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Abstract

We analyze the recently discovered $D_{sJ}(2860)$ meson using arguments based on the heavy quark expansion together with the experimental observations. We consider the possible quantum number assignments, in particular the interpretation of the meson as the $J^P = 3^- c\bar{s}$ state.
The observation of the meson \( D_{sJ} (2860) \), recently announced by the BaBar Collaboration [1], provides us with another interesting piece of information about the \( c\bar{s} \) system. The reported features of the new state are the following:

- it is observed in the \( DK \) system inclusively produced in the process \( e^+e^- \rightarrow DKX \);
- it is reconstructed in \( D^0K^+ \), with \( D^0 \) both decaying to \( K^-\pi^+ \) and \( K^-\pi^+\pi^0 \), and in \( D^+K^0_S \);
- the resonance parameters are:
  \[
  M(D_{sJ} (2860)) = 2856.6 \pm 1.5 \pm 5.0 \text{ MeV} \\
  \Gamma(D_{sJ} (2860) \rightarrow DK) = 47 \pm 7 \pm 10 \text{ MeV}
  \]

where \( DK \) represents the sum of the \( D^0K^+ \) and \( D^+K^0_S \) modes.

Together with these features, the BaBar Collaboration noticed that:

- no structures seem to appear in the \( D^{*}K \) invariant mass distribution in the same range of mass (\( \simeq 2860 \text{ MeV} \));
- an additional broad contribution seems to be present in the \( DK \) distribution; if fitted by a Breit-Wigner form, it corresponds to the parameters \( M = 2688 \pm 4 \pm 3 \) MeV and \( \Gamma = 112 \pm 7 \pm 36 \) MeV.

The Collaboration also reported new measurements of the properties of the spin two \( D_{s2} (2573) \) meson, in particular of the decay width \( \Gamma(D_{s2} \rightarrow DK) \): \( \Gamma(D_{s2} (2573) \rightarrow DK) = 27.1 \pm 0.6 \pm 5.6 \text{ MeV} \). Considering the other possible decay modes of \( D_{s2} (2573) \), this value essentially corresponds to the meson full width; it must be compared to the previous value reported by the Particle Data Group: \( \Gamma(D_{s2} (2573)) = 15^{+5}_{-4} \text{ MeV} \) [2].

To interpret the new \( c\bar{s} \) resonance we observe that the analysis of mesons comprising a single heavy quark \( Q \) is simplified in the heavy quark limit \( m_Q \rightarrow \infty \). Indeed, in this limit the spin \( s_Q \) of the heavy quark and the angular momentum \( s_\ell \) of the meson light degrees of freedom: \( s_\ell = s_q + \ell \) (\( s_q \) being the light antiquark spin and \( \ell \) the orbital angular momentum of the light degrees of freedom relative to the heavy quark) are decoupled in QCD, so that the spin-parity \( s_\ell^P \) of the light degrees of freedom is conserved in strong interaction processes [3]. Mesons can be classified as doublets of \( s_\ell^P \). Two states correspond to orbital angular momentum \( \ell = 0 \); in general we denote them as \( (P, P^*) \) with \( J^P = (0^-, 1^-) \). The four states corresponding to \( \ell = 1 \) can be collected in two doublets, one with \( s_\ell^P = \frac{1}{2}^+ \)
and $J^P = (0^+,1^+)$, and another one with $s^P_\ell = \frac{3+}{2}$ and $J^P = (1^+,2^+)$. The states in the two doublets are generically denoted as $(P_0^*, P_1^*)$ and $(P_1, P_2)$, respectively. For $\ell = 2$ the doublets have $s^P_\ell = \frac{3-}{2}$ and $\frac{5-}{2}$.

