The $D_{sJ}^*(2860)$ Mesons as Excited D-wave $c\bar{s}$ States

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A new charm-strange meson, the $D_{sJ}^*(2863)$, has recently been observed by the LHCb collaboration which also determined the $D_{sJ}^*(2860)$ to have spin 3. One of the speculations about the previously observed $D_s^*(2710)$ is that it is the $1D_1(c\bar{s})$ state. In this paper we reexamine the quark model properties and assignments of these three states in light of these new measurements. We conclude that the $D_s^*(2863)$ and $D_{sJ}^*(2863)$ are the $1D_1(c\bar{s})$ and $1D_3(c\bar{s})$ states respectively and the $D_s^*(2710)$ is the $2^3S_1(c\bar{s})$ state. In addition to these three states there are another three excited $D_s$ states in this mass region still to be found; the $2S_0$ and two $1D_2$ states. We calculate the properties of these states and expect that LHCb has the capability of observing these states in the near future.

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I. INTRODUCTION

Over the past few years a proliferation of new meson states have been observed by various collider experiments leading to a renaissance in hadron spectroscopy [3, 5]. While many of these new states do not fit into the quark model description of hadrons and remain enigmas, some, on the surface, appear to be conventional quark model states. The challenge is then of classification and being able to describe the properties of the latter set as conventional quark model states. Sharpening our descriptive power for conventional states is a necessary prerequisite to understanding the nature of the exotic states.

Recently the LHCb collaboration presented evidence for overlapping spin-1 and spin-3 $D^0K^-$ resonances at 2.86 GeV/$c^2$ [6, 7]. These follow the observation of three new excited charm-strange mesons: the $D_{sJ}^*(2700)^\pm$ [8–11], $D_{sJ}^*(2860)^\pm$ [8, 10, 11, and $D_{sJ}^*(3040)^+$ [12]. It is the first two states that are most relevant to the new LHCb measurements.

The $D_{sJ}^*(2710)^\pm$ has been identified with the first radial excitation of the $D_{sJ}^*(2212)^\pm$ or the $D_s^*(1^3D_1)$ or some mixture of them [12, 25] and the $D_{sJ}^*(2860)^\pm$ as the $D_s^*(1^3D_1)$ or the $D_s^*(1^3D_3)$ [12, 14, 21, 23, 24]. The theoretical predictions for these states are not totally consistent with their observed properties and it was suggested that a quark model identification that best described the observed properties is to identify $D_{sJ}^*(2710)^\pm$ as the $D_s^*(1^3D_1)$ and the $D_{sJ}^*(2860)^\pm$ as the $D_{sJ}^*(1^3D_3)$ but overlapping with the $1D_2(c\bar{s})$ states to explain the observed $D^*K/DK$ branching ratios [12, 16, 25]. Furthermore, it was proposed that studying the angular distributions of the final states would test this possibility. LHCb did this analysis and found that the $D_{sJ}^*$ was actually comprised of $J = 1$ and $J = 3$ states. The LHCb measurements undermine the explanation given above and suggest that a reexamination of these states is warranted.

The LHCb collaboration determined the masses and widths of the $D_{s1}^*(2860)$ and $D_{s3}^*(2860)$ to be [6, 7]:

$$M(D_{s1}^*(2860)^-) = 2859 \pm 12 \pm 6 \pm 23 \text{ MeV}$$

$$\Gamma(D_{s1}^*(2860)^-) = 159 \pm 23 \pm 27 \pm 72 \text{ MeV}$$

$$M(D_{s3}^*(2860)^-) = 2860.5 \pm 2.6 \pm 2.5 \pm 6.0 \text{ MeV}$$

$$\Gamma(D_{s3}^*(2860)^-) = 53 \pm 7 \pm 4 \pm 6 \text{ MeV}$$

where the first uncertainty is statistical, the second is due to experimental systematic effects and the third is due to model variations. The Particle Data Group averages for the masses, decay widths and ratios of branching fractions for the $D_{s1}^*(2700)^\pm$ and $D_{sJ}^*(2860)^\pm$ are [27]:

