Properties of the Charmed P-wave Mesons

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Two broad charmed mesons, the \(D_0^\ast\) and \(D_1^\ast\), have recently been observed. We examine the quark model predictions for the \(D_0^\ast\) and \(D_1^\ast\) properties and discuss experimental measurements that can shed light on them. We find that these states are well described as the broad, \(j \approx 1/2\) non-strange charmed P-wave mesons. Understanding the \(D_0^\ast\) and \(D_1^\ast\) states can provide important insights into the \(D_{sJ}^\ast(2317), D_{sJ}^\ast(2460)\) states whose unexpected properties have led to renewed interest in hadron spectroscopy.

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I. INTRODUCTION

It has long been pointed out that light-heavy mesons act as the hydrogenic atoms of QCD and represent a unique laboratory to test our understanding of QCD \[1, 2\]. In the limit that the heavy quark mass becomes infinite, the properties of the meson are determined by those of the light quark \[1, 2, 3\]. The light quarks are characterized by their total angular momentum, \(j_q = s_q + L\), where \(s_q\) is the light quark spin and \(L\) is its orbital angular momentum. \(j_q\) is combined with \(S_Q\), the spin of the heavy quark, to give the total angular momentum of the meson. The quantum numbers \(S_Q\) and \(j_q\) are individually conserved. Thus, the four \(L = 1\) P-wave mesons can be grouped into two doublets characterized by the angular momentum of the light quark \(j_q = 3/2\) with \(J^P = 1^+, 2^+\) and \(j_q = 1/2\) with \(J^P = 0^+, 1^+\) where \(J\) and \(P\) are the total angular momentum and parity of the excited meson. In the heavy quark limit the members of the doublets will be degenerate in mass which is broken by \(1/m_Q\) corrections \[3, 4\]. Similarly, heavy quark symmetry and the conservation of parity and \(j_q\) predicts that the strong decays \(D_{sJ}^{(s)}(j_q = 3/2) \rightarrow D^{(*)}\pi(K)\) proceed only through a D-wave while the decays \(D_{sJ}^{(s)}(j_q = 1/2) \rightarrow D^{(*)}\pi(K)\) proceed only via an S-wave \[5, 6\]. The states decaying to a D-wave are expected to be narrow while whose decaying to an S-wave are expected to be broad. The properties of the charmed and charm-strange \(j_q = 3/2\) states are consistent with this prediction.

The observed properties of the \(D_{sJ}^\ast(2317)\) \[7\] and the \(D_{sJ}^\ast(2460)\) \[8\] did not agree with most theoretical predictions for the \(j_q = 1/2\) states. While most models predicted the \(j = 1/2\) doublet to be broad, decaying to \(DK\) and \(D^*K\) for the \(J = 0\) and \(J = 1\) state respectively, the states observed by Babar and CLEO were below the \(DK\) and \(D^*K\) thresholds and were quite narrow, decaying to \(D^+_s\pi^0\) and \(D^{*_s}\pi^0\) respectively. This led to considerable theoretical speculation about the nature of these states ranging from a conventional \(c\bar{s}\) meson to exotic \(DK\) molecules or tetraquarks \[9\]. A number of authors pointed out that if the masses of the conventional \(c\bar{s}\) states are taken to be the measured \(D_{sJ}^{(s)}\) masses, the predicted \(D_{sJ}^{(s)}\) properties agree with the measured properties \[6, 10, 11, 12\]. While the \(D_{sJ}^{(s)}\) states have attracted most of the attention, the first observations of the the non-strange \(j_{\pi} = 1/2\) P-wave partner states, the \(D_0^\ast\) and \(D_1^\ast\) \[13, 14, 15\] has also taken place. Comparing the theoretical predictions for these \(D_{sJ}^{(s)}\) states against their observed properties is an important complementary test of the reliability of the models \[8, 16, 17\]. This in turns acts as a baseline against which to measure the predicted properties of the \(D_{sJ}^\ast\) states.