In case of charm, the heavy quark mass $m_c$ is greater than the strong interaction scale $\Lambda_{QCD}$ but it is not very large; therefore, corrections can be expected compared to the infinite limit. Two $O(\frac{1}{m_c})$ effects affecting the spectroscopy of the six $\ell = 0,1$ states are the hyperfine splitting between mesons belonging to the same $s^P_\ell$ doublet, and the mixing of the two axial vector states with $s^P_\ell \frac{1+}{2}$ and $\frac{3+}{2}$ to provide the two physical states. However, it is noticeable that the six known $c\bar{s}$ states reported by the Particle Data Group [2] can be classified according to this scheme as doublets of $s^P_\ell$, as reported in Table 1. As a matter of fact, $D_s$ and $D^*_s$ correspond to the states belonging to the $s^P_\ell = \frac{1-}{2}$ doublet. For the four states corresponding to $\ell = 1$ we have four candidates: $D^*_s\ell(2317)$ ($J^P = 0^+$), $D_s\ell(2460)$ and $D_{s1}(2536)$ ($J^P = 1^+$), and $D_{s2}(2573)$ ($J^P = 2^+$). The natural assignment is $D^*_s\ell(2317)$ to the $s^P_\ell = \frac{1+}{2} c\bar{s}$ doublet and $D_{s2}(2573)$ to the $s^P_\ell = \frac{3+}{2} c\bar{s}$ doublet. As for $D_{s1}(2460)$ and $D_{s1}(2536)$, they can be a mixing of the $1^+ s^P_\ell = \frac{1+}{2}$ and $\frac{3+}{2}$ $c\bar{s}$ states. However, in the case of the non strange axial-vector $c\bar{q}$ mesons the mixing angle has been measured and it is small: $\omega = -0.10 \pm 0.03 \pm 0.02 \pm 0.02$ rad [5], a result confirmed by an analysis of $O(\frac{1}{m_c})$ effects breaking the heavy quark spin symmetry [6].

Invoking $SU(3)_F$, also the mixing angle in the case of $c\bar{s}$ is expected to be small, so that the two $1^+$ states $D_{s1}(2536)$ and $D_{s1}(2460)$ essentially coincide with the $s^P_\ell = \frac{3+}{2}$ and $\frac{1+}{2}$ states. A puzzling aspect to be mentioned is that the two $s^P_\ell = \frac{1+}{2}$ $c\bar{s}$ states are almost degenerate in mass with the corresponding non-strange mesons, a physical effect not reproduced by the calculation of chiral corrections to the meson masses [8].

Table 1: $c\bar{s}$ states organized according to $s^P_\ell$ and $J^P$. The mass of known mesons is indicated.

| $s^P_\ell$ | $\frac{1-}{2}$ | $\frac{1+}{2}$ | $\frac{3+}{2}$ | $\frac{3-}{2}$ | $\frac{5-}{2}$ |
|-----------|----------------|----------------|----------------|----------------|----------------|
| $J^P = s^P_\ell - \frac{1}{2}$ | $D_s(1695)$ ($0^-$) | $D^*_s\ell(2317)$ ($0^+$) | $D_{s1}(2536)$ ($1^+$) | $(P^*_1)$ ($1^-$) | $(P^*_2)$ ($2^-$) |
| $J^P = s^P_\ell + \frac{1}{2}$ | $D^*_s(2112)$ ($1^-$) | $D_{s2}(2460)$ ($1^+$) | $D_{s2}(2573)$ ($2^+$) | $(P^*_2)$ ($2^-$) | $(P_{s2})$ ($3^-$) |

$c\bar{s}$ doublet. For the four states corresponding to $\ell = 1$ we have four candidates: $D^*_s\ell(2317)$ ($J^P = 0^+$), $D_{s1}(2460)$ and $D_{s1}(2536)$ ($J^P = 1^+$), and $D_{s2}(2573)$ ($J^P = 2^+$). The natural assignment is $D^*_s\ell(2317)$ to the $s^P_\ell = \frac{1+}{2} c\bar{s}$ doublet and $D_{s2}(2573)$ to the $s^P_\ell = \frac{3+}{2} c\bar{s}$ doublet. As for $D_{s1}(2460)$ and $D_{s1}(2536)$, they can be a mixing of the $1^+ s^P_\ell = \frac{1+}{2}$ and $\frac{3+}{2}$ $c\bar{s}$ states. However, in the case of the non strange axial-vector $c\bar{q}$ mesons the mixing angle has been measured and it is small: $\omega = -0.10 \pm 0.03 \pm 0.02 \pm 0.02$ rad [5], a result confirmed by an analysis of $O(\frac{1}{m_c})$ effects breaking the heavy quark spin symmetry [6].

