Towards an Understanding of the New Charm and Charm-Strange Mesons

Stephen Godfrey
Ottawa-Carleton Institute for Physics, Department of Physics, Carleton University, Ottawa, Canada K1S 5B6
E-mail: godfrey@physics.carleton.ca

Abstract. The observation of the $D_{sJ}^*(2317)$, $D_{sJ}(2460)$, and SELEX $D_{sJ}^*(2632)$ states with properties differing considerably from what was expected has led to a renewed interest in hadron spectroscopy. In addition to these states, non-strange partners of the $D_{sJ}$ states have also been observed. Understanding the $D_0^*$ and $D_1^*$ states can provide important insights into the $D_{sJ}$ states. In this contribution I examine quark model predictions for the $D_{sJ}^*$ and $D_{sJ}$ states and discuss experimental measurements that can shed light on them. I find that these states are well described as the broad, $j = 1/2$ non-strange charmed $P$-wave mesons. In the latter part of this writeup I discuss the $c\bar{s}$ possibilities for the SELEX $D_{sJ}^*(2632)$ and measurements that can shed light on it.

1. Introduction
The last eighteen months have been exciting times for hadron spectroscopists with the first observation of many charmed and charmonium states. It started with the observation of the $D_{sJ}^*(2317)$ [1] which was described as having properties “quite different from those predicted by quark potential models”. The $D_{sJ}(2460)$ [2] was observed shortly thereafter with similar discrepancies between theory and experiment. To understand the nature of the discrepancies we note that the four $L = 1$ $P$-wave mesons can be grouped into two doublets characterized by the angular momentum of the light quark; $j = 3/2, 1/2$. The $j = 3/2$ $c\bar{s}$ states were predicted to be relatively narrow and are identified with the $D_{s1}(2536)$ and $D_{s2}(2573)$ states while the $D_{s0}^*$ and $D_{s1}^*$, $j = 1/2$ states were expected to have large $S$-wave widths decaying to $DK$ and $D^*K$ respectively [3]. However, the states observed by Babar and CLEO are below $D^{(*)}K$ threshold and are very narrow. This has led to considerable theoretical speculation that these states may be something new such as multiquark states or meson-molecules [4]. My view is that the $D_{sJ}^{(*)}$ states are conventional $q\bar{q}$ states with their masses shifted due to coupling to the nearby $DK$ and $D^*K$ open channels. Diagnostic tests have been proposed to help understand the nature of these newly discovered states [4, 5, 6, 7]. In addition, the non-strange $j = 1/2$ $P$-wave states, $D_0^*$ and $D_1^*$, have been observed [8, 9, 10] and comparing their observed properties with theoretical predictions can give us some sense of how reliable the models are [11, 12]. The first part of this writeup examines quark model predictions of properties of the charm and charm-strange $P$-wave mesons and some diagnostic tests of the $q\bar{q}$ explanation.

The most recent addition to the family of charm meson misfits is the $D_{sJ}^*(2632)$ state observed...
by the SELEX collaboration [12]. Again, there has been considerable speculation about what this state might be. In the second part of this writeup I discuss the quark model possibilities and outline some measurements that can be used to test them [13, 14].

2. The Charmed P-wave Mesons
Almost all the theoretical effort has been devoted to explain the $D_{sJ}^{(*)}$ states. The non-strange partners have received almost no attention although they also contain important spectroscopic information and could hold the key to understanding the $D_{sJ}^{(*)}$‘s or at least tell us how reliable our models are.

The measured properties of the $L = 1$ charm mesons are summarized in Table 1 along with quark model predictions [3, 11, 15]. The quark model gives a $P$-wave cog that is $\sim 40$ MeV too high but the splittings are in very good agreement with the measured masses. The width predictions are given for the pseudoscalar emission model with the flux-tube model giving qualitatively similar results [3]. We note that Belle [8] and FOCUS [9] measure $\Gamma(D_2^{(*)}) = 37 \pm 4.0$ MeV and $\Gamma(D_1^{(*)}) = 23.7 \pm 4.8$ MeV which are larger than the PDG values. They attribute differences with older results to taking into account interference with the broader $D$ states. Overall the agreement between theory and experiment is quite good. Note that the physical $D_1^{(*)}$ states are linear combinations of the $3P_1$ and $1P_1$ states so that the good agreement for the decay widths reflects a successful prediction for the $1^{3}P_1 - 1^{1}P_1$ mixing angle.