In this note we examine the properties of the charmed P-wave mesons. We concentrate on the non-strange states, recalculating the strong widths using the measured masses and present new results on radiative transitions of these states. These are the main new results presented here \[16\]. We begin with a summary of the experimental properties of charmed P-wave mesons including recent results. This is followed by the new results on the properties of the charmed P-wave mesons. We then briefly revisit the charm-strange P-wave mesons, discussing possible explanations of their unexpected properties. In the last section we conclude with some final comments and suggestions for further measurements.

II. THE CHARMED P-WAVE MESONS

In this section we study predictions for charmed P-wave meson properties and compare them to the experimental measurements. The results for the strong decay widths are an update of previous results \[8\] taking into account the measured masses. We also present the results of a new calculation of radiative transitions and suggest some tests of the models.
TABLE I: Summary of experimental measurements of the $L = 1$ charmed mesons properties.

| State Property | PDG [18] | Belle [13] | FOCUS [14] | CLEO [15] | CDF [19] | Average |
|----------------|----------|------------|------------|------------|----------|---------|
| $D_s^0$ Mass (MeV) | 2458.9 ± 2 | 2461.6 ± 3.9 | 2464.5 ± 2.2 | 2463.3 ± 1.0 | 2462.7 ± 0.9 | |
| Width (MeV) | 23 ± 5 | 45.6 ± 8.0 | 38.7 ± 6.0 | 49.2 ± 2.4 | 43.8 ± 2.0 | |
| $D_s^+$ Mass (MeV) | 2459 ± 4 | 2467.6 ± 1.7 | 2466.3 ± 1.6 | |
| Width (MeV) | 25.4 ± 2 | 34.1 ± 7.7 | 29.4 ± 5.4 | |
| $D_s^0$ Mass (MeV) | 2422.2 ± 1.8 | 2421.4 ± 1.7 | 2421.7 ± 0.9 | 2421.7 ± 0.7 | |
| Width (MeV) | 18.9 ± 4.6 | 23.7 ± 4.8 | 20.0 ± 2.1 | 20.3 ± 1.7 | |
| $D_s^+$ Mass (MeV) | 2427 ± 42 | 2461 ± 34 | 2441 ± 32 | |
| Width (MeV) | 384 ± 130 | 290 ± 110 | 329 ± 76 | |
| $D_s^0$ Mass (MeV) | 2308 ± 36 | | 2308 ± 36 | |
| Width (MeV) | 276 ± 66 | | 276 ± 66 | |

A. Experimental Summary of charmed $P$-wave Mesons

We start by summarizing the experimental measurements of charmed $P$-wave meson properties in Table I. Note that the recent Belle [13], FOCUS [14], and CDF [19] measurements of $\Gamma(D_s)$ are larger than the PDG values. Belle and FOCUS attribute differences with the older results to taking into account interference with the broader $D$ states. In the final column of Table I the various experimental measurements are combined into weighted averages.

In addition to the Belle and CLEO observations of the $D_s^0$ and $D_s^+$ states FOCUS [14] reports two broad states, $D_s^+$ and $D_s^0$ with $M(D_s^+) = 2403\pm 38$ MeV and $\Gamma(D_s^+) = 283\pm 42$ MeV and $M(D_s^0) = 2407\pm 41$ MeV and $\Gamma(D_s^0) = 240 \pm 81$ MeV. They are unable to distinguish whether the broad states are due to the $D_s^0$ or $D_s^+$ or whether both states contribute because of the large width.

B. Spectroscopy

Mass predictions are a first test of QCD motivated potential models and other calculational approaches used to confront the data. In QCD-motivated models the spin-dependent splittings test the Lorentz nature of the confining potential. Furthermore, the observation of heavy-light mesons is an important validation of heavy quark effective theory and lattice QCD calculations. In Table II we summarize predictions for the charmed $P$-wave mesons. The two $J = 1$ states are linear combinations of $^3P_1$ and $^1P_1$ because for $q$ and $\bar{q}$ of different flavour, charge conjugation parity, $C$, is no longer a good quantum number. We label these the $D_1$ and $D'_1$ defined as:

