Investigating quantum numbers of new $c\bar{s}$ states

F. De Fazio

Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Italy

I would like to dedicate this paper to Beppe Nardulli, who died on June 26th 2008. Beppe was full professor at Bari University teaching theoretical Physics. He gave an important contribution to the formulation of the effective Lagrangian describing heavy meson interactions with light mesons, as is summarized in a well known review paper [1]. More recently, he applied similar methods to build an effective theory valid in the high density regime of QCD [2]. He obtained important results in this field as well [3]. It is impossible to summarize here all his contributions to Physics, which comprehend not only particle Physics, but also statistical mechanics and neural network Physics. This paper is just my personal tribute to him. In the following I discuss how the use of effective Lagrangians for heavy mesons interacting with light pseudoscalars can shed light on new issues in charm spectroscopy.

1. PREMISE

The analysis of hadron properties may be simplified exploiting the symmetries that Quantum Chromodynamics (QCD) exhibits in specific limits. An example is chiral $SU(N_f)_L \times SU(N_f)_R$ symmetry holding in the limit of $N_f$ massless quarks. This symmetry is spontaneously broken to $SU(N_f)_V$ and light pseudoscalar mesons are identified as Goldstone bosons acquiring mass when explicit symmetry breaking mass terms are considered. An effective theory (chiral perturbation theory) can be built as an expansion in the light quark masses and momenta [1].

Moreover, in the infinite heavy quark mass limit $m_Q \to \infty$, the QCD Lagrangian is invariant under heavy quark spin and flavour rotations. The corresponding effective theory is known as Heavy Quark Effective Theory (HQET) [2].

Interactions of heavy mesons with light ones can be described by an effective Lagrangian displaying both heavy quark symmetries, both chiral symmetry. The approach was first formulated in the case of light pseudoscalars [3], and later on it was extended to light vector mesons [4].

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2. NEW $c\bar{s}$ MESONS

Since 2003 there have been many new discoveries of open and hidden charm hadrons [5]. Here we focus on $c\bar{s}$ mesons.

Before the B-factory era the known $c\bar{s}$ spectrum consisted of the pseudoscalar $D_0(1670)$ and vector $D_1^*(2112)$ mesons, corresponding to s-wave states of the quark model, and the axial-vector $D_{s1}(2536)$ and tensor $D_{s2}(2573)$ mesons, p-wave states. In 2003, two narrow resonances: $D_{sJ}(2317)$ with $J^P = 0^+$ and $D_{sJ}^*(2460)$ with $J^P = 1^+$ were discovered by BaBar [6] and CLEO [7] Collaborations. Their identification as proper $c\bar{s}$ states was debated [8]; however, they have the quantum numbers of the states needed to complete the $p$-wave multiplet, and their radiative decays occur accordingly, so that their interpretation as ordinary $c\bar{s}$ states is natural [9].

In 2006, BaBar observed another $c\bar{s}$ meson, $D_{sJ}(2860)$, decaying to $D^0 K^+$ and $D^+ K_S$, with mass $M = 2856.6 \pm 1.5 \pm 5.0$ MeV and width $\Gamma = 47 \pm 7 \pm 10$ MeV [10]. Shortly after, analysing the $M^2(D^0 K^+)$ distribution in $B^+ \to D^0 D^0 K^+$ Belle Collaboration [11] established the presence of a $J^P = 1^-$ resonance, $D_{sJ}(2700)$, with $M = 2708 \pm 9^{+10}_{-16}$ MeV and $\Gamma = 108 \pm 23^{+36}_{-31}$ MeV.
3. DECAYS OF $D_{sJ}(2860)$ AND $D_{sJ}(2700)$ TO LIGHT PSEUDOSCALARS

The study of mesons with a single heavy quark $Q$ is simplified in the heavy quark limit $m_Q \to \infty$ when the spin $s_Q$ of the heavy quark and the angular momentum $s_t$ of the light degrees of freedom: $s_t = s_q + \ell$ ($s_q$ being the light antiquark spin and $\ell$ the orbital angular momentum of the light degrees of freedom relative to $Q$) are decoupled. Hence spin-parity $s^P_t$ of the light degrees of freedom is conserved in strong interactions \[2\] and mesons can be classified as doublets of $s^P_t$. Two states with $J^P = (0^-, 1^-)$, denoted as $(P, P^*)$, correspond to $\ell = 0$. The four states corresponding to $\ell = 1$ can be collected in two doublets, $(P_0^*, P_1^*)$ with $s^P_t = \frac{1}{2}^+$ and $J^P = (0^+, 1^+)$, $(P_1, P_2)$ with $s^P_t = \frac{3}{2}^+$ and $J^P = (1^+, 2^+)$. For $\ell = 2$ the doublets have $s^P_t = \frac{3}{2}^-$, consisting of states with $J^P = (1^-, 2^-)$, or $s^P_t = \frac{3}{2}^-$ with $J^P = (2^-, 3^-)$ states. And so on.