$$M(D_{s1}^*(2710)^\pm) = 2709 \pm 4 \text{ MeV}$$

$$\Gamma(D_{s1}^*(2710)^\pm) = 117 \pm 13 \text{ MeV}$$

$$\Gamma(D_{s1}^\rightarrow D^*K)/\Gamma(D_{s1}^\rightarrow DK) = 0.91 \pm 0.13(\text{stat}) \pm 0.12(\text{syst})$$

and

$$M(D_{sJ}^*(2860)^\pm) = 2863^{+4.0}_{-2.6} \text{ MeV}$$

$$\Gamma(D_{sJ}^*(2860)^\pm) = 58 \pm 11 \text{ MeV}$$

$$\Gamma(D_{sJ}^\rightarrow D^*K)/\Gamma(D_{sJ}^\rightarrow DK) = 1.10 \pm 0.15(\text{stat}) \pm 0.19(\text{syst})$$.
In this paper we reexamine these states in light of the new LHCb measurements by comparing the observed properties to the mass predictions of the relativized quark model \[28\] and the decay predictions of the \[3P_0\] pair creation decay model \[29, 32\]. In the following section we compare the observed masses to the predictions of the relativized quark model for charm-strange mesons \[12, 28\] and give the partial decay widths for the \[2S\] and \[1D\] charm-strange mesons calculated using the \[3P_0\] model. In section III we discuss these results and we give a brief summary in section IV.

II. 2S AND 1D \(D_s\) PROPERTIES

A. Spectroscopy

We compare the observed masses to the predictions for the charm-strange mesons of the relativized quark model \[12\] in Table 1. The details of this model can be found in Ref. \[28\] and \[33, 37\] to which we refer the interested reader. The parameters of the model, including the constituent quark masses, are given in Ref. \[28\]. This model has been reasonably successful in describing most known mesons although in recent years an increasing number of states have been observed that do not fit into this picture and are often referred to as “exotics” \[5\]. An important limitation of this model is that it is restricted to the \(q\bar{q}\) sector of the Fock space and does not take into account higher components that can be described by coupled channel effects \[38–40\]. As a consequence of neglecting these effects and the crudeness of the relativization procedure we do not expect the mass predictions to be accurate to better than \(\sim 10 - 20\) MeV.

For the case of a quark and antiquark of unequal mass, charge conjugation parity is no longer a good quantum number so that states with different total spins but with the same total angular momentum, such as \(3P_0 - 1P_1\) and \(3D_2 - 1D_2\) pairs, can mix via the spin orbit interaction or some other mechanism such as mixing via coupled channels. Consequently, the physical \(J = 2\) \(D\)-wave states are linear combinations of \(3D_2\) and \(1D_2\) which we describe by:

\[
D_2 = 1D_2 \cos \theta_{nD} + 3D_2 \sin \theta_{nD} \\
D_2 = -1D_2 \sin \theta_{nD} + 3D_2 \cos \theta_{nD}
\]

where \(D = L = 2\) designates the relative orbital angular momentum of the \(q\bar{q}\) pair and the subscript \(J = 2\) is the total angular momentum including spin of the \(q\bar{q}\) pair which is equal to \(L\) with analogous expressions for other values of \(L\). This notation implicitly implies \(L - S\) coupling between the quark spins and the relative orbital angular momentum. \(\theta_{1D}\) is found by diagonalizing the mass matrix for the antisymmetric piece of the spin-orbit interaction (which arises for unequal mass quarks and antiquarks) in the basis of eigenvectors of the \(|jm; ls\rangle\) sectors. We obtain \(\theta_{1D} = -38.5^\circ\) (for \(c\bar{s}\)) \[12\]. The details are given in Ref. \[28\]. In the heavy quark limit (HQL) in which the heavy quark mass \(m_Q \to \infty\), the states can be described by the total angular momentum of the light quark, \(j_q\), which couples to the spin of the heavy quark and corresponds to \(j - j\) coupling. In this limit the state that is mainly spin singlet has \(j_q = l + \frac{1}{2}\) while the state that is mainly spin triplet has \(j_q = l - \frac{1}{2}\) and is labelled with a prime \[41\]. For \(L = 2\) the HQL gives rise to two doublets, \(j_q = 3/2\) and \(j_q = 5/2\) with \(\theta_{1D} = -\tan^{-1}(\sqrt{2}/3) = -39.2^\circ\) where the minus sign arises from our \(c\bar{s}\) convention \[15, 17, 18, 24, 26, 35, 41, 42\]. We note that the definition of the mixing angles is fraught with ambiguities and one should be extremely careful comparing predictions from different papers \[43\].