$$D_1 = \frac{1}{\sqrt{2}} P_1 \cos \theta + \frac{1}{\sqrt{2}} P_1 \sin \theta$$

$$D'_1 = -\frac{1}{\sqrt{2}} P_1 \sin \theta + \frac{1}{\sqrt{2}} P_1 \cos \theta$$

with the mixing angle determined by the details of the model. In the quark model it is due to the spin-dependent $LS$ mixing but more generally there are other contributions such as coupling via common decay channels. If the mixing is dominated by decay channels the mixing might not be well represented by the orthogonal mixing given by Eqn. 1 [32]. Measurement of the ratio of $D/S$ decay amplitudes for the $D_1$ and $D_{1s}$ states could provide an important test of this possibility [32]. However, for the $^3P_1 - 1P_1$ mixing, because the states are almost degenerate it is likely that the linear combinations due to decay channel loops will be also be orthogonal [33].

Quark model calculations and heavy quark symmetry predict that the $4 L = 1$ c$q$ (where $q = u$ or $d$) are grouped into two doublets with properties characterized by the angular momentum of the lightest quark, $j_q = 1/2$ and $j_q = 3/2$. The heavy quark limit corresponds to two physically independent mixing angles $\theta = -\tan^{-1}(\sqrt{2}/\lambda) \simeq -54.7^\circ$ and $\bar{\theta} = \tan^{-1}(1/\sqrt{2}) \simeq 35.3^\circ$ [34]. The $j_q = 3/2$ states are identified with the previously observed $D_s^0(D_{460})$ and $D_s^+(D_{420})$ states while the $j = 1/2$ have only recently been observed.

Predictions from various quark model and other calculations are summarized and compared to the experimental masses in Table II. There is a considerable spread among the predictions. The mass splittings of the GI model [2] [20] are in good agreement with the measured splittings although the $P$-wave c.o.g. is $\sim 40$ MeV too high. Other models are consistent with the two previously observed states but do not do particularly well with one or more of the $j_q = 1/2$ states. In any case, the spread of predictions underlines the importance of more precise measurements to test these models. In any case, the spread of predictions underlines the importance of more precise measurements to test these models.

C. Strong Transitions

The $P$-wave meson strong decays can be described by $D$ and $S$-wave amplitudes [2] [6] [9] [17] [20]. The amplitude formulas for the decays are given in Table III. To obtain values for $D$ and $S$ we rely on models of meson
decay. Here, we give results using the pseudoscalar emission model and update the predictions of Godfrey and Kokoski [5] by adjusting the phase space for the \( D_1^0 \) and \( D_1^+ \) decays. The \( 3P_0 \) flux-tube models [5] and chiral quark model calculations [22] give qualitatively similar results. In the pseudoscalar emission model the \( D \) and \( S \) amplitudes are given by [20]:

\[
D = A_Q \left( \frac{m_Q}{m_Q + m_\bar{q}} \right) \left( \frac{q}{\beta} \right)^2 \left( \frac{\beta}{\beta_Q} \right) \left( \frac{q}{2\pi} \right)^{1/2} F(q^2) \tag{2}
\]

and

\[
S = S_Q \left( \frac{q}{2\pi} \right)^{1/2} F(q^2) \tag{3}
\]

where

\[
F(q^2) = \exp \left[ - \left( \frac{m_Q}{m_Q + m_\bar{q}} \right)^2 \frac{q^2}{4\beta_Q} \right] \tag{4}
\]