$D_1(1698)$, $D_{s1}(2512)$ can be identified with the members of the lowest lying $s^P_t = \frac{3}{2}^-$ doublet, $D_{s1}(2536)$, $D_{s2}(2573)$, together with $D_{sJ}(2317)$, $D_{sJ}^*(2460)$, fill the four p-wave levels: in particular, $D_{s2}(2573)$ corresponds to $s^P_t = \frac{3}{2}^-$, $J^P = 2^+$ state, while $D_{sJ}(2317)$ to $s^P_t = \frac{1}{2}^-$, $J^P = 0^+$. The $J^P = 1^+$ mesons $D_{s1}(2536)$ and $D_{sJ}^*(2460)$ could be a mixing of $s^P_t = \frac{3}{2}^+$ and $s^P_t = \frac{1}{2}^+$ states, allowed at $O(1/m_Q)$; however, for non-strange charm mesons such a mixing was found to be small \[15,16]\, so that we can identify $D_{s1}(2536)$ and $D_{sJ}^*(2460)$ with the $J^P = 1^+$ $s^P_t = \frac{3}{2}^+$ and $s^P_t = \frac{1}{2}^+$ states, respectively.

In the heavy quark limit, the doublets are represented by effective fields: $H_\alpha$ for $s^P_t = \frac{1}{2}^+$ ($a = u, d, s$ is a light flavour index), $S_\alpha$ and $T_\alpha$ for $s^P_t = \frac{1}{2}^+$ and $s^P_t = \frac{3}{2}^+$, respectively; $X_\alpha$ and $X'_\alpha$ for $s^P_t = \frac{3}{2}^-$ and $s^P_t = \frac{5}{2}^-$, respectively:

$$H_\alpha = \frac{1 + \hat{y}}{2} [P^\mu_{1\alpha} \gamma^\mu - P^\mu_{0\alpha}]$$

$$T^\mu_\alpha = \frac{1 + \hat{y}}{2} \left\{ P^\mu_{2\alpha} \gamma^\nu \right\}$$

$$X^\mu_\alpha = \frac{1 + \hat{y}}{2} \left\{ P^\mu_{3\alpha} \gamma^\nu \right\}$$

$$X'^{\mu\nu}_\alpha = \frac{1 + \hat{y}}{2} \left\{ P^\mu_{3\alpha} \gamma^\nu \right\}$$

with the various operators annihilating mesons of four-velocity $v$ (conserved in strong interactions) and containing a factor $\sqrt{m_P}$. Light pseudoscalars are introduced using $\xi = e^{i \frac{\mu}{2}}$, with:

$$\mathcal{M} = \begin{pmatrix} \sqrt{\frac{1}{2}} \pi^0 + \sqrt{\frac{1}{6}} \eta & \pi^+ & K^+ \\ \pi^- & -\sqrt{\frac{1}{2}} \pi^0 + \sqrt{\frac{1}{6}} \eta & K^0 \\ K^- & K^0 & -\sqrt{\frac{1}{2}} \eta \end{pmatrix}$$

($f_\pi = 132$ MeV). At the leading order in the heavy quark mass and light meson momentum expansion the decays $F \to HM$ ($F = H, S, T, X, X'$ and $M$ a light pseudoscalar meson) can be described by the Lagrangian interaction terms (invariant under chiral and heavy-quark spin-flavour transformations) \[34\]:

$$\mathcal{L}_H = g Tr[H_\alpha H_\beta \gamma_\mu \gamma_5 A^\mu_{ba}]$$

$$\mathcal{L}_S = h Tr[H_\alpha S_\beta \gamma_\mu \gamma_5 A^\mu_{ba}] + h.c.$$.

$$\mathcal{L}_T = \frac{k'}{\Lambda_X} Tr[H_\alpha T^\mu_\beta (iD_\mu A + i \partial_\mu A_\beta) \gamma_5] + h.c.$$.

$$\mathcal{L}_X = \frac{k}{\Lambda_X} Tr[H_\alpha X^\mu_\beta (iD_\mu A + i \partial_\mu A_\beta) \gamma_5] + h.c.$$.

