Testing the Nature of the $D_{sJ}^*(2317)^+$ and $D_{sJ}^*(2463)^+$ States Using Radiative Transitions

Stephen Godfrey*

Ottawa-Carleton Institute for Physics
Department of Physics, Carleton University,
Ottawa, Canada K1S 5B6

and

Special Research Centre for the Subatomic Structure of Matter
University of Adelaide,
Adelaide South Australia 5000, Australia

(Dated: March 25, 2022)

The Babar and CLEO collaborations have recently observed states decaying to $D_s^+\pi^0$ and $D_s^+\pi^0$ respectively and suggest the possible explanation that they are the missing P-wave $c\bar{s}$ states with $J^P = 0^+ \text{ and } 1^+$. In this note we compare the properties of the $D_{sJ}^*(2317)^+$ and $D_{sJ}^*(2463)^+$ states to those expected of the $c\bar{s}$ $D_{s0}^*$ and $D_{s1}^*$ states. We expect the $D_{s0}^*$ and $D_{s1}^*$ with the reported masses to be extremely narrow, $\Gamma \sim \mathcal{O}(10 \text{ keV})$, with large branching ratios to $D_s^*\gamma$ for the $D_{s0}^*$ and to $D_s^*\gamma$ and $D_{s1}^*\gamma$ for the $D_{s1}^*$. Crucial to this interpretation of the Babar and CLEO observations is the measurement of the radiative transitions. We note that it may be possible to observe the $D_{sJ}(2536)$ in radiative transitions to the $D_s^*$. 

PACS numbers: 12.39.-x, 13.20.Fc, 13.25.Ft, 14.40.Lb

I. INTRODUCTION

Over the last decade there has been considerable progress in our understanding of mesons, strongly interacting bound states of quarks and antiquarks. Mesons made of one heavy and one light quark have played an important role [1]. However the theoretical predictions have not been sufficiently tested by experimental data to say that we truly understand the strong interaction. This situation has recently been highlighted by the discovery of a state, the $D_{sJ}^*(2317)^+$, with mass 2317 MeV decaying to $D_s^+\pi^0$ by the Babar Collaboration at the Stanford Linear Accelerator Center (SLAC) [2] and a second state, the $D_{sJ}^*(2463)^+$, with mass 2463 GeV decaying to $D_s^+\pi^0$ by the CLEO Collaboration at the Cornell Electron Storage Ring [3]. These states have also been observed by the Belle Collaboration at KEK [5]. The $D_{sJ}^*(2317)^+$ was observed in the inclusive $D_s^+\pi^0$ invariant mass distribution [2]. The state has natural spin-parity and the Babar collaboration suggest it to be a $J^P = 0^+$ state based on its low mass. The quantum numbers of the final state indicate that the decay violates isospin conservation. Babar found no evidence for the decay $D_{sJ}^*(2317)^+ \to D_s^+\pi^0 \gamma$ or $D_s^+\gamma$ and although they found no evidence for the decay $D_{sJ}^*(2317)^+ \to D_s^+\gamma$ they see a peak near 2.46 GeV in the $D_s^+\pi^0\gamma$ mass distribution but do not claim this as evidence for a new state.

The CLEO collaboration subsequently reported on a signal in the $D_s^+\pi^0$ channel at a mass of 2463 GeV which they refer to as the $D_{sJ}(2463)^+$ [3]. Because the $D_{sJ}(2463)$ lies above the kinematic threshold to decay to $DK$ but not $D^*K$ the narrow width suggests the decay to $DK$ does not occur. Since angular momentum and parity conservation forbids a $1^+$ state from decaying to two pseudoscalars, CLEO suggests the comaptability of the $D_{sJ}(2463)$ with the $J^P = 1^+$ hypothesis. CLEO puts limits on the widths of the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2463)^+$ of $\Gamma < 7 \text{ MeV} \text{ at } 90\% \text{ C.L.}$ [2]. More importantly for the purpose of this analysis, they give limits on radiative transitions of the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2463)^+$ to $D_s^*\gamma$ and $D_{sJ}^*\gamma$ final states.