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1We consider $D^*_s\ell(2317)$ and $D_{s1}(2460)$ as ordinary $c\bar{s}$ states. Other interpretations of this controversial resonances are described in [4].

2The mixing angle between the two $1^+$ states turns out to be sizeable in the unitarized meson model in [7].
In this classification a new $c\bar{s}$ meson decaying in two pseudoscalar mesons $(DK)$ can be either the $J^P = 1^-$ state of the $s_\ell^P = \frac{3}{2}^-$ doublet, or the $J^P = 3^-$ state of the $s_{\ell}^P = \frac{5}{2}^-$ doublet; in both cases it would correspond, in the constituent quark model, to a state with orbital angular momentum $\ell = 2$ and lowest radial quantum number. As a matter of fact, we expect that these doublets have lower mass than all the other states with higher $s_{\ell}^P$. The other possibility is that $D_{sJ}(2860)$ is a radial excitation of already observed $c\bar{s}$ mesons: it could be the $J^P = 1^-$ state of the $s_{P\ell} = \frac{1}{2}^-$ doublet, a $J^P = 0^+$ state (the first radial excitation of $D_{sJ}^*(2317)$) or a $J^P = 2^+$ state (the first radial excitation of $D_{s2}(2573)$). The analysis of the helicity distribution of the final state would be useful in constraining the various possibilities for the quantum numbers of the particle. In the absence of that, arguments can be provided to support a particular assignment of $J^P$ on the basis of the observed mass, the decay modes and width.

A first information comes from the mass of the resonance. Let us consider the spin averaged mass of the mesons belonging to the $s_{P\ell} = \frac{1}{2}^-$ and $s_{P\ell} = \frac{3}{2}^+$ doublets:

$$M_H = \frac{3M_{P^*} + M_P}{4}, \quad M_S = \frac{3M_{P_2^*} + M_{P_1^*}}{4}, \quad M_T = \frac{5M_{P_2} + 3M_{P_1}}{4}.$$  \hspace{1cm} (2)

Their numerical values are $M_H = 2.0761(5)$ GeV, $M_S = 2.424(1)$ GeV and $M_T = 2.558(1)$ GeV. Using these values, we can draw a Chew-Frautschi plot: $\alpha = l$ vs $t$, with a point at $(t, \alpha) = (M_H^2, 0)$ and the points $(t, \alpha) = (M_S^2, 1)$. A Regge trajectory $\alpha(t) = \alpha_0 + \alpha' t$ is obtained, with parameters: $\alpha_0 = -2.75$, $\alpha' = 0.64 GeV^{-2}$ or $\alpha_0 = -1.93$, $\alpha' = 0.45 GeV^{-2}$, as shown in fig.1. Notice that, neglecting the light quark spin-orbit interaction, $M_S$ and $M_T$ should be equal. If we attribute to $D_{sJ}(2860)$ the orbital angular momentum $\ell = 2$ we find in the same plot that the point $(t, \alpha) = (M_{D_{sJ}(2860)}^2, 2)$ belongs to a region comprised by the two lines, an expected feature if the assignment is correct. This observation does not exclude that, being a radial excitation, the particle belongs to a different trajectory, but it can be used as a first hint to support the assignment to the $\ell = 2 c\bar{s}$ states.

Another piece of information comes from the measured $DK$ width. In ref. [9] it was suggested that a few high mass and high spin charm states could be narrow enough to be observed. In particular, it was suggested that the $3^-$ state belonging to the $s_{\ell}^P = \frac{5}{2}^-$ $(c\bar{q})$ doublet should be not too broad since it decays to $D\pi$ $(DK)$ in $f$-wave.

