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Canonical interpretation of the $D_{sJ}(2860)$ and $D_{sJ}(2690)$

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Abstract

The spectrum and decay properties of radially excited D_s states are examined in a new model. Good agreement is obtained with the properties of two recently announced D_s mesons identified as $D_{s0}(2860) = c\bar{s}(2P)$ and $D_s^*(2690) = c\bar{s}$ as a possible mixture of $(2S;{}^3S_1)$ and $(1D;{}^3D_1)$. Searching for these mesons in B decays is advocated due to large predicted branching ratios.

1. Introduction

BaBar have recently announced the discovery of a new D_s state seen in e^+e^- collisions decaying to $K^-\pi^+K^+$, $K^-\pi^+\pi^0K^+$ (D^0K^+), or $D^+K_S^0$ [1]. The Breit–Wigner mass of the new state is

$$M\big(D_{sJ}(2860)\big) = 2856.6 \pm 1.5 \pm 5.0\ \text{MeV} \tag{1}$$

and the width is

$$\Gamma\big(D_{sJ}(2860)\big) = 48 \pm 7 \pm 10\ \text{MeV}. \tag{2}$$

The signal has a significance greater than 5 σ in the D^0 channels and 2.8 σ in the D^+ channel. There is no evidence of the $D_{sJ}(2860)$ in the D^*K decay mode [1] or the $D_s\eta$ mode [2].

There is, furthermore, structure in the DK channel near 2700 MeV that yields Breit–Wigner parameters of

$$M\big(D_{sJ}(2690)\big) = 2688 \pm 4 \pm 2\ \text{MeV} \tag{3}$$

and

$$\Gamma\big(D_{sJ}(2690)\big) = 112 \pm 7 \pm 36\ \text{MeV}. \tag{4}$$

The significance of the signal was not stated.

The discovery of these states is particularly germane to the structure of the $D_s(2317)$. For example, the low mass and isospin violating decay mode, $D_s\pi^0$, of the $D_s(2317)$ imply that the state could be a DK molecule [3]. If this is the case, the $D_{sJ}(2690)$ could be a supernumerary scalar $c\bar{s}$ state. Alternatively, the $D_s(2317)$ could be the ground state scalar $c\bar{s}$ state and the new D_{sJ}'s could be canonical radial excitations. Clearly, constructing a viable global model of all the D_s states is important to developing a solid understanding of this enigmatic sector [4].

Previous efforts to understand the new BaBar states have argued that the $D_{sJ}(2860)$ is a scalar $c\bar{s}$ state predicted at 2850 MeV in a coupled channel model [5] or that it is a $J^P = 3^-$ $c\bar{s}$ state [6].

Here we pursue a simple model that assumes that all of the known D_s states are dominated by simple $c\bar{s}$ quark content. It is known that this is difficult to achieve in the 'standard' constituent quark model with $O(\alpha_s)$ spin-dependent mass shifts because the $D_{s0}(2317)$ is much lighter than typical predictions (for example, Godfrey and Isgur obtain a D_{s0} mass of 2480 MeV [7]). An essential feature in such phenomenology has been the assumption of two static potentials: a Lorentz scalar confining potential and a short range Coulombic vector potential. Following the discovery of the $D_s(2317)$, Cahn and Jackson [8] analysed the D_s states with a scalar potential S, whose shape they allowed to be arbitrary, while retaining a vector potential V that they assumed to be Coulombic. In the limit

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that the mass $m_2 \gg m_1$ this enabled the spin-dependent potential applicable to P-states to take the form

$$V_{SD} = \lambda L \cdot S_1 + 4\tau L \cdot S_2 + \tau S_{12} \tag{5}$$

(see the discussion around Eq. (1) of [8] for details). For $\lambda \gg \tau$ a reasonable description of the masses could be obtained though a consistent picture of D_s, D spectroscopies and decays remained a problem. As the authors noted, "the ansatz taken for the potentials V and S may not be as simple as assumed". The more general form [9] is

$$V_{SD} = \lambda L \cdot S_1 + 4\tau L \cdot S_2 + \mu S_{12} \tag{6}$$

only in the particular case of a Coulomb potential need $\mu = \tau$ [9]. Direct channel couplings (such as to DK and D^*K thresholds [3,10]) will induce effective potentials that allow the above more general form. Similarly, higher order gluon exchange effects in pQCD will also. Indeed, the full spin-dependent structure expected at order α_s^2 in QCD has been computed [11] and reveals that an additional spin–orbit contribution to the spin-dependent interaction exists when quark masses are not equal. When these are incorporated in a constituent quark model there can be significant mass shifts leading to a lowered mass for the D_{s0} consistent with the $D_{s0}(2317)$ [12]. Here we apply this model to the recently discovered D_s states.