The simplest interpretation is to identify these states as the missing $j = 1/2$ members of the $c\bar{s}L = 1$ multiplet where $j = 1/2$ is the angular momentum of the $s$-quark. The observation of these states is surprising because they are narrower than expected, are observed in isospin violating $D_{sJ}^*\pi^0$ and $D_{sJ}^*\pi^0$ final states, and are lower in mass than expected by most (but not all) calculations [6, 7, 8, 9, 10, 11, 12, 13, 14]. The Babar and CLEO observations have led to conflicting interpretations. Although the observed mass for the $D_{s0}$ candidate (the $J^P = 0^+$ member of the ground state $L = 1$ $c\bar{s}$ multiplet) is consistent with some predictions of chiral quark models [11, 12, 13] in which broken chiral symmetry views them as the positive-parity partners of the $D_s^*$ and $D_s^*$ states, it is considerably lower than expected by most quark models [6, 7, 8, 9, 10, 11] and lattice QCD calculations [12, 13]. This has led to considerable interest in including the proposal that the $D_{sJ}(2317)^+$ is a multiquark state [11, 12, 13], possibly a $DK$ molecule analogous to the $KK$ interpretation of the $f_0(980)$ and $a_0(980)$.

In this letter we confront the $c\bar{s}L = 1 D_{s0}^*$ and $D_{s1}^*$ interpretations of these states with the theoretical exp-
tations for conventional $c\bar{s}$ states.

II. SPECTROSCOPY

Mass predictions are an important test of QCD motivated potential models as well as other calculational approaches for hadron spectroscopy \[12\]. In QCD-motivated potential models the spin-dependent splittings test the Lorentz nature of the confining potential with different combinations of Lorentz scalar, vector,...interactions \[12\]. Furthermore, the observation of heavy-light mesons is an important test of any assignment for a comparison between theory and experiment of the branchings. While the $DK$ and lattice QCD calculations \[12\] in agreement with experiment \[24\]. In contrast, assuming the higher masses predicted by the quark model, \[6\], in agreement with experiment \[24\]. In Table I we summarize predictions for the P-wave $c\bar{s}$ states. The two $J = 1$ states are linear combinations of $3P_1$ and $1P_1$ because for unequal mass quarks, $C$ is no longer a good quantum number. We label these as the $D^+_1$ and $D^+_1$. Most, but not all, models predict the masses of the $D^+_1$ and the missing $D^+_1$ state to be substantially higher than the masses reported by Babar \[2\] and CLEO \[3\]. Although it is possible that these models need revision it seems unlikely that they would disagree with experiment to such a large degree given their general success in describing the meson spectrum. A more serious problem is the large discrepancy with lattice QCD calculations which give $M(D^+_1) = 2499(13)(5)$ MeV and $M(D_{s1}(2500)) = 2500(16)(2)$ MeV \[12\]. If the $D^*_s(2317)^+$ and $D^*_{s0}(2463)^+$ are identified as the missing $3P_0(c\bar{s})$ and $P_1(c\bar{s})$ states it would pose a serious challenge for the lattice calculations.

Quark model calculations \[1\] and heavy quark symmetry \[22\] predict that the 4 $L = 1$ $c\bar{s}$ mesons are grouped into two doublets with properties characterized by the angular momentum of the lightest quark, $J = 1/2$ and $j = 3/2$. The $j = 3/2$ states are identified with the previously observed $D_{s0}(2536)^+$ and $D_{s1}(2573)^+$ states \[24\] while the $j = 1/2$ have not previously been observed. The $j = 3/2$ states are predicted to be relatively narrow \[6\], in agreement with experiment \[24\]. In contrast, assuming the higher masses predicted by the quark model, the $j = 1/2$ states are expected to be rather broad, decaing to $DK$ and $D^*K$ respectively with large S-wave widths. The large width is presumed to explain why they have yet to be observed. However, if these states are identified with the recently observed $D_{s0}(2317)$ and $D_{s1}(2463)$ states their masses would be below the $DK$ and $D^*K$ thresholds so that they would be quite narrow, especially for mesons with such high mass.