B. Strong Decays

We calculate decay widths using the \(3P_0\) quark creation model \[29, 32, 44\]. There are a number of predictions for \(D_s\) decay widths in the literature using the \(3P_0\) model \[13, 14, 19–21, 43\] and other models \[16, 18, 24, 26, 42\].

In our calculations we use for the quark creation parameter \(\gamma = 0.4\) which has been found to give a good description of strong decays \[44, 45\]. We use harmonic oscillator wave functions with the oscillator parameter, \(\beta_{cs}\), by equating the rms radius of the harmonic oscillator wavefunction for the specified \((n, l)\) quantum numbers to the rms radius of the wavefunctions calculated using the relativized quark model of Ref. \[28\] except for light mesons for which we use a universal \(\beta = 0.40\) GeV (see also Ref. \[32, 45\]). The harmonic oscillator wavefunction parameters found in this way are: \(\beta_{cs}(2^1S_1) = 0.46\) GeV, \(\beta_{cs}(1^3S_0) = 0.48\) GeV, \(\beta_{cs}(1^3D_3) = 0.43\) GeV, \(\beta_{cs}(1^3D_2) = 0.45\) GeV, \(\beta_{cs}(1^1D_2) = 0.44\) GeV, \(\beta_{cs}(1^1D_1) = 0.47\) GeV \(\beta_{cs}(3^1S_1) = 0.56\) GeV, \(\beta_{cs}(1^3S_0) = 0.65\) GeV, \(\beta_{cs}(1^3S_1) = 0.52\) GeV, and \(\beta_{cs}(1^3S_0) = 0.56\) GeV. For the constituent quark masses in our calculations of both the meson masses and of the strong decay widths we use \(m_c = 1.628\) GeV, \(m_s = 0.419\) GeV and \(m_q = 0.220\) GeV. Finally, we use “relativistic phase space” as described in Ref. \[31, 32\].

As stated above we used standard values of \(\gamma = 0.4\) and \(\beta = 0.4\) GeV for the light quark mesons. These typical values were found from fits to light meson decays \[32, 45, 46\]. The predicted widths are fairly insensitive to the precise values used for \(\beta\) provided \(\gamma\) is appropriately rescaled. However \(\gamma\) can vary as much as 30% and still give reasonable overall fits of light meson decay widths \[45, 46\]. This can result in factor of two changes to predicted widths, both smaller or larger.