Table 1. Comparison of Quark Model Predictions to Experiment for the $L=1$ Charm Mesons.

| State | Mass (MeV) | Width (MeV) |
|-------|------------|-------------|
|       | Theory     | Expt        | Theory | Expt |
| $D_2^*$ | 2460       | 2459 ± 2 $^c$ | 54      | 23 ± 5 $^e$ |
| $D_1$  | 2418       | 2422 ± 1.8 $^c$ | 24      | 18.9$^{+4.6}_{-3.5}$ $^c$ |
| $D_1'$ | 2428       | 2438 ± 30 $^d$ | 250     | 329 ± 84 $^d$ |
| $D_0$  | 2357       | 2308 ± 36 $^e$ | 280     | 276 ± 66 $^e$ |

$a$ The $P$-wave cog [3, 15] was shifted down 42 MeV.

$b$ Using the masses from column 2.

d Average of the Belle [8] and CLEO [10] $D_1^{(*)}$ measurements

e Belle Collaboration [8]

Radiative transitions probe the internal structure of hadrons [5, 6, 7]. Table 2 gives the quark model predictions for $E1$ radiative transitions between the $1P$ and $1S$ charm mesons [11]. The $D_2^{(*)} \rightarrow D^{(*)} \gamma$, $D_1^{(*)} \rightarrow D^{(*)} \gamma$ and $D_0^{(*)} \rightarrow D^{(*)} \gamma$ transitions should be observable. The latter two are of particular interest since the ratio of these partial widths measure the $3P_1 - 1P_1$ mixing angle in the charm meson sector which is a good test of how well the Heavy Quark Limit is satisfied.

The overall conclusion is that the quark model describes the $P$-wave charm mesons quite well and models invoked to describe the $D_{sJ}^{(*)}$($2317$) and $D_{sJ}^{(*)}$($2460$) states should also explain their non-strange charm meson partners. Better data would further test the models.

3. The Charm-Strange P-wave Mesons
Turning to the $D_{sJ}$ states, the narrow $j = 3/2$ states are identified with the $D_{s1}(2536)$ and $D_{s2}(2573)$ with their observed properties in good agreement with quark model predictions [3, 15].
Table 2. Partial widths and branching ratios for E1 transitions between 1P and 1S charm mesons. The widths are given in keV unless otherwise noted. The $M_i$ and the total widths used to calculate the BR’s are taken from Table 1. The matrix elements are calculated using the wavefunctions of Ref. 15.

| Initial state | Final state | $M_i$ (GeV) | $M_f$ (GeV) | $k$ (MeV) | $\langle 1P|r|nS\rangle$ (GeV$^{-1}$) | Width (keV) | BR  |
|---------------|-------------|-------------|-------------|-----------|---------------------------------|-------------|-----|
| $D_s^+$       | $D^{*+}\gamma$ | 2.459       | 2.010       | 408       | 2.367                           | 57          | 0.25% |
| $D_{s0}^+$    | $D^{*0}\gamma$ | 2.459       | 2.007       | 411       | 2.367                           | 559         | 2.4%  |
| $D_1^{++}$    | $D^{*+}\gamma$ | 2.422       | 2.010       | 377       | 2.367                           | 8.8 $\times$10$^{-4}$ | 0.3% |
| $D_1^{+}$     | $D^{*0}\gamma$ | 2.422       | 1.869       | 490       | 2.028                           | 58          | 0.3%  |
| $D_1^{0}$     | $D^{0}\gamma$  | 2.422       | 1.865       | 493       | 2.028                           | 571         | 3.0%  |
| $D_2^{++}$    | $D^{*+}\gamma$ | 2.428       | 2.010       | 382       | 2.367                           | 37          | 10$^{-4}$ |
| $D_2^{+}$     | $D^{+}\gamma$  | 2.428       | 1.869       | 494       | 2.028                           | 15          | 4 $\times$10$^{-5}$ |
| $D_2^{0}$     | $D^{0}\gamma$  | 2.428       | 1.865       | 498       | 2.028                           | 144         | 4 $\times$10$^{-4}$ |
| $D_3^{++}$    | $D^{*+}\gamma$ | 2.357       | 2.010       | 321       | 2.345                           | 27          | 10$^{-4}$ |
| $D_3^{+}$     | $D^{0}\gamma$  | 2.357       | 2.007       | 324       | 2.345                           | 270         | 0.1%  |

The $j = 1/2$ states were predicted to be broad and to decay to $DK$ and $D^*K$ and were not previously observed. But the $D_{s1}^*(2317)$ is below $DK$ threshold and the $D_{s1}(2460)$ is below $D^*K$ threshold so the only allowed strong decays are $D_{sJ}^{(*)} \rightarrow D_s^{(*)}\pi^0$ which violate isospin and are expected to have small widths $\mathcal{O}(10)$ keV [5] [6] [7]. As a consequence, the radiative transitions are expected to have large BR’s and are an important diagnostic tool to understand the nature of these states [5] [6] [7]. Although there are discrepancies between the quark model predictions and existing measurements they can be accommodated by the uncertainty in theoretical estimates of $\Gamma(D_{sJ}^{(*)} \rightarrow D_s^{(*)}\pi^0)$ and by adjusting the $^{3}P_1 - ^{1}P_1$ mixing angle for the $D_{s1}$ states. As in the case of the $D_1$ states, the radiative transitions to $D_s$ and $D_s^*$ can be used to constrain the $^{3}P_1 - ^{1}P_1$ $(cs)$ mixing angle.