We can elaborate on this point, using an analysis based on the heavy quark limit [10]. We define the fields representing the various heavy-light meson doublets: $H_a$ for $s_{\ell}^P = \frac{1}{2}^-$ ($a = u, d, s$ is a light flavour index), $S_a$ and $T_a$ for $s_{\ell}^P = \frac{1}{2}^+$ and $s_{\ell}^P = \frac{3}{2}^+$, respectively;
we also consider the fields $X_a$ and $X'_a$ for the doublets corresponding to orbital angular momentum $\ell = 2$, i.e. $s^p_\ell = \frac{3}{2}^-$ (we denote the states $(1^-, 2^-)$ as $(P_1^*, P_2^*)$) and $s^p_\ell = \frac{5}{2}^-$ (the states $(2^-, 3^-)$ denoted as $(P_2^*, P_3)$), respectively:

\[
\begin{align*}
H_a &= \frac{1 + y}{2} \left[ P^*_{a\mu} \gamma^\mu - P_a \gamma_5 \right] \\
S_a &= \frac{1 + y}{2} \left[ P^\mu_{1a} \gamma_\mu \gamma_5 - P_{0a}^* \right] \\
T^\mu_a &= \frac{1 + y}{2} \left\{ P^\mu_{2a} \gamma_\nu - P^*_{1a} \gamma_5 \sqrt{\frac{3}{2}} \frac{1}{\gamma_5} \left[ g^{\mu\nu} - \frac{1}{3} \gamma^\nu (\gamma^\mu - v^\mu) \right] \right\} \\
X^\mu_a &= \frac{1 + y}{2} \left\{ P^\mu_{2a} \gamma_5 \gamma_\nu - P^*_{1a} \gamma_5 \sqrt{\frac{3}{2}} \frac{1}{\gamma_5} \left[ g^{\mu\nu} - \frac{1}{3} \gamma^\nu (\gamma^\mu - v^\mu) \right] \right\} \\
X'^{\mu\nu}_a &= \frac{1 + y}{2} \left\{ P^\mu_{3a} \gamma_\sigma - P^*_{2a} \gamma_5 \sqrt{\frac{5}{3}} \frac{1}{\gamma_5} \left[ g^\mu_\alpha g^\nu_\beta - \frac{1}{5} \gamma_\alpha g^\nu_\beta (\gamma^\mu - v^\mu) - \frac{1}{5} \gamma_\beta g^\mu_\alpha (\gamma^\nu - v^\nu) \right] \right\}
\end{align*}
\]

with the various operators annihilating mesons of four-velocity $v$ which is conserved in strong interaction processes (the heavy field operators contain a factor $\sqrt{m_P}$ and have dimension 3/2). The interaction of these particles with the octet of light pseudoscalar mesons, introduced using $\xi = e^{i M \pi}$, $\Sigma = \xi^2$ and the matrix $M$ containing $\pi, K$ and $\eta$
\[ M = \begin{pmatrix} \sqrt{\frac{1}{2}} \pi^0 + \sqrt{\frac{1}{6}} \eta & \pi^+ & K^+ \\ \pi^- & -\sqrt{\frac{1}{2}} \pi^0 + \sqrt{\frac{1}{6}} \eta & K^0 \\ K^- & 0 & -\sqrt{\frac{\pi}{2}} \eta \end{pmatrix} \] (4)

\((f_\pi = 132 \text{ MeV})\) can be described by an effective Lagrangian which is invariant under chiral and heavy-quark spin-flavour transformations. The kinetic term of the Lagrangian

\[ L = i \text{Tr} \{ \bar{H}_b v^\mu D_\mu ba H_a \} + \frac{f_\pi^2}{8} \text{Tr} \{ \partial^\mu \Sigma \partial_\mu \Sigma^\dagger \} + \sum_{F=H,S,T;X,\bar{X}} \text{Tr} \{ \bar{F}_b (i v^\sigma D_\sigma ba - \delta_{ba} \Delta_F) F_a \} \]

involves the operators \(D\) and \(A\):

\[ D_{\mu ba} = -\delta_{ba} \partial_\mu + \mathcal{V}_{\mu ba} = -\delta_{ba} \partial_\mu + \frac{1}{2} (\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger)_{ba} \]

\[ A_{\mu ba} = \frac{i}{2} (\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger)_{ba} \]

and the mass parameters \(\Delta_F\) which represent the mass splittings between the excited and the low-lying (negative parity) doublets expressed in terms of the spin-averaged masses:

\[ \Delta_F = M_F - M_H. \]