III. RADIATIVE TRANSITIONS

While masses are one test of models of hadrons, transitions probe the internal structure of the state. Comparison between theory and experiment of the branching ratios is an important test of any assignment for a state. The Babar collaboration observed the $D^*_s(2317)^+$ in the $D_s\pi^0$ final state and report no observation of its decay via radiative transitions \[2\]. The CLEO collaboration put limits on branching ratios of various radiative decays of the $D^*_s(2317)^+$ and $D_{s0}(2463)^+$ relative to $\Gamma(D^*_s(2317)^+ \rightarrow D^+_s\pi^0)$ and $\Gamma(D_{s0}(2463)^+ \rightarrow D^+_s\pi^0)$ respectively \[3\]. Because the $D^*_s(2317)^+$’s mass is below the kinematic threshold for the decay $D_{s0} \rightarrow DK$, the only kinematically allowed strong decay is $D_{s0} \rightarrow D_s\pi^0$. Likewise, the $D_{s0}(2463)$ is kinematically forbidden to decay to its expected dominant decay mode $D_{s1} \rightarrow D^+_sK$ so that the $D_{s1} \rightarrow D^+_s\pi^0$ is expected to be dominant. In both cases the decays $D_{s0} \rightarrow D_s\pi^0$ and $D_{s1} \rightarrow D^+_s\pi^0$ violate isospin and are expected to have quite small partial widths. Thus, the radiative transitions $D^*_s(2317)^+ \rightarrow D^*_s\gamma$ and $D_{s0}(2463)^+ \rightarrow D^*_s\gamma$ would be expected to have prominent branching ratios.

The $E1$ radiative transitions are given by

$$\Gamma(i \rightarrow f + \gamma) = \frac{4}{27} \alpha^2 \langle e_Q \rangle^2 \omega^2 (2J_f + 1) | \langle 2s + 1, 1P_J | r | 2s + 1, 1P_J \rangle |^2 S_{ij}$$

where $S_{ij}$ is a statistical factor with $S_{ij} = 1$ for the transitions between spin-triplet states, $D^*_s(1P) \rightarrow D^*_s\gamma$ and $D_{s0}(2S) \rightarrow D_{s0}(1P)\gamma$, and $S_{ij} = 3$ for the transition between spin-singlet states, $D_{s1} \rightarrow D_s\gamma$, $\langle e_Q \rangle$ is an effective quark charge given by

$$\langle e_Q \rangle = \frac{m_c e_c - m_s e_s}{m_c + m_s}$$

where $e_c = 2/3$ and $e_s = 1/3$ are the charges of the c-quark and s-antiquark given in units of $|e|$, $m_c = 1.628$ GeV, $m_s = 0.419$ GeV are the mass of the c and s quarks taken from Ref. \[3\], $\alpha = 1/137.036$ is the fine-structure constant, and $\omega$ is the photon’s energy. The

| Reference        | $3P_0$ | $D^*_s$ | $D^*_1$ | $3P_1$ |
|------------------|--------|---------|---------|--------|
| Babar \[2\]      | 2.32   |         |         |        |
| CLEO \[3\]       |        | 2.463   |         |        |
| PDG \[24\]       |        | 2.535   | 2.574   |        |
| GI \[5, 6\]      | 2.48   | 2.56    | 2.55    | 2.59   |
| ZVR \[7\]        | 2.38   | 2.52    | 2.51    | 2.58   |
| EGF \[8\]        | 2.508  | 2.569   | 2.515   | 2.560  |
| DE \[9\]         | 2.487  | 2.605   | 2.535   | 2.581  |
| GJ \[10\]        | 2.388  | 2.536   | 2.521   | 2.573  |
| LNR \[11\]       | 2.455  | 2.522   | 2.502   | 2.586  |
| LW [LGT] \[12\]  | 2.499  | 2.511   | 2.500   | 2.554  |
| GB [LGT] \[13\]  | 2.437  |         |         |        |
matrix elements $\langle S|r|P\rangle$, given in Table II, were evaluated using the wavefunctions of Ref. 3. Relativistic corrections are included in the $E1$ transition via Siegert’s theorem. 25, 26, 27 by including spin dependent interactions in the Hamiltonian used to calculate the meson masses and wavefunctions. To calculate the appropriate photon energies the PDG 24 values were used for observed mesons while the predictions from Ref. 2 were used for unobserved states with the following modifications. While splittings between $c\bar{s}$ states predicted by Ref. 2 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 II have been adjusted lower by 18 MeV from the predictions of Ref. 2.