$$\mathcal{L}_{X'} = \frac{1}{\Lambda_X^2} Tr[H_\alpha X'^{\mu\nu}_\beta \{k_1 \{D_\mu, D_\nu\} A_\lambda + k_2 (D_\mu D_\nu A_\lambda + D_\nu D_\mu A_\lambda) \gamma_5\}] + h.c.$$.

where $D_{\mu ba} = -\delta_{\mu a} \partial_\mu + \frac{1}{2} (\xi^1 \partial_\mu \xi + \xi \partial_\mu \xi^1)_\beta$, $A_{\mu ba} = \frac{1}{2} (\xi^1 \partial_\mu \xi - \xi \partial_\mu \xi^1)_\beta$. $\Lambda_X \approx 1$ GeV is
the chiral symmetry-breaking scale, $g, h, h', k'$, $k_1$ and $k_2$ represent effective coupling constants.

The structure of the Lagrangian terms for radial excitations of $H, S$ and $T$ does not change, but $g, h, h'$ should be substituted by $\tilde{g}, \tilde{h}, \tilde{h}'$.

Let us start with $D_{sJ}(2860)$. A new $c\bar{s}$ meson decaying to $DK$ can be either the $J^P = 1^-$ state of the $s^p = \frac{1}{2}^-$ doublet, or the $J^P = 3^-$ state of the $s^p = \frac{3}{2}^+$ one, in both cases with lowest radial quantum number. Otherwise $D_{sJ}(2860)$ could be a radial excitation of already observed $c\bar{s}$ mesons: the first radial excitation of $D_s^*(J^P = 1^- s^p = \frac{1}{2}^-)$ or of $D_{sJ}^*(2317) (J^P = 0^+ s^p = \frac{1}{2}^-)$ or of $D_{sJ}^*(2573) (J^P = 2^+ s^p = \frac{3}{2}^+)$. As for $D_{sJ}(2700)$, two possibilities can be considered, the spin having been already fixed: i) $D_{sJ}(2700)$ belongs to the $s^p = \frac{1}{2}^-$ doublet and is the first radial excitation ($D_{sJ}^*$); ii) $D_{sJ}(2700)$ is the low lying state with $s^p = \frac{3}{2}^-$ ($D_{sJ}^*$).

In [17] we investigated the decay modes of $D_{sJ}(2860)$ and $D_{sJ}(2700)$ according to the various possible assignments with the aim of discriminating among them. The results are collected in Table 1, where we report the ratios $R_1 = \frac{\Gamma(D_{sJ} \rightarrow D^* K)}{\Gamma(D_{sJ} \rightarrow D K)}$ and $R_2 = \frac{\Gamma(D_{sJ} \rightarrow D^* K)}{\Gamma(D_{sJ} \rightarrow D^* K)}$ (with $D^{(*)}K = D^{(*)}K_S + D^{(*)}K^+$) obtained for various quantum number assignments to $D_{sJ}(2860)$ and $D_{sJ}(2700)$ using eqs. (1) and (2). The ratios do not depend on the coupling constants, but only on the quantum numbers. We first discuss the entries in Table 1 concerning $D_{sJ}(2860)$. In particular, non observation (at present) of a $D^* K$ signal in the $D_{sJ}(2860)$ range of mass implies that the production of $D^* K$ is not favoured, therefore the assignments $s^p = \frac{1}{2}^-, J^P = 1^-, n = 2$, and $s^p = \frac{3}{2}^+, J^P = 3^+, n = 2$ can be excluded.

The case $s^p = \frac{3}{2}^-, J^P = 1^-, n = 1$ can also be excluded since, using the relevant term in [2] and $k' \approx h' \approx 0.45 \pm 0.05$ (as the $h'$ was determined in [18]), would give $\Gamma(D_{sJ} \rightarrow D K) \approx 1.5$ GeV, a result incompatible with the measured width.

In the assignment $s^p = \frac{1}{2}^+, J^P = 0^+, n = 2$ the decay to $D^* K$ is forbidden. However, if $D_{sJ}(2860)$ is a scalar radial excitation, it should have a spin partner with $J^P = 1^+ (s^p = \frac{1}{2}^+, n = 2)$ decaying to $D^* K$ with a small width, a rather easy signal to detect. For $n = 1$ both $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ are produced in charm continuum at $e^+e^-$ factories. To explain the absence of the $D^* K$ in charm continuum events at mass around 2860 MeV, one should invoke some mechanism favouring the production of the $0^+ n = 2$ state and inhibiting the production of $1^+ n = 2$ state, a mechanism which discriminates the first radial excitation from the low lying state $n = 1$. Such a mechanism is difficult to imagine.