The resulting partial widths for the \(2S\) and \(1D\) multiplets are given in Table 1. The widths given in column 4 were obtained using the predicted masses for the excited states and the PDG values for the decay products while the widths given in column 5 use the measured masses for the \(D_{s1}\) and \(D_{s3}\) states as input values: \(M(2^1S_1) = 56\) GeV, \(M(2^3S_1) = 628\) GeV, \(M(2^1D_1) = 60\) GeV. The widths given in column 5 use the measured masses for the \(D_{s1}\) and \(D_{s3}\) states as input values: \(M(2^1S_1) = 56\) GeV, \(M(2^3S_1) = 628\) GeV, \(M(2^1D_1) = 60\) GeV. The widths given in column 5 use the measured masses for the \(D_{s1}\) and \(D_{s3}\) states as input values: \(M(2^1S_1) = 56\) GeV, \(M(2^3S_1) = 628\) GeV, \(M(2^1D_1) = 60\) GeV. The widths given in column 5 use the measured masses for the \(D_{s1}\) and \(D_{s3}\) states as input values: \(M(2^1S_1) = 56\) GeV, \(M(2^3S_1) = 628\) GeV, \(M(2^1D_1) = 60\) GeV.
$M(D^*_4) = 2709$ MeV, $M(1^3D_1) = M(D^*_3) = 2859$ MeV and $M(1^3D_3) = M(D^*_2) = 2863$ MeV. We also use these observed masses to shift our input masses for the remaining states. For the $2^1S_0$ mass we subtracted the predicted $2^3S_1 - 2^1S_0$ splitting from the measured $D^*_4(2710)$ mass and for the $D_2$ states we calculated the predicted mass differences with respect to the $D^*_3$ state and subtracted them from the observed $D^*_3(2860)$ mass. In all cases we calculated the mass splittings using the mass predictions given in column 4.

III. DISCUSSION

The predicted masses and widths of the $D^*_3(2^3S_1)$, $D^*_3(1^3D_1)$ and $D^*_3(1^3D_3)$ are in reasonably good agreement with the observed properties of the $D^*_3(2710)$, $D^*_3(2860)$ and $D^*_3(2860)$. The largest discrepancy in the masses is for the $1^3D_3$ state. The predicted total widths agree with the measured widths within the experimental error and the expected predictive power of the decay model. In addition, the predicted value for the ratio of branching ratios $B(1^3D_3 \to D^*K)/B(1^3D_3 \to DK)$ is in reasonable agreement with the measured ratio but the analogous ratio for the $2^3S_1$ state is roughly a factor of two larger than the measured value. This is the largest discrepancy between predicted and observed quantities.

As suggested in previous studies the $D^*_3(2710)$ properties could be explained by treating it as a mixture of $2^3S_1(cs)$ and $1^3D_1(cs)$ [12, 13, 16, 18, 22]. We find that a small $2^3S_1 - 1^3D_1$ mixing angle of $\sim 10^\circ$ and $7.3^\circ$ ($5.1^\circ$) brings the $B(2^3S_1 \to D^*K)/B(2^3S_1 \to DK)$ ratio to the central value and within one (two) standard deviations of the measured value. With these mixings we find that for the orthogonal partner, the $D^*_3(2860)$, the $B(1^3D_1 \to D^*K)/B(1^3D_1 \to DK)$ ratio is 1.04, 0.87 and 0.75 for $\theta = 10^\circ$, $7.3^\circ$ and $5.1^\circ$ respectively. Thus, measuring the $D^*K$ branching ratio of the $D^*_3(2860)$ would be a consistency check for this description of the $D^*_3(2710)$ meson.

Overall the three recently discovered excited charm-strange mesons are well described as the $2^3S_1$, $1^3D_1$ and $1^3D_3$ charm-strange mesons. A recent paper by Song et al [17] also using the $3P_1$ model but with different input parameters gives results in reasonable agreement to those reported here and comes to the same conclusions. However, many previous studies concluded that the $D^*_3(2710)$ properties were inconsistent with that of the $D^*_2(2^3S_1)$ because the $D^*_3(2^3S_1)$ was predicted to be significantly narrower than the measured width $12$, $14$, $16$, $19$, $22$ and the predicted $B(2^3S_1 \to D^*K)/B(2^3S_1 \to DK)$ ratio is much larger than what was measured. Although there were some exceptions to this conclusion [13, 21] the general consensus was that the $D^*_3(2710)$ is the $D^*_3(1^3D_1)$ or perhaps a $2^3S_1 - 1^3D_1$ mixture [13, 16, 18, 19, 21]. So although the results we give in this paper are in good agreement with the observed properties, one should take the variation in predictions by different calculations as a cautionary reminder about the precision of the predictions.