For the $D_{s0}$ and $D_{s1}$ states we give one set of predictions using the Babar and CLEO masses and a second set of predictions using the quark model mass predictions of Ref. 3.

A final subtlety is that the $J = 1$ states are linear combinations of $^3P_1$ and $^1P_1$ because for unequal mass quarks, $C$ is no longer a good quantum number. Thus,

$$D_{s1}^{3/2} = P_1 \cos \theta + P_1 \sin \theta$$
$$D_{s1}^{1/2} = -P_1 \sin \theta + P_1 \cos \theta$$

we use $\theta = -38^\circ$ and the conventions of Ref. 6 in calculating the widths in Table II which include the appropriate factors of $\cos^2 \theta$ and $\sin^2 \theta$ as appropriate. The resulting widths are given in Table II.

In addition to the $E1$ transitions the $M1$ transitions $D_{s1} \to D_{s0} \gamma$ can also take place. However, we found these partial widths to be quite small and unlikely to be observable.

IV. STRONG TRANSITIONS

The transition $D_{s0} \to D_{s} \pi^0$ is expected to be quite small as it violates isospin. Although there are a number of theoretical predictions for hadronic transitions between quarkonium levels 20, 31, 32, 33 we know of none for the transition $D_{s0} \to D_{s} \pi^0$. To estimate this partial width we turn to known transitions and use existing theoretical calculations for guidance. This approach should at least help us gauge the relative importance of this partial width. The only measured transition is $\psi(2S) \to J/\psi(1S) + \pi^0$ with $B = 9.7 \times 10^{-4}$ 24 implying $\Gamma(\psi' \to J/\psi + \pi^0) = 0.27$ keV. A limit exists on the transition $\Upsilon(2S) \to \Upsilon(1S) + \pi^0$ of $B(\Upsilon(2S) \to \Upsilon(1S)\pi^0) < 1.1 \times 10^{-3}$ 90% C.L. implying $\Gamma(\Upsilon(2S) \to \Upsilon(1S)\pi^0) < 0.05$ keV 24. The BR for the transition $D_{s}^* \to D_{s} + \pi^0$ is $5.8 \pm 2.5\%$ but the total width is not known. We can estimate the width by using the measured branching ratio $B(D_{s}^* \to D_{s} \gamma) = (94.2 \pm 2.5\%)$ with a quark model calculation of the radiative transition $D_{s}^* \to D_{s} \gamma$. Combining the partial width given by Ref. 3 of $\Gamma(D_{s}^* \to D_{s} \gamma) = 0.125$ keV with the measured branching ratio 24 gives $\Gamma(D_{s}^* \to D_{s} \pi^0) \approx 7.7$ eV. For comparison Goity and Roberts 28 obtain $\Gamma(D_{s}^* \to D_{s} \gamma) = 0.165$ keV giving $\Gamma(D_{s}^* \to D_{s} \pi^0) = 10$ eV (for the $\kappa = 0.45$ solution) and Ebert et al. 8 find $\Gamma(D_{s}^* \to D_{s} \gamma) = 0.19$ keV giving $\Gamma(D_{s}^* \to D_{s} \pi^0) = 12$ eV.

For our first attempt to estimate $\Gamma(D_{s0} \to D_{s} \pi^0)$ we rescale $\Gamma(D_{s0} \to D_{s} \pi^0)$ assuming a $k_2^2$ dependence for the partial widths and find $\Gamma(D_{s0} \to D_{s} \pi^0) \approx 2$ keV. One should take this estimate with a grain of salt as the $D_{s}^* \to D_{s} \pi^0$ is an $S \to S$ transition with the final states in a relative $P$-wave while the $D_{s0} \to D_{s} \pi^0$ transition is a $P \to S$ transition with the final states in a relative $S$-wave so there are wavefunction effects we have totally ignored in addition to a generally cavalier attitude to kinematic factors. All we have attempted to do is establish the order of magnitude.