and \( m_Q = m_u = m_d = 0.3 \text{ GeV} \), \( m_c = 1.7 \text{ GeV} \) are the relevant constituent quark masses used in the decay calculation, \( \beta = 0.4 \text{ GeV} \) and \( \beta_Q = 0.5 \) are harmonic oscillator wavefunction parameters used in obtaining these amplitudes. \( \beta \) is taken from the light meson decay analysis of Ref. [20] and \( \beta_Q \) was obtained by fitting the rms radii of HO wavefunctions to the rms radii of the GI wavefunctions. \( S_Q = 3.27 \) and \( A_Q = 1.67 \) come from the light meson decay analysis of Ref. [20]. In Table III \( \theta_0 = \tan^{-1}(\sqrt{1/2}) \) arises from the Clebsch-Gordan coefficients of the \( 3P_1 \) and \( 1P_1 \) contributions to the decay amplitudes. We stress that the calculated widths are predictions of the model with no free parameters. The results are compared to experimental measurements in Table III. The \( D_0^* \) and \( D_1^+ \) masses used in Table III came about from adjusting the \( P \)-wave c.o.g. of the GI calculation downward by 40 MeV so that the \( D_2^* \) and \( D_1 \) masses are in better agreement with experiment in order to give more reliable phase space estimates for the \( D_0^* \) and \( D_1^+ \) decays.

Overall the agreement between theory and experiment is good. The experimental widths for the \( D_2^* \) and \( D_1 \) are the weighted averages given in Table I obtained by averaging the PDG values [18] and the Belle [13], FOCUS [14] and CDF [15] results. As already noted the Belle and FOCUS widths are larger than the PDG values and are in better agreement with our results than the PDG values. However, it should be noted that there is some sensitivity in these results to phase space. (The observer reader has probably noted that we included the \( D_2^0 \) rather than the smaller (but with larger error) \( D_2^+ \) width. Nevertheless, we consider the results perfectly acceptable given the limitations of the model [35].)

Treating the \( D \) and \( S \) amplitudes (modulo the \( q^{2L+1} \) phase space factor) and mixing angle as free parameters does not qualitatively improve the agreement with experiment. Similarly, fitting the mixing angle to the \( D_1 \) and \( D_1^+ \) widths results in a mixing angle consistent with both the GI result and the HQL within errors.

In the HQL the \( D_1 \) decay is purely \( D \)-wave and the \( D_1^+ \) decay is purely \( S \)-wave. Because the \( S \)-wave partial width is so large, even relatively small deviations from the HQL would broaden the \( D_1 \) width quite substantially. Thus, these strong decays are a good test of the HQL.

Considering the experimental uncertainties and the inherent limitations of the simple decay model the agreement is excellent. It would be interesting to see if the agreement survives comparison with future, more precise measurements.

### D. Electromagnetic Transitions

Radiative transitions probe the internal structure of hadrons [10, 11, 12, 34] and as such give an additional tool to understand hadronic states. Because the recently observed \( D_1^+ \) and \( D_5^0 \) states are quite broad it is unlikely that radiative decays of these states will be observable. However, it is a priori possible that they might be observed for the \( D_2^* \) and \( D_1 \) states. The decays \( D_1 \rightarrow D^* \gamma \) and \( D_1 \rightarrow D \gamma \) would be especially interesting as they would give some insights into the \( 3P_0 \) \(-1\ P_1 \) mixing.

The \( E1 \) radiative transitions are given by [37]

\[
\Gamma(i \rightarrow f + \gamma) = \frac{4}{27} \alpha^2 \langle e_Q \rangle^2 \omega^3 \left( 2J_f + 1 \right) \left( 2s^+ S_J |r| 2s^+ P_J \right)^2 S_{if}
\]
TABLE III: Predictions for strong decay widths of the charmed P-wave mesons. All widths are given in MeV. The $D_s^*$ and $D_1$ masses are taken from Table I and the masses used for the $D_1'$ and $D_0'$ are described in the text. We took $m_s = 140$ MeV/c$^2$.