The problems with the newly found $D_{sJ}$ states are the mass predictions. Once the masses are fixed the narrow widths follow. My view is that the strong coupling to $DK$ (and $D^*K$) is the key to solving this puzzle. A number of people have studied this and have found that coupled channel effects lead to the required mass shifts [17]. Unfortunately, coupled channel effects also appear to lead to comparable shifts in states that were previously in good agreement with experiment [18]. So it is still an open question whether coupled channel effects can account for the discrepancy between quark model predictions for the $D_{sJ}$ masses and experiment.

4. Options for the $D_{sJ}^*(2632)$

The SELEX collaboration recently observed a narrow charm-strange meson decaying into $D_s^{+}\eta$ and $D^0K^+$ final states in the ratio of $\Gamma(D^0K^+)/\Gamma(D_s^{++}\eta) = 0.16 \pm 0.06$ with $M = 2632.6 \pm 1.6$ MeV/$c^2$ and $\Gamma < 17$ MeV/$c^2$ at 90% C.L. [12]. A number of possible assignments have been suggested: a conventional $2^3S_1(c\bar{s})$ state, a $c\bar{s}$ hybrid, or a two-meson molecule [13]. In this section we consider the conventional $c\bar{s}$ options for the $D_{sJ}^*(2632)$ [13].

The most plausible $c\bar{s}$ state is the $2^3S_1(c\bar{s})$ state with $M = 2730$ MeV although the $1^3D_1(c\bar{s})$ is somewhat higher with a mass of 2900 MeV [15]. As suggested with respect to the $D_{sJ}^*(2317)$
and $D_{sJ}(2460)$ states, the $q\bar{q}$ predictions could be shifted through mixing with the two-meson continuum. Note that the mass of the $K^*(1410)$ is also lower than quark model predictions and its partial widths also disagree with decay models. So it is possible that the discrepancies of the $K^*(1410)$ and $D_{sJ}^*(2632)$ properties are somehow related.

The allowed open flavour decay modes of a $2^3S_1(c\bar{s})$ state with mass $M = 2632$ MeV are $D^0K$, $D_s\eta$, and $D^*K$. We found that $\Gamma(D_{sJ}^*(2632)) = 36$ MeV with $\Gamma(D^*K) > \Gamma(D^0K) \gg \Gamma(D_s\eta)$. In particular $\Gamma(D^0K)/\Gamma(D_s\eta) \simeq 9$. For comparison, SELEX finds $\Gamma(D^0K^+)/\Gamma(D_s^{+}\eta) = 0.32 \pm 0.12$, (taking into account $D^0K$ and $D^+K^0$). Clearly there is an inconsistency. $2^3S_1 - 1^3D_1$ mixing, which could be generated by coupling to decay channels, could alter this ratio but it would require both fine tuning of the mixing angle and of a quark model parameter to an unlikely value. Although this tuning cannot be ruled out we consider it unlikely. We further estimate $\Gamma(2^3S_1(c\bar{s}) \to D_s^{*}\pi\pi) \simeq 220$ keV implying $\text{BR} \geq 1\%$. If the SELEX state is indeed the $2^3S_1(c\bar{s})$ state the $D^*K$ decay mode must be seen. The $D_{sJ}^*(2632)$ should be seen in $B$-decay, the $D_s\pi\pi$ mode should be present with $\text{BR} \geq 1\%$, and the $1^3D_1$ state should be $\sim 200$ MeV higher in mass.

5. Summary
To summarize, we found that the $P$-wave charm mesons are well described by the quark model. However, it is important to confirm the broad $j = 1/2$ states and obtain more precise measurements of their properties. The $D_{sJ}^*(2317)$ and $D_{sJ}^*(2460)$ states have masses lower than expected for the missing $0^+$ and $1^+ j = 1/2 c\bar{s}$ states. This may be due to coupling to decay channels but further work is needed. In any case, radiative transitions are a good way of testing the nature of these states.

If the SELEX $D_{sJ}^*(2632)$ state is the $2^3S_1(c\bar{s})$ state it should decay to $D^*K$ with a sizable branching ratio. The $2^3S_1(c\bar{s}) \to D_s^{*}\pi\pi$ decay mode should also be present with a partial width of $\sim 220$ keV and a BR of $\sim 1\%$. We expect that the $2^3S_1(c\bar{s})$ should be seen in $B$-decays. The $1^3D_1(c\bar{s})$ should also be present with a mass roughly $200$ MeV higher. We encourage experimenters to search for these states in $B$-decay.

Acknowledgments
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