A more relevant starting point is the transition $h_c(1P_1) \to J/\psi \pi^0$ which is a $P \to S$ spin-flip transition which proceeds via the $E1 - M1$ interference term in a multipole expansion of the gluonic fields, similar to the $^3P_0 \to ^1S_0$ transition we are attempting to estimate. Ko estimates $\Gamma(h_c \to J/\psi \pi^0) \approx 2.5$ keV 33. This transition is related to the transition $\psi' \to h_c \pi^0$ 33, 34 for which Ko 33 obtains $B(\psi' \to h_c \pi^0) = 3 \times 10^{-3}$. For comparison Voloshin 30 finds $B(\psi' \to h_c \pi^0) = 10^{-3}$ so that we should assume a factor of 3 in uncertainty. These transitions are proportional to the pion momentum so that by rescaling the estimate of $\Gamma(h_c \to J/\psi \pi^0)$ we find $\Gamma(D_{s0} \to D_{s} \pi^0) \approx 2$ keV. There are two important uncertainties in this estimate. The first is that the matrix elements are proportional to $\langle S|r|P\rangle$. Using the wavefunctions of Ref. 3 we find $\langle 1^3P_0|r|1^3S_0\rangle_{cs}/\langle 1^3S_1|r|1^3P_1\rangle_{cc} = 1.1$. The second uncertainty is that the matrix elements are $O(\alpha_s)$ so that the ratio of the widths go like $(\alpha_s(c\bar{s}))/\alpha_s(c\bar{c})$ which, given that the relevant energy scale is the light quark mass, could contribute an additional factor of 4 in the width. Given these uncertainties we estimate that $\Gamma(D_{s0}^* \to D_{s} \pi^0) \approx 10$ keV. We expect similar rates for the decays $D_{s1} \to D_{s}^* \pi^0$ 34. In addition to the one-pion decay modes, the $D_{s1}$ state can decay via two-pion transitions to the $D_{s}$ state. (The decay $D_{s0} \to D_{s} \pi^0$ is forbidden by parity conservation.) Using Ko’s estimate of the ratio $\Gamma(h_c \to J/\psi + \pi^0)/\Gamma(h_c \to J/\psi + \pi^0) \approx 0.16$ 33 we estimate $\Gamma(D_{s1} \to D_{s} \pi\pi) \approx 1.6$ keV. The resulting partial widths and branching ratios are summarized in Table II.

For comparison we also include in Table II the partial widths and branching ratios expected for the $1^3P_0(c\bar{s})$ state with mass 2.466 MeV and the $D_{s1}^{1/2}$ state with mass 2.536 MeV. The dominant decays for these masses are $D_{s0} \to DK$ and $D_{s1}^{1/2} \to D^*K$ with large partial widths. Although there is considerable uncertainty in the estimate of these widths 3, 37 we do expect the $D_{s0}$ and $D_{s1}^{1/2}$ states with these masses to be rather broad with small branching ratios for the radiative transition. These decays are S-wave so the widths scale linearly with the decay products momentum.
For completeness we also include in Table II other E1 transitions involving the $c\bar{s}$ P-wave states. We note that the $D_{s1}(2536)^+$ should have a relatively large branching ratio for its radiative transition to $D^*_s\gamma$ so that it may be possible to observe the $D_{s1}(2536)^+$ in this mode.

CLEO has obtained 90% C.L. limits on radiative transitions of the $D_{sJ}^*(2317)$ and $D_{sJ}(2463)$ which we summarize along with our predictions in Table III.

V. OTHER POSSIBILITIES

If the radiative transitions are not observed with BR’s consistent with those of the conventional $D_s^0$ and $D_s^1$ states what are the alternatives? One possibility suggested by the Babar collaboration is that the $D_{sJ}^*(2317)^+$ is some sort of multiquark state, either a $DK$ molecule or a $c\bar{q}q\bar{s}$ multiquark object. This seems to be a likely possibility which has much in common with the description of the $f_0(980)$ and $a_0(980)$ as multiquark states: The $D_{sJ}^*(2317)^+$ lies just below the $DK$ threshold while the $f_0(980)/a_0(980)$ lie just below the $KK$ threshold and both couple strongly to these nearby channels. This explanation has been promoted by Barnes, Close and Lipkin [20] and is supported by a recent dynamical calculation by van Beveren and Rupp [21]. Likewise, the $D_{sJ}(2463)$ could be a $D^*K$ bound state similar to the $K^*K$ molecule interpretation advocated as the solution to the longstanding $E/\ell$ puzzle [36].