| Decay | Amplitude Formula | $M_i$ | $M_f$ | $q$ | Width | Expt. Width |
|-------|------------------|-------|-------|-----|-------|-------------|
| $D_2^* \rightarrow D^* \pi$ | $-\sqrt{2/3} D$ | 2463 | 2010 | 391 | 18 | |
| $\rightarrow D \pi$ | $-\sqrt{2/3} D$ | 2463 | 1869 | 507 | 37 | |
| $\rightarrow D^* \pi + D \pi$ | 55 | | | | | |
| $D_1 \rightarrow [D^* \pi]_S$ | $\sqrt{2/3} \sin(\theta + \theta_0) S$ | 2422 | 2010 | 354 | 7 | |
| $\rightarrow [D^* \pi]_D$ | $\sqrt{2/3} \cos(\theta + \theta_0) D$ | 2422 | 2010 | 354 | 18 | |
| $\rightarrow [D^* \pi]_S + [D^* \pi]_D$ | 25 | | | | | |
| $D_1' \rightarrow [D^* \pi]_S$ | $\sqrt{2/3} \cos(\theta + \theta_0) S$ | 2420 | 2010 | 352 | 244 | |
| $\rightarrow [D^* \pi]_D$ | $-\sqrt{2/3} \sin(\theta + \theta_0) D$ | 2420 | 2010 | 352 | 0.5 | |
| $\rightarrow [D^* \pi]_S + [D^* \pi]_D$ | 244 | | | | | |
| $D_s^0 \rightarrow D \pi$ | $-\sqrt{2} S$ | 2359 | 1869 | 421 | 277 | 276 ± 66 |

where $S_{ij}$ is a statistical factor with $S_{ij} = 1$ for the transitions between spin-triplet states ($D_j^{(c)}(1P) \rightarrow D^*\gamma$) and $S_{ij} = 3$ for the transition between spin-singlet states ($D_1 \rightarrow D\gamma$), $(e_Q)$ is an effective quark charge given by

$$\langle e_Q \rangle = \frac{m_q e_c - m_c e_\bar{u}}{m_c + m_q},$$

where $e_c = 2/3$ is the charge of the c-quark and $e_\bar{u} = 1/3$, $e_\bar{d} = -2/3$ are the charges of the d and u antiquarks given in units of $|e|$, $m_c = 1.628$ GeV, $m_q = 0.22$ GeV are the mass of the c and q = u, d quarks taken from Ref. 20, $\alpha = 1/137.036$ is the fine-structure constant, and $\omega$ is the photon’s energy. The matrix elements $\langle S|r|P \rangle$ given in Table IV were evaluated using the wavefunctions of Ref. 20. Relativistic corrections are included in the E1 transition via Siegert’s theorem 38, 39, 40 by including spin dependent interactions in the Hamiltonian used to calculate the meson masses and wavefunctions. To calculate the appropriate photon energies the PDG 18 values were used for observed mesons while the predictions from Ref. 21 were used for unobserved states with the following modification: While splittings between $c\bar{q}$ states predicted by Ref. 20 are in good agreement with experiment, the masses are slightly higher than observed so to give a more reliable estimate of phase space, the masses used in Table IV have been adjusted down by 40 MeV from the predictions of Ref. 21.

A final subtlety is that the $J = 1$ states are linear combinations of $^3P_1$ and $^1P_1$ as described by eqn. 1. The radiative widths were calculated using $\theta = -26^\circ$ and include the appropriate factors $\cos^3 \theta$ and $\sin^2 \theta$.

Table IV gives the quark model predictions for E1 radiative transitions between the 1P and 1S charmed mesons 16. One should appreciate that the predictions for the BR’s are imprecise given the uncertainties in the strong widths used to calculate the BR’s. For completeness we include results for both the charged and neutral $D$ states but due to cancellations in $\langle e_Q \rangle$ the radiative widths of the charged states are much smaller than those of the neutral states. The radiative decays of the narrow states are the most likely to be observed. The $D_s^0 \rightarrow D^{*0}\gamma$ and $D_1^0 \rightarrow D^{*0}\gamma$ transitions are of particular interest since the ratio of these partial widths is a measure of the $^3P_1 \rightarrow^1P_1$ mixing angle in the charmed meson sector:

$$\frac{\Gamma(D_1 \rightarrow^3S_1 + \gamma)}{\Gamma(D_1 \rightarrow^1S_0 + \gamma)} = \frac{\omega^2_3 |\langle r_3 |s \rangle|^2 \sin^2 \theta}{\omega^2_1 |\langle r_1 |s \rangle|^2 \cos^2 \theta}$$

and can therefore test how well the HQL is satisfied. As already mentioned, measurement of the $^3P_1 \rightarrow^1P_1$ mixing angle could reveal mixing effects due to decay channel coupling 52 which would shed light on the nature of the new $D_j^{(c)}$ states.