For \(H, S, T\) doublets the spin-averaged masses \(M_{H,S,T}\) are given in eq.(2), while for the doublets \(X, X'\) they read:

\[ M_X = \frac{5M_{P_2} + 3M_{P_2'}}{8}, \quad M_{X'} = \frac{7M_{P_3} + 5M_{P_2'}}{12}. \]

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 [11]:

\[
\mathcal{L}_H = g \text{Tr}[\bar{H}_a H_b \gamma_\mu \gamma_5 A^\mu_{ba}]
\]

\[
\mathcal{L}_S = h \text{Tr}[\bar{H}_a S \gamma_\mu \gamma_5 A^\mu_{ba}] + h.c.,
\]

\[
\mathcal{L}_T = \frac{h'}{\Lambda_\chi} \text{Tr}[\bar{H}_a T^\mu_b (i D_\mu A + i D A_\mu)_{ba} \gamma_5] + h.c.
\]

\[
\mathcal{L}_X = \frac{k'}{\Lambda_\chi} \text{Tr}[\bar{H}_a X^\mu_b (i D_\mu A + i D A_\mu)_{ba} \gamma_5] + h.c.
\]

\[
\mathcal{L}_{X'} = \frac{1}{\Lambda_\chi} \text{Tr}[\bar{H}_a X'^{\mu
u}_b [k_1 (D_\mu, D_\nu) A_\lambda + k_2 (D_\mu D_\nu A_\lambda + D_\nu D_\lambda A_\mu)]_{ba} \gamma^\lambda \gamma_5] + h.c.
\]

where \(\Lambda_\chi\) is the chiral symmetry-breaking scale; we use \(\Lambda_\chi = 1 \text{ GeV}\). \(\mathcal{L}_S\) and \(\mathcal{L}_T\) describe transitions of positive parity heavy mesons with the emission of light pseudoscalar mesons
in $s$- and $d$- wave, respectively, $g, h$ and $h'$ representing effective coupling constants. On the other hand, $\mathcal{L}_X$ and $\mathcal{L}_{X'}$ describe the transitions of higher mass mesons of negative parity with the emission of light pseudoscalar mesons in $p$- and $f$- wave with coupling constants $k'$, $k_1$ and $k_2$. We only consider these terms: the light meson momenta involved in the $D_{sJ}(2860)$ decays are $q_K = 0.59$ GeV for $D^*K$ final state and $q_K = 0.7$ GeV for $DK$ final state, so it is possible that other terms in the light-meson momentum expansion, involving other structures and couplings, should be taken into account in the interaction Lagrangian. However, at present these terms are unknown, therefore we only consider the interaction terms in eq.(9).

At the same order in the expansion in the light meson momentum, the structure of the Lagrangian terms for radial excitations of the $H, S$ and $T$ doublets does not change, since it is only dictated by the spin-flavour and chiral symmetries, but the coupling constants $g, h$ and $h'$ have to be substituted by $\tilde{g}, \tilde{h}$ and $\tilde{h}'$. The advantage of this formulation is that meson transitions into final states obtained by $SU(3)$ and heavy quark spin rotations can be related in a straightforward way.

In Table 2 we report the ratios $\frac{\Gamma(D_{sJ}(2860) \to D^*K)}{\Gamma(D_{sJ}(2860) \to DK)}$ and $\frac{\Gamma(D_{sJ}(2860) \to D_s\eta)}{\Gamma(D_{sJ}(2860) \to DK)}$ obtained for various quantum number assignments to $D_{sJ}(2860)$ using eqs.(3) and (9). The ratios do not depend on the coupling constants, but only on the quantum numbers and on the kinematics of the various processes.