2. Canonical $c\bar{s}$ states

Predictions of the new model in the D_s sector are summarised in Table 1 (the 'high' parameters of Ref. [12] are employed).

Since the $D_{sJ}(2690)$ and $D_{sJ}(2860)$ decay to two pseudoscalars, their quantum numbers are $J^P = 0^+, 1^-, 2^+$, etc. Given the known states [13] and that the energy gap for radial excitation is hundreds of MeV, on almost model independent grounds the only possibility for a $D_{sJ}(2690)$ is an excited vector. Table 1 shows that the $D_{sJ}(2690)$ can most naturally be identified with the excited vector $D_s^*(2S)$; the D-wave vector is predicted to be somewhat too high at 2784 MeV though mixing between these two basis states may be expected. For the $D_{sJ}(2860)$, Table 1 indicates that this is consistent with the radially excited scalar state $D_{s0}(2P)$. It appears that the $D_{s2}(2P)$ is too heavy to form a viable identification.

Table 1
D_s spectrum

State	Mass (GeV)	Expt [13] (GeV)
$D_s(1^1S_0)$	1.968	1.968
$D_s(2^1S_0)$	2.637	
$D_s(3^1S_0)$	3.097	
$D_s^*(1^3S_1)$	2.112	2.112
$D_s^*(2^3S_1)$	2.711	2.688?
$D_s^*(3^3S_1)$	3.153	
$D_s(1^3D_1)$	2.784	
$D_{s0}(1^3P_0)$	2.329	2.317
$D_{s0}(2^3P_0)$	2.817	2.857?
$D_{s0}(3^3P_0)$	3.219	
$D_{s1}(1P)$	2.474	2.459
$D_{s1}(2P)$	2.940	
$D_{s1}(3P)$	3.332	
$D'_{s1}(1P)$	2.526	2.535
$D'_{s1}(2P)$	2.995	
$D'_{s1}(3P)$	3.389	
$D_{s2}(1^3P_2)$	2.577	2.573
$D_{s2}(2^3P_2)$	3.041	
$D_{s2}(3^3P_2)$	3.431	

3. Decay properties

Mass spectra alone are insufficient to classify states. Their production and decay properties also need to be compared with model expectations. For example, strong decay widths can be computed with the quark model wavefunctions and the strong decay vertex of the $^3P_0$ model. An extensive application of the model to heavy-light mesons is presented in Ref. [14]. Here we focus on the new BaBar states with the results given in Table 2.

3.1. $D_{sJ}(2690)$

The total width of the $D_s^*(2S)$ agrees very well with the measured width of the $D_{sJ}(2690)$ (112 ± 37 MeV), lending support to this identification. No signal in $D_s\eta$ is seen or expected, whereas the predicted large D^*K partial width implies that this state should be visible in this decay mode. The data in $D^{*0}(K) \to D^0\pi^0(K)$ do not support this contention; however, the modes $D^{*+}(K) \to D^0\gamma(K)$ and $D^{*+}(K) \to D^+\pi^0(K)$ show indications of a broad structure near 2700 MeV [1]. There is the possibility that 1^3D_1 mixing with 2^3S_1 shift the mass down by 30 MeV to that observed and also suppress the D^*K mode. For a specific illustration, take the model masses for the 2^3S_1 as 2.71 GeV and 1^3D_1 as 2.78 GeV. A simple mixing matrix then yields a solution for the physical states with masses