E. Discussion

Overall the agreement between quark model predictions and experiment is quite good. Although the GI mass prediction for the $P$-wave c.o.g. is slightly high, the splittings are in good agreement with experiment. The strong decay widths also agree well with experiment. In fact, the predicted widths agree better with the more recent Belle, FOCUS, and CDF measurements than the older PDG values. More precise measurements would be welcomed to further test the models. Note that the physical $D_j^{(c)}$ 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 $^3P_1 \rightarrow^1P_1$ mixing angle. This can be further tested by measuring the $D_0^{*0} \rightarrow D^{*0}\gamma$ and $D_1^{*0} \rightarrow D^{*0}\gamma$ partial widths.

The overall conclusion is that the $P$-wave charmed mesons are well described by the quark model and models invoked to describe the $D_s^* (2317)$ and $D_{sJ} (2460)$ states must also explain their non-strange charmed meson partners.
III. THE CHARM-STRANGE P-WAVE MESONS

Motivated by the successful description of the charmed P-wave mesons we briefly revisit the charm-strange P-wave mesons. We start by comparing in Table V the observed properties to the quark model predictions of Ref. [11] and [3]. The predicted properties are shown assuming the measured masses of the $D_{sJ}(2317)$ and $D_{sJ}(2460)$ states. The predictions using the quark model mass predictions can be found in Ref. [11].

The narrow $j = 3/2$ states are identified with the $D_{sJ}(2536)$ and $D_{s2}(2573)$ states. Their observed properties are in good agreement with quark model predictions [3, 20]. In contrast, the $j = 1/2$ states were predicted to be broad and to decay to $DK$ and $D^*K$ and had not been previously observed. The recently discovered $D_{sJ}(2317)$ is below $DK$ threshold and the $D_{sJ}(2460)$ is below $D^*K$ threshold so the only allowed strong decays are $D_{sJ}^{(*)} \rightarrow D_s^{(*)} \pi^0$ which violates isospin and is expected to have a small width [10, 11, 12]. This led to considerable speculation about the nature of these states [3]. However, if one assumes they are the conventional $j = 1/2$ $c\bar{s}$ states, *albeit* with a much lower mass than generally expected, their properties can be calculated using models of hadrons.

The strong decays $D_{sJ}^{(*)} \rightarrow D_s^{(*)} \pi^0$ and radiative transitions were calculated by a number of authors [10, 11, 12]. They concluded that radiative transitions should have large BR's and are important diagnostic probes for understanding the nature of these states [10, 11, 12].

Although there are discrepancies between some of the quark model predictions and existing measurements they can easily be accommodated by the uncertainty in theoretical estimates of $\Gamma(D_{sJ}^{(*)} \rightarrow D_s^{(*)} \pi^0)$ and by adjusting the $^3P_1 - ^1P_1$ mixing angle for the $D_{s1}$ states. For example, Ref. [10] predicts a $\Gamma(D_{sJ}^{(*)} \rightarrow D_s^{(*)} \pi^0)$ width about twice as large as the values used to calculate the BR's in Table V which were taken from Ref. [11]. One should also note that there is still considerable uncertainty in the experimental width measurements. As in the case of the $D_1$ states, the radiative transitions to $D_s$ and $D_s^*$ can be used to constrain the $^3P_1 - ^1P_1$ ($c\bar{s}$) mixing angle using eqn. 7.

The problem with the newly found $D_{sJ}$ states are the mass predictions. Once the masses are fixed the narrow widths follow. As a first step to understanding the discrepancy between quark model predictions and the observed masses we revisited the relativized quark model [20] to see if the observed masses could be accommodated with a change of the model’s parameters. We were not able to find a set of parameters that could accommodate the masses of the new states while at the same time preserving the successful mass predictions of the model.