### Table 2: Predicted ratios $\frac{\Gamma(D_{sJ} \to D^*K)}{\Gamma(D_{sJ} \to DK)}$ and $\frac{\Gamma(D_{sJ} \to D_s\eta)}{\Gamma(D_{sJ} \to DK)}$ for the various assignment of quantum numbers to $D_{sJ}(2860)$. For $DK$ we mean the sum $DK = D^0K^+ + D^+K^0_S$.

| $D_{sJ}(2860)$ | $D_{sJ}(2860) \to DK$ | $\frac{\Gamma(D_{sJ} \to D^*K)}{\Gamma(D_{sJ} \to DK)}$ | $\frac{\Gamma(D_{sJ} \to D_s\eta)}{\Gamma(D_{sJ} \to DK)}$ |
|----------------|-----------------------|---------------------------------|---------------------------------|
| $s_{1/2}^p$    | $1/2^-$, $J^P = 1^-$, $n = 1$ | p-wave                          | 1.23                            | 0.27                            |
| $s_{1/2}^p$    | $1/2^+$, $J^P = 0^+$, $n = 1$ | s-wave                          | 0                               | 0.34                            |
| $s_{1/2}^p$    | $3/2^+$, $J^P = 2^+$, $n = 1$ | d-wave                          | 0.63                            | 0.19                            |
| $s_{1/2}^p$    | $3/2^-$, $J^P = 1^-$, $n = 0$ | p-wave                          | 0.06                            | 0.23                            |
| $s_{1/2}^p$    | $5/2^-$, $J^P = 3^-$, $n = 0$ | f-wave                          | 0.39                            | 0.13                            |

The ratios in Table 2 must be considered together with the experimental observation. In particular, non observation (at present) of a $D^*K$ signal in the $D_{sJ}$ range of mass implies

\[3\text{In our framework, calculations of widths do not include possible effects such as couplings to meson-meson continuum. An approach to these effects is described in a model in [7] and references therein.}\]
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 $s_p^\ell = \frac{3}{2}^+$, $J^P = 2^+$, $n = 1$ can be excluded: $D_{sJ}$ is not a radial excitation of $D_s^*$ and of $D_{s2}$.

The assignment $s_p^\ell = \frac{5}{2}^-$, $J^P = 1^-$, $n = 0$ can also be excluded, even though in this case the decay into $D^*K$ would be suppressed. As a matter of fact, the width $\Gamma(D_{sJ} \to DK) = \frac{8}{3}\frac{k'^2}{\pi}\frac{M_D}{f_p^2}E_K^2q_K^3$ (with $E_K$ and $q_K$ being kaon energy and momentum in the $D_{sJ}$ rest frame), obtained using the relevant term of the interaction Lagrangian in (9), would be $\Gamma(D_{sJ} \to DK) \approx 1.5$ GeV if we use a coupling $k' \approx h' \approx 0.45 \pm 0.05$, as the $h'$ was determined in [6]. The large width is expected since the transition $D_{sJ} \to DK$ occurs in this case in $p-$wave. There is no reason to presume that the coupling constant $k'$ is sensibly smaller, so that the small value of $\Gamma(D_{sJ} \to DK)$ seems incompatible with a $p-$wave transition.