Table 2
Strong partial widths for candidate D_s states

State (mass)	Decay mode	Partial width (MeV)
$D_s^*(2S)(2688)$	DK	22
	D^*K	78
	$D_s\eta$	1
	$D_s^*\eta$	2
	total	103
$D_{s0}(2P)(2857)$	DK	80
	$D_s\eta$	10
	total	90
$D_{s2}(2P)(2857)$	DK	3
	$D_s\eta$	0
	D^*K	18
	DK^*	12
	total	33
$D_{s2}(2P)(3041)$	DK	1
	$D_s\eta$	0
	D^*K	6
	DK^*	47
	D^*K^*	76
	total	130

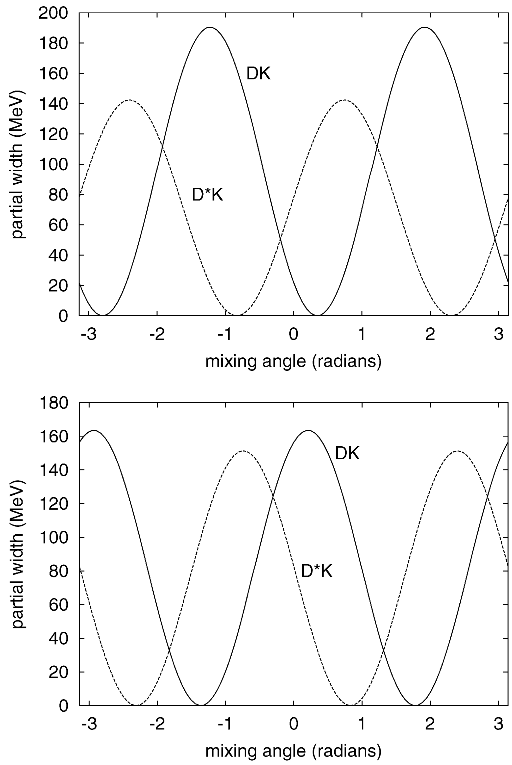

Fig. 1. DK and D^*K partial widths vs. mixing angle. Low vector (top); high vector (bottom).

2.69 GeV and its predicted heavy partner at around 2.81 GeV with eigenstates

$$\big|D_s^*(2690)\big\rangle \approx \frac{1}{\sqrt{5}}\big(-2|1S\rangle + 1|1D\rangle\big),$$
$$\big|D_s^*(2810)\big\rangle \approx \frac{1}{\sqrt{5}}\big(|1S\rangle + 2|1D\rangle\big) \tag{7}$$

and hence a mixing angle consistent with -0.5 radians.

The results of an explicit computation in the $^3P_0$ model are shown in Fig. 1. One sees that a mixing angle of approximately -0.5 radians suppresses the D^*K decay mode of the low vector (with mass set to 2688 MeV) and produces a total width of approximately 110 MeV, in agreement with the data. The orthogonal state would then have a mass around 2.81 GeV and has a significant branching ratio to both DK and D^*K, albeit with a broad width, greater than 200 MeV.

In summary, if the $D_{sJ}(2690)$ is confirmed as vector resonance, then signals in the D^*K channel are expected, either in the low lying state (if the mixing is weak) or in a higher vector near 2.8 GeV.

3.2. $D_{sJ}(2860)$

For the $D_{sJ}(2860)$, the $D_{s2}(2P)$ assignment is further disfavored. At either its model mass of 3041 MeV or at 2860 MeV the DK mode is radically suppressed, due to the D-wave barrier factor. BaBar see their $D_{sJ}(2860)$ signal in DK and do not observe it in the D^*K decay mode, making the $D_{s2}(2P)$ assignment unlikely.

Table 3
D_s E1 radiative transitions (keV)

Decay mode (mass)	q_γ (MeV)	Non Rel rate	Rel Rate
$D_s^*(2S)(2688) \to D_{s0}\gamma$	345	12.7	4.6
$D_s^*(1D)(2784) \to D_{s0}\gamma$	428	116	82
$D_{s0}(2P)(2857) \to D_s^*\gamma$	648	13	0.4
$D_{s2}(2P)(3041) \to D_s^*\gamma$	787	6.8	1.9

By contrast, the properties of $D_{sJ}(2860)$ are consistent with those predicted for the $D_{s0}(2P)$. Within the accuracy typical of the $^3P_0$ model for S-wave decays, the total width is in accord with the prediction that the $D_{s0}(2P)$ total width is less than that of the excited vectors, and qualitatively in accord with the measured 48 ± 12 MeV.