A possible solution, long suggested in the literature, is that the strong $S$-wave coupling of the $D_{sJ}^{(*)}$ states to the $DK$ ($D^*K$) decay channel (and the nearness to the $D_s^{(*)}K$ thresholds) shifts the respective masses [11, 12, 44, 45, 46]. Including these coupled channel effects, van Beveren Rupp and Kleefeld [11, 46], Hwang and Kim [42], Simonov and Tjon [47], and Becirevic Fahr and Prelowski [44] are able to explain the low $D_{sJ}^{(*)}(2317)$ and $D_{sJ}(2460)$ masses. However, others found that when more and more intermediate states are included the mass of the state is not stable [32]. It was also found that coupled channel effects appear to lead to comparable shifts in states that were previously in

### TABLE IV: Partial widths and branching ratios for E1 transitions between 1P and 1S charmed mesons. The $M_i$ and the total widths used to calculate the BR’s are taken from Table I. The matrix elements are calculated using the wavefunctions of Ref. [20]. To calculate the BR’s we used the following total widths: for the $D_2^{0*}$ and $D_3^{0*}$ the averages given in Table I, for $D_1^*$ and $D_1^0$ the average for the $D_1^0$ given in Table I, and for the $D_1^+$ and $D_6^0$ the predicted widths given in Table III.

| Initial state | Final state | $M_i$ (MeV) | $M_f$ (MeV) | $k$ (MeV) | $\langle 1P|\tau|nS \rangle$ (GeV$^{-1}$) | Width (keV) | BR |
|---------------|-------------|-------------|-------------|-----------|--------------------------------|-------------|-----|
| $D_2^{0*}$    | $D^0\gamma$ | 2466        | 2010        | 414       | 2.367                                           | 59          | 2.0 $\times 10^{-3}$ |
| $D_2^{0*}$    | $D^0\gamma$ | 2463        | 2007        | 414       | 2.367                                           | 572         | 1.3 $\times 10^{-2}$ |
| $D_2^+$       | $D^0\gamma$ | 2422        | 1869        | 377       | 2.367                                           | 490         | 2.9 $\times 10^{-3}$ |
| $D_2^0$       | $D^0\gamma$ | 2420        | 1869        | 490       | 2.028                                           | 2.028       | 85          |
| $D_2^0$       | $D^0\gamma$ | 2422        | 1869        | 377       | 2.367                                           | 574         | 2.8 $\times 10^{-2}$ |
| $D_2^+$       | $D^0\gamma$ | 2420        | 1869        | 378       | 2.367                                           | 491         | 1.4 $\times 10^{-3}$ |
| $D_2^0$       | $D^0\gamma$ | 2420        | 1869        | 378       | 2.367                                           | 135         | 5.5 $\times 10^{-4}$ |
| $D_2^+$       | $D^0\gamma$ | 2359        | 2010        | 323       | 2.345                                           | 274         | 9.9 $\times 10^{-4}$ |
good agreement with experiment. It was suggested that including these virtual meson loops has, to a large extent, the effect of “renormalizing” the string tension except near thresholds. The exception to this result is for the low lying 0++ states where Geiger and Isgur found that loop effects manifest themselves as large shifts in the masses. Isgur suggested that this was due to S-wave channels having a cusp discontinuity at threshold. For the mass shifts depend on the position of the valence mass relative to threshold. For the mass shifts in the pseudoscalars. This is van Beveren and Rupp’s explanation of the states where Geiger and Isgur found that the shifts are rather modest, of order tens of MeV and that the loop effects result in weak binding of the pseudoscalars. This was also noted by Kalashnikova. The resulting threshold expects a large negative shift. We should stress, however, that other calculations applied to scalar meson masses find that the shifts are rather modest, of order tens of MeV and that the loop effects result in weak binding of the pseudoscalars. This is van Beveren and Rupp’s explanation of the states. One concludes that one way or another the strong S-wave coupling to the states with a nearby threshold is the likely solution to the puzzle, but it is not clear what the exact mechanism is, nor has this been unquestionably demonstrated. To do so one would have to demonstrate not only that the contributions to the states converge, but that one can successfully explain all states including those that are already well described by the constituent quark model. In other words, states that are well described remain so and the agreement of others improves.