Three of the six excited $c\bar{s}$ states in this mass region have now been identified. We expect the spin-singlet partner of the $D^*_3(2710)$ (the $2^3S_1$) to lie $\sim 60$ MeV lower in mass [12, 16] $M(2^3S_1(c\bar{s})) \sim 2650$ MeV and predict its width to be $\sim 78$ MeV and decaying to $D^*K$. The $2^3S_1 - 2^1S_0$ mass splitting was obtained using the predicted masses given in Table I. Similarly, taking the $1^3D_3 c\bar{s}$ mass to be that of the $D^*_3(2860)$ and using the splittings between the $j = 2$ states and the $1^3D_3$ state obtained from the predicted masses given in column 4 of Table I we expect the $D_2^*$ mass to be $\sim 2872$ MeV and the $D_2$ to be $\sim 2846$ MeV. Using these masses we obtain the decay properties of the $j = 2$ members of the $D$-wave multiplet given in column 5 of Table I. In the heavy quark limit we would have expected one of the $j = 2$ states to be degenerate with the $1^3D_3$ state and be relatively narrow while the other $j = 2$ state is expected to be degenerate with the $1^3D_1$ state and relatively broad. This does not seem to be born out by our calculations so it would be interesting for experiment to test these conflicting pictures. A distinguishing feature of these states is that the $D_2$ is expected to decay predominantly to $D^*K$ with a sizeable BR to $D^*\gamma$ while the $D_2^*$ is expected to decay predominantly to $DK^*$ with a sizeable BR to $D^*K$. We expect that with the expected increased statistics LHCb should be able to complete the $2S$ and $1D$ multiplets and further test and improve our understanding of this spectroscopy.

IV. SUMMARY

The observation of the $D^*_3(2710)$ and $D^*_3(2860)$ mesons by the BaBar [10] and Belle collaborations [9] resulted in considerable theoretical interest which led to a number of possible quark model assignments. The recent LHCb results showing that there were in fact two overlapping resonances at 2860 MeV [6, 7] with $j = 1$ and $j = 3$ added considerably to our understanding. The calculations presented in this paper indicate that the two states at 2860 MeV are almost certainly the $1^3D_3$ and $1^3D_3 c\bar{s}$ states and the $D^*_3(2710)$ is almost certainly the $2^3S_1(c\bar{s})$ state. The discrepancy between the predicted and measured $M(D^*_3(2710))$ branching ratios to $D^*K$ and $DK$ can be accommodated with a small $2^3S_1 - 1^3D_1$ mixing. Six excited $D_3$ mesons are expected in this mass region leaving three of them still undiscovered. We predict the properties for these states and expect that the discovery of the missing states is well within the capabilities of LHCb in the near future. Their observation and measurement of their properties would be a valuable test of the various models describing these states.

Note added: At the completion of this paper, a paper by Wang appeared [45] which analyzed the $D^*_1$ states using a heavy meson effective Lagrangian with chiral symmetry breaking corrections. He found that he
could describe the $D_s^*$ (2860) branching ratios by suitable choice of model parameters but did not give numerical values for the partial widths.

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TABLE I: Partial widths for the 2S and 1D c\bar{s} mesons calculated using the \(^3P_0\) quark pair creation model. The widths in column 4 were calculated using the predicted masses for the initial states and the PDG values \([27]\) for the final states. The widths given in the last column were calculated using \(M = 2709\) MeV for the 2\(^S_1\) initial state and \(M = 2859\) and 2863 MeV for the 1\(^S_0\) and 1\(^D_3\) initial states respectively. The 2\(^1S_0\) and 2\(^2S_0\) masses were obtained by subtracting the predicted splittings using the masses given in column 4 from the measured 2\(^3S_1\) and 1\(^3D_3\) masses as described in the text.