The last possibility is: $s^p = \frac{3}{2}^-, J^P = 3^-, n = 1$. In this case, the small $DK$ width is due to the huge suppression related to the kaon momentum factor: $\Gamma(D_{sJ} \rightarrow DK) \propto q_K^7$. The spin partner would be $D_{s2}$, the $s^p = \frac{3}{2}^-$, $J^P = 2^-$ state, which can decay to $D^* K$ and not to $DK$. It would also be narrow but only in the $m_Q \rightarrow \infty$ limit, where the transition $D_{s2} \rightarrow D^* K$ occurs in $f$-wave. As an effect of $1/m_Q$ corrections this decay can occur in $p$-wave, so that $D_{s2}$ could be broader; therefore, it is not necessary to invoke a mechanism inhibiting the production of this state with respect to $J^P = 3^-$. If $D_{sJ}(2860)$ has $J^P = 3^-$, it is not expected to be produced in non leptonic $B$ decays such as $B \rightarrow D D_{sJ}(2860)$: the non leptonic amplitude in the factorization approximation vanishes since the vacuum matrix element of the weak $V - A$ current with a spin three particle.

1The interpretation of $D_{sJ}(2860)$ as the first radial excitation of $D_{sJ}^*(2317)$ has been proposed in [18].
is zero. Therefore, the quantum number assignment can be confirmed by studies of $D_{sJ}(2860)$ production in $B$ transitions. Actually, in the Dalitz plot analysis of $B^+ \rightarrow D^0 D^0 K^+$ Belle Collaboration [4] has reported no signal of $D_{sJ}(2860)$.

The conclusion of our study is that $D_{sJ}(2860)$ is likely a $J^P = 3^-$ state, a predicted high mass and relatively narrow $c\bar{s}$ state [19].

We now consider $D_{sJ}(2700)$. As Table I shows, $R_1$ is very different if $D_{sJ}(2700)$ is $D_s^*\pi$ or $D_s^{*+}$: the $D^*K$ mode is the main signal to be investigated in order to distinguish between the two possible assignments. From the computed widths, assuming that $\Gamma(D_{sJ}(2700))$ is saturated by modes with a heavy meson and a light pseudoscalar meson in the final state, we can determine the couplings $\tilde{g}$ and $\tilde{k}$ governing the decays in the two cases. Identifying $D_{sJ}(2700)$ with $D_s^{*\pi}$ we obtain: $\tilde{g} = 0.26 \pm 0.05$ while if $D_{sJ}(2700)$ is $D_s^{*+}$ we get $\tilde{k} = 0.14 \pm 0.03$. These values are similar to those obtained for analogous couplings appearing in the effective heavy quark chiral Lagrangians [20].

The results for $\tilde{g}$ and $\tilde{k}$ can provide information about the spin partner of $D_{sJ}(2700)$, i.e. the state belonging to the same $s_F^*$ doublet from which $D_{sJ}(2700)$ differs only for the total spin. The partner of $D_s^{*\pi}$ ($s_F^* = \frac{1}{2}^+$) has $J^P = 0^-$; it is denoted $D_s^*$, the first radial excitation of $D_s$, while the partner of $D_s^{*+}$ ($s_F^* = \frac{3}{2}^-$) is the state $D_{s2}$ with $J^P = 2^-$. In both cases, the decay modes to $D^0 K^+$, $D^{*+}K^0_S L(J)$, $D_s^{*+} \eta$, are permitted. In the heavy quark limit, these partners are degenerate. Using the obtained values for $\tilde{g}$ and $\tilde{k}$, we get: $\Gamma(D_s^*) = (70 \pm 30) \text{ MeV}$ and $\Gamma(D_{s2}) = (12 \pm 5) \text{ MeV}$, so that in the two assignments the spin partners differ for their total width.

4. CONCLUSIONS

Studying decay rates of $D_{sJ}(2860)$ to light pseudoscalar mesons we conclude that most likely $D_{sJ}(2860)$ has $J^P = 3^-$. The detection of the final state $D^*K$ would support this interpretation. As for $D_{sJ}(2700)$, the decay mode to $D^*K$ has very different branching ratios in the two possible assignments, so that measuring such a branching fraction could help to identify $D_{sJ}(2700)$.

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