3.3. Radiative transitions

The meson assignments made here can be tested further by measuring radiative transitions for these states. Predictions made with the impulse approximation, with and without non-relativistic reduction of quark spinors, are presented in Table 3.

4. Production

The production of the radially excited D_{s0} in B decays can be estimated with ISGW and other formalisms [15,16]. Since vector and scalar $c\bar{s}$ states can be produced directly from the W current, the decays $B \to D_s^*(2S)D_{(J)}$ or $D_{s0}(2P)D_{(J)}$ serve as a viable source excited D_s states. Computationally, the only differences from ground state D_s production are kinematics and the excited D_s decay constants.

Production systematics can reveal structural information. For example, the decay $B^0 \to D_s^+D^-$ goes via W emission with a rate proportional to $V_{bc}V_{cs}$, while W exchange gives rise to $B^0 \to D_s^-K^+ \sim V_{bc}V_{ud}$ and $B^0 \to D_s^+K^- \sim V_{cd}V_{bu}$. W exchange is suppressed compared to W emission, thus the expected hierarchy of rates is

$$\Gamma\big(B^0 \to D_s^+D^-\big) \gg \Gamma\big(B^0 \to D_s^-K^+\big) \gg \Gamma\big(B^0 \to D_s^+K^-\big). \tag{8}$$

This suppression of W exchange is confirmed by the data [13] with $BR(B^0 \to D_s^+D^-) = (6.5 \pm 2.1) \times 10^{-3}$ and $BR(B^0 \to D_s^-K^+) = (3.1 \pm 0.8) \times 10^{-5}$. The decay to $D_s^+K^-$ has not been observed.

It is therefore intriguing that the observed rate for $B^0 \to D_s(2317)^+K^-$ ($(4.3 \pm 1.5) \times 10^{-5}$) is comparable to $B^0 \to D_s^-K^+$. Assuming accurate data, one must conclude either that this simple reasoning is wrong, the $D_s(2317)^-K^+$ mode will be found to be large, or the $D_s(2317)$ is an unusual state. Searching for the process $B^0 \to D_s(2317)^-K^+$ is clearly of great interest.

With the previous warning in mind, we proceed to analyse the production of excited D_s states in a variety of models. Rates with decay constants set to 1 MeV for $D_s(2317)$ and $D_s(2860)$ production assuming that they are simple $c\bar{s}$ scalar and excited scalar states are presented in Table 4.

Table 4
Branching ratios to scalars in different models with decay constants set to 1 MeV

Decay mode	ISGW	HQET—Luo & Rosner [17]	Pole [17]	HQET—Colangelo [18]
$D_s(2317)D$	2.78×10^{-7}	1.95×10^{-7}	1.91×10^{-7}	2.24×10^{-7}
$D_s(2317)D^*$	1.06×10^{-7}	8.82×10^{-8}	8.79×10^{-8}	1.23×10^{-7}
$D_s(2860)D$	2.09×10^{-7}	1.72×10^{-7}	1.66×10^{-7}	1.83×10^{-7}
$D_s(2860)D^*$	4.57×10^{-8}	3.61×10^{-8}	3.55×10^{-8}	4.66×10^{-8}

Table 5
Branching ratios to vectors in different models with decay constants set to 1 MeV

Decay mode	ISGW	HQET—Luo & Rosner [17]	Pole [17]	HQET—Colangelo [18]
D_s^*D	1.97×10^{-7}	1.33×10^{-7}	1.32×10^{-7}	1.57×10^{-7}
$D_s^*D^*$	4.20×10^{-7}	3.22×10^{-7}	3.23×10^{-7}	4.52×10^{-7}
$D_s(2690)D$	1.01×10^{-7}	8.06×10^{-8}	7.77×10^{-8}	8.79×10^{-8}
$D_s(2690)D^*$	4.66×10^{-7}	3.55×10^{-7}	3.49×10^{-7}	4.65×10^{-7}