| State | Property | Experiment (MeV) | Predicted (MeV) |
|-------|----------|-----------------|-----------------|
| \(D^*_s(2^S_1)\) | Mass | 2709 ± 4 | 2732 2709\(^a\) |
| \(D^*_s(2^S_1)\) & \(\rightarrow DK\) | 41. | 40. |
| \(D^*_s(2^S_1)\) & \(\rightarrow D^*K\) | 82. | 75. |
| \(D^*_s(2^S_1)\) & \(\rightarrow D_s\eta\) | 7.9 | 6.9 |
| \(D^*_s(2^S_1)\) & \(\rightarrow D_s^*\eta\) | 5.4 | 3.1 |
| \(\Gamma\) & \(\text{Total}\) | 117 ± 13 | 136. 125. |
| \(\Gamma(\rightarrow D^*K)/\Gamma(\rightarrow DK)\) | 0.91 ± 0.18 | 2.0 1.8 |
| \(D_s(2^1S_0)\) | Mass | 2673 | 2650\(^a\) |
| \(D_s(2^1S_0)\) & \(\rightarrow D^*K\) | 94. | 78. |
| \(D_s(2^1S_0)\) & \(\rightarrow D_s^*\eta\) | 0.6 | 0 |
| \(\Gamma\) & \(\text{Total}\) | 94. | 78. |
| \(D^*_s(1^3D_3)\) | Mass | 2863\(^a\) | 2917 2863\(^a\) |
| \(D^*_s(1^3D_3)\) & \(\rightarrow DK\) | 28. | 20. |
| \(D^*_s(1^3D_3)\) & \(\rightarrow D^*K\) | 20. | 12. |
| \(D^*_s(1^3D_3)\) & \(\rightarrow D_s\eta\) | 1.7 | 1.0 |
| \(D^*_s(1^3D_3)\) & \(\rightarrow D_s^*\eta\) | 0.7 | 0.3 |
| \(\Gamma\) & \(\text{Total}\) | 58 ± 11 | 64. 34. |
| \(\Gamma(\rightarrow D^*K)/\Gamma(\rightarrow DK)\) | 0.91 ± 0.18 | 0.72 0.62 |
| \(D_s(D'_2)\) | Mass | 2926 | 2872\(^a\) |
| \(D_s(D'_2)\) & \(\rightarrow D^*K\) | 40. | 28. |
| \(D_s(D'_2)\) & \(\rightarrow DK^*\) | 125. | 83. |
| \(D_s(D'_2)\) & \(\rightarrow D^*K^*\) | 7.9 | 0 |
| \(D_s(D'_2)\) & \(\rightarrow D_s^*\eta\) | 2.4 | 1.5 |
| \(\Gamma\) & \(\text{Total}\) | 175. | 112. |
| \(D_s(D_2)\) | Mass | 2900 | 2846\(^a\) |
| \(D_s(D_2)\) & \(\rightarrow D^*K\) | 156. | 148. |
| \(D_s(D_2)\) & \(\rightarrow DK^*\) | 2.1 | 0.4 |
| \(D_s(D_2)\) & \(\rightarrow D^*K^*\) | 0.07 | 0 |
| \(D_s(D_2)\) & \(\rightarrow D_s^*\eta\) | 23. | 17. |
| \(\Gamma\) & \(\text{Total}\) | 181. | 166. |
| \(D^*_s(1^3D_1)\) | Mass | 2859 ± 27 | 2899 2859\(^a\) |
| \(D^*_s(1^3D_1)\) & \(\rightarrow DK\) | 93. | 94. |
| \(D^*_s(1^3D_1)\) & \(\rightarrow D^*K\) | 51. | 49. |
| \(D^*_s(1^3D_1)\) & \(\rightarrow D^*K^*\) | 32. | 22. |
| \(D^*_s(1^3D_1)\) & \(\rightarrow D_s\eta\) | 18. | 16. |
| \(D^*_s(1^3D_1)\) & \(\rightarrow D_s^*\eta\) | 7.2 | 5.8 |
| \(\Gamma\) & \(\text{Total}\) | 159 ± 80 | 201. 187. |
| \(\Gamma(\rightarrow D^*K)/\Gamma(\rightarrow DK)\) | 0.55 | 0.52 |

\(^a\)input as described in the text