In the case of the assignment $s_p^\ell = \frac{3}{2}^+$, $J^P = 0^+$, $n = 1$ the decay $D_{sJ} \to D^*K$ is forbidden. On the other hand, $D_{sJ} \to DK$ would occur in $s-$wave, with $\Gamma(D_{sJ} \to DK) = \frac{3}{4}\frac{\tilde{h}^2}{\pi}\frac{M_D}{f_p^2}E_K^2q_K$. For the state with the lowest radial quantum number $n = 0$ the coupling constant was computed: $h \approx -0.55$ with phenomenological consequences essentially in agreement with observation [12, 4]; using this value for $\tilde{h}$ we would obtain $\Gamma(D_{sJ} \to DK) \approx 1.4$ GeV. But it is reasonable to suppose that $|\tilde{h}| < |h|$, although no information is available about the couplings of radially excited heavy-light mesons to low-lying states. Using the experimental width we would obtain $\tilde{h} = 0.1$. A large signal would be expected in the $D_{sJ}\eta$ channel, as reported in Table 2. A problem with this assignment is the following. If $D_{sJ}(2860)$ is a scalar radial excitation, it should have a spin partner with $J^P = 1^+$ ($s_p^\ell = \frac{1}{2}^+$, $n = 1$) decaying to $D^*K$ with a small width, of the order of 40 MeV, a rather easy signal to detect. For $n = 0$ both the states $D_{sJ}^*(2317)$ 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 $0^+$ $n = 1$ state and inhibiting the production of $1^+ n = 1$ state, a mechanism which discriminates the first radial excitation from the low lying state $n = 0$. We consider a mechanism of this kind difficult to imagine. Finally, this assignment seems not compatible with the argument concerning the meson mass provided above.

Let us consider the last possibility: $s_p^\ell = \frac{5}{2}^-$, $J^P = 3^-$, $n = 0$. In this case, the

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4The interpretation of $D_{sJ}(2860)$ as the first radial excitation of $D_{sJ}^*(2317)$ has been proposed in [13] within a unitarized meson model, and in [14] in a quark model with modified spin-orbit and spin-spin interaction.
small $DK$ width is due to the huge suppression related to the kaon momentum factor: 
\[ \Gamma(D_{sJ} \to DK) = \frac{6}{35} \frac{(k_1 + k_2)^2}{\pi f_K^2 M_{D_{sJ}}} M_D q_K. \]

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, see Table 2. From the observed width, the combination of the coupling constants $k_1 + k_2$ turns out to be $k_1 + k_2 = 0.52$, similar to the couplings of the other doublets to light pseudoscalars. For the same value of the coupling, the state of spin two belonging to the $s^P_{\ell} = \frac{5}{2}^-$ doublet, $D^*_{s2}$, which has $J^P = 2^-$ and can decay to $D^*K$ and not to $DK$, would be narrow: 
\[ \Gamma(D^*_{s2} \to D^*K) \simeq 50 \text{ MeV}. \]

But this is only true in the $m_Q \to \infty$ limit, where the $J^P = 2^-$ state transition into $D^*K$ occurs in $f$-wave. As an effect of $1/m_Q$ corrections the $D^*_{s2} \to D^*K$ decay can occur in $p$-wave, in which case the width of $D^*_{s2}$ 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 $B^0 \to D^- D_{sJ}(2860)^+$ and $B^+ \to \bar{D}^0 D_{sJ}(2860)^+$: 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 is zero. Therefore, the quantum number assignment can be confirmed by studies of $D_{sJ}$ production in $B$ transitions. \(^5\)

The conclusion of our study is that $D_{sJ}(2860)$ is likely a $J^P = 3^-$ state, a predicted high mass, high spin and relatively narrow $c\bar{s}$ state [9]. Its non-strange partner $D_3$, if the mass splitting $M_{D_{sJ}(2860)} - M_{D_3}$ is of the order of the strange quark mass, is also expected to be narrow: 
\[ \Gamma(D_3^+ \to D^0 \pi^+) \simeq 37 \text{ MeV}. \]

It can be produced in semileptonic as well as in non leptonic $B$ decays, such as $B^0 \to D_3^- \ell^+ \bar{\nu}_\ell$ and $B^0 \to D_3^- \pi^+ [9]$: its observation could be used to confirm the quantum number assignment to the resonance $D_{sJ}(2860)$ found by BaBar.

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\(^5\)After completion of this work, Belle Collaboration [15] has reported the evidence of a rather broad state, $D_{sJ}(2715)$, with $M = 2715 \pm 11^{+14}_{-11} \text{ MeV}$, $\Gamma = 115 \pm 20^{+36}_{-32} \text{ MeV}$ and $J^P = 1^-$, found in the Dalitz plot analysis of $B^+ \to \bar{D}^0 D^0 K^+$. It is worth noticing that no signal of $D_{sJ}(2860)$ is found in the analysis of this decay mode.
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