Unfortunately, decay constants cannot be accurately computed at this time. We have evaluated ratios of decay constants assuming a simple harmonic oscillator quark model, a Coulomb + linear + hyperfine quark model, and a relativised quark model. The resulting ratio for scalar mesons fall in the range $\frac{f_{D_s(2860)}}{f_{D_s(2317)}} \approx 0.9$–$1.4$. The final estimates of the production of excited scalar D_s mesons in B decays are thus

$$\frac{B \to D_s(2860)D}{B \to D_s(2317)D} = 0.6\text{–}1.8 \tag{9}$$

and

$$\frac{B \to D_s(2860)D^*}{B \to D_s(2317)D^*} = 0.3\text{–}0.9. \tag{10}$$

A similar analysis for vector D_s^* production is presented in Table 5.

Estimating vector decay constant ratios as above yields $\frac{f_{D_s(2690)}}{f_{D_s^*}} \approx 0.7$–$1.1$. Finally, predicted ratios of excited vector production are

$$\frac{B \to D_s(2690)D}{B \to D_s^*(2110)D} = 0.3\text{–}0.7 \tag{11}$$

and

$$\frac{B \to D_s(2690)D^*}{B \to D_s^*(2110)D^*} = 0.5\text{–}1.3. \tag{12}$$

We note that Eq. (11) agrees well with the earlier prediction of Close and Swanson [14].

5. Summary and conclusions

Given the controversial nature of the $D_s(2317)$, establishing a consistent picture of the entire D_s spectrum is very important. The new states claimed by BaBar can be useful in this regard. We have argued that the six known D_s and two new states can be described in terms of a constituent quark model with novel spin-dependent interactions. Predicted strong decay properties of these states appear to agree with experiment.

Perhaps the most important tasks at present are (i) discovering the $D_{s2}(2P)$ state, (ii) searching for resonances in D^*K and DK^* up to 3100 MeV, (iii) analysing the angular dependence of the DK final state in $D_{sJ}(2860)$ decay, (iv) assessing whether the $D_{sJ}(2690)$ appears in the D^*K channel, (v) searching for these states in $B \to D_{sJ}D^{(*)}$ with branching ratios of $\sim 10^{-3}$.

5.1. Postscript: Belle discovery

Subsequent to these calculations, and as this Letter was being completed, Belle [19] has reported a vector state whose mass, width, and possibly production rate and decay characteristics are consistent with our predictions. Specifically, their measured mass and total width are $M = 2715 \pm 11^{+11}_{-14}$ MeV and $\Gamma = 115 \pm 20^{+36}_{-32}$ MeV, in remarkable agreement with our predictions. The specific parameters we have used in our analysis are contained within their uncertainties.

Belle [19] find the new state in B decays, which we have proposed as a likely source. They report $Br(B \to \bar{D}^0 D_s^*(2700)) \times Br(D_s^*(2700) \to D^0K^+) = (7.2 \pm 1.2^{+1.0}_{-2.9}) \times 10^{-4}$. When compared to the production of the ground state vector [13] which is $Br(B \to \bar{D}^0 D_s^*(2112)) = (7.2 \pm 2.6) \times 10^{-3}$, the ratio of production rates in B decay is then $\mathcal{O}(0.1)/Br(D_s^*(2700) \to D^0K^+)$. From our Table 2, and assuming flavor symmetry for the strong decay, we predict that $Br(D_s^*(2690) \to D^0K^+) \sim 10\%$, which within the uncertainties will apply also to the Belle state. Thus the absolute production rate, within the large uncertainties, appears to be consistent with that predicted in Section 4. If the central value of the Belle mass is a true guide, then a significant branching ratio in D^*K would be expected (Table 2 and Fig. 1). The orthogonal vector state would then be dominantly 1D at 2.78 GeV, but hard to produce in B decays. These statements depend on the dynamics underlying $2S$–$1D$ mixing, which is poorly understood. It is therefore very useful that B decay systematics and the strength of the D^*K decay channel in the excited vector D_s mesons can probe this dynamics.

Searching for this state in the other advocated modes, and improving the uncertainties, now offers a significant test of the dynamics discussed here.

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