this work.

Name	Mass	Ref.	$n^{2S+1}L_J$	QM
$X(3940)$	$3943 \pm 6 \pm 6$	[18]	2^1P_1	3923
–	–		2^3P_0	3878
$Y(3940)$	$3943 \pm 11 \pm 13$	[19]	2^3P_1	3915
$X'_{c2}(3940)$	$3931 \pm 4 \pm 2$	[20]	2^3P_2	3936
$Y(4260)$	$4260 \pm 8 \pm 2$	[21]	4^3S_1	4307
$B_c(6287)$	$6287 \pm 4.8 \pm 1.1$	[22]	1^1S_0	6277

through the study of their electromagnetic decay widths. In table 3 we compare our results with different theoretical approaches and the experimental limits reported by Belle and CLEO. The main difference is the suppression predicted for the $D_{sJ}(2460) \to D_s^{*+}\gamma$ decay relative to the $D_{sJ}(2460) \to D_s^{+}\gamma$. A ratio

$$D_{sJ}(2460) \to D_s^+\gamma / D_{sJ}(2460) \to D_s^{*+}\gamma \approx 1\text{–}2$$

has been obtained assuming a $q\bar{q}$ structure for both states [13,14] (which seems incompatible with their properties). We find a much 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 in contrast to a previous calculation of the same authors using vector meson dominance [17].

Let us finally mention that the difficulties encountered for the interpretation of the new open-charm states as two-quark systems do not appear for the case of the recent charmed and B_c states measured at different facilities. They do nicely agree with the predictions of the $q\bar{q}$ model, see table 4, giving confidence to the results obtained in the present work.

In summary, we have obtained a rather satisfactory description of the positive-parity open-charm mesons in terms of two- and four-quark configurations. The mixing between these two components is responsible for the unexpected low mass and widths of the $D_{sJ}^*(2317)$, $D_{sJ}(2460)$, and $D_0^*(2308)$. The same mechanism has been used to account for the spectroscopic properties of the light-scalar mesons. The obtained electromagnetic decay widths give hints that would help in distinguishing the nature of these states. We predict a ratio

$$D_{sJ}(2460) \to D_s^+\gamma / D_{sJ}(2460) \to D_s^{*+}\gamma$$

much larger than the one obtained in a pure $q\bar{q}$ scheme, as a consequence of the small $^3P_1$ $c\bar{s}$ component of the $D_{sJ}(2460)$. We encourage experimentalists to measure the electromagnetic decay widths of the $D_{sJ}^*(2317)$ and the $D_{sJ}(2460)$, which would help to clarify the exciting situation of the open-charm mesons.

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