IV. SUMMARY

To summarize, we found that the charmed P-wave 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. In particular, measuring the radiative decay BR’s of the D_s(2420) measures the P^+ mixing angle and is a good test of the HQL. In contrast, 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. We suggest that the strong S-wave coupling of the states to DK (and D^0 K) is the key to the unusual properties of the new light D_{sJ} mesons but further work is needed for a definitive answer. Radiative transitions are important diagnostic tests of the nature of these states and should be pursued.

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TABLE V: Comparison of predicted and measured charm-strange P-wave meson properties. The BR’s are based on the theoretical values for the partial widths. Experimental numbers come from the PDG. The theoretical predictions come from Ref. except for the strong decay widths of the $D_s^*$ which comes from Ref. rescaled for the correct phase space.

| State | Property | Expt.       | Theory       | BR |
|-------|----------|-------------|--------------|----|
| $D_{s1}^{*}$ | Mass (MeV) | 2537.5 ± 1.7 | 2574         |    |
|       | $\Gamma(D_{s1}^{*} \to D^* K)$ (MeV) | 1           |              |    |
|       | $\Gamma(D_{s1}^{*} \to DK)$ (MeV) | 20          |              |    |
|       | $\Gamma(D_{s1}^{*} \to D_s\gamma)$ (keV) | 19          | ~ $1.3 \times 10^{-3}$ |    |
|       | $\Gamma_{total}$ (MeV) | $15_{-4}^{+5}$ | 21          |    |
| $D_{s1}$ | Mass (MeV) | 2535.3 ± 0.31 | 2535        |    |
|       | $\Gamma(D_{s1} \to D^* K)$ (keV) | 340°         | 97%         |    |
|       | $\Gamma(D_{s1} \to D_s\gamma)$ (keV) | 5.6         | 1.6%        |    |
|       | $\Gamma(D_{s1} \to D_s\gamma)$(keV) | 15          | 4.2%        |    |
|       | $\Gamma_{total}$ (keV) | < 2300 (90% CL) | 371         |    |
| $D_{s1}^{*}(2.463)$ | Mass (MeV) | 2458.9 ± 0.9 | 2487.5  |    |
|       | $\Gamma(D_{s1}^{*} \to D_s\gamma)$ (keV) | 5.5         | 24%        |    |
|       | $\Gamma(D_{s1}^{*} \to D_s\gamma)$ (keV) | 6.2         | 27%        |    |
|       | $\Gamma(D_{s1}^{*} \to D_s\pi^0)$ (keV) | 10          | 43%        |    |
|       | $\Gamma(D_{s1}^{*} \to D_s\pi^0)$ (keV) | ~ 10        | 7%         |    |
|       | $\Gamma(D_{s1}^{*} \to D_s\pi^0)$ (keV) | < 0.16 (90% CL) | 0.55      |    |
|       | $\Gamma(D_{s1}^{*} \to D_s\pi^0)$ (keV) | 0.31 ± 0.06 | 0.62       |    |
|       | $\Gamma(D_{s1}^{*} \to D_s\pi^0)$ (keV) | 0.14 ± 0.045 | 0.16       |    |
| $D_{s0}^{*}(2317)^+$ | Mass (MeV) | 2317.3 ± 0.6 | 2317.3  |    |
|       | $\Gamma(D_{s0}^{*} \to D_s\gamma)$ (keV) | 1.9         | ~ 16%      |    |
|       | $\Gamma(D_{s0}^{*} \to D_s\pi^0)$ (keV) | ~ 10        | ~ 84%      |    |
|       | $\Gamma(D_{s0}^{*} \to D_s\pi^0)$ (keV) | < 0.05 (90% CL) | 0     |    |
|       | $\Gamma(D_{s0}^{*} \to D_s\pi^0)$ (keV) | < 0.05 (90% CL) | ~ 0.19 |    |

*The PDG gives $\Gamma < 2.3$ MeV 90% C.L.. We used the width given in Ref. rescaled for phase space.

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