VI. CONCLUSIONS

The discovery of the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2463)$ has presented an interesting puzzle to meson spectroscopists. The Babar and CLEO collaborations believe that they may be the missing $J^P = 0^+$ and $1^+$ members of the $L = 1(c\bar{s})$ multiplet. However their masses are significantly lower than expected by most models and also lattice QCD calculations and would pose a serious challenge to these calculations. It is therefore important to test these assignments. If the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2463)$ are conventional $D_s^0$ and $D_s^{1/2}$ ($c\bar{s}$) states we have argued that they should have very small total widths, $\mathcal{O}(10)$ keV, with large branching ratios to $D^*_s\gamma$ (and $D_s\gamma$ for the $D_{s1}^{1/2}$). It is therefore important to make a better determination of the total width of these states and to search for the radiative transitions. In contrast, the absence of the radiative transitions and a relatively large total width of $\mathcal{O}(MeV)$ would support the $D_s^{(*)}K$ molecule designations. In this case the conventional $D_s^0$ and $D_s^{1/2}$ states have yet to be discovered, presumably due to their large width. However, observation of their non-strange partners by the Belle collaboration [37] with their expected properties leads us to be hopeful that they can be found.

Acknowledgments

The author thanks Ted Barnes and Sheldon Stone for useful comments and suggestions and Frank Close, Randy Lewis, and Jon Rosner for helpful communications. This research was supported in part by the Natural Sciences and Engineering Research Council of Canada.

[1] J. Bartelt and S. Shukla, Ann. Rev. Nucl. Part. Sci. 45, 133 (1995).
[2] B. Aubert et al. [BABAR Collaboration], arXiv:hep-ex/0304021.
[3] D. Besson et al. [CLEO Collaboration], arXiv:hep-ex/0305100.
[4] T. Browder [Belle Collaboration], talk given at the 8th Conference on the Intersections of Particle and Nuclear Physics (19 - 24, May 2003, New York, USA).
[5] S. Godfrey and N. Isgur, Phys. Rev. D 32 (1985) 189.
[6] S. Godfrey and R. Kokoski, Phys. Rev. D 43, 1679 (1991).
[7] J. Zeng, J. W. Van Orden and W. Roberts, Phys. Rev. D 52, 5229 (1995) arXiv:hep-ph/9412269.
[8] D. Ebert, V. O. Galkin and R. N. Faustov, Phys. Rev. D 57, 5663 (1998) [Erratum-ibid. D 59, 019902 (1999)] arXiv:hep-ph/9712318.
[9] M. Di Pierro and E. Eichten, Phys. Rev. D 64, 114004 (2001) arXiv:hep-ph/0104208.
[10] S. N. Gupta and J. M. Johnson, Phys. Rev. D 51, 168 (1995) arXiv:hep-ph/9409432.
[11] T. A. Lahde, C. J. Nyfalt and D. O. Riska, Nucl. Phys. A 674, 141 (2000) arXiv:hep-ph/9908485.
[12] R. Lewis and R. M. Woloshyn, Phys. Rev. D 62, 114507 (2000); Nucl. Phys. Proc. Suppl. 94, 359 (2001).
[13] G. S. Bali, arXiv:hep-ph/0305209.
[14] W. A. Bardeen, E. J. Eichten and C. T. Hill, arXiv:hep-ph/0305049.
[15] M. A. Nowak, M. Rho and I. Zahed, Phys. Rev. D 48, 4370 (1993) arXiv:hep-ph/9209272; M. A. Nowak and I. Zahed, Phys. Rev. D 48 (1993) 356; W. A. Bardeen and C. T. Hill, Phys. Rev. D 49, 409 (1994) arXiv:hep-ph/9304263.
[16] R.N. Cahn and J.D. Jackson, arXiv:hep-ph/0305012.
[17] H. Y. Cheng and W. S. Hou, arXiv:hep-ph/0305038.
[18] A.P. Szczepaniak, arXiv:hep-ph/0305060.
[19] P. Colangelo and F. De Fazio, arXiv:hep-ph/0305140.
[20] T. Barnes, F. E. Close and H. J. Lipkin, arXiv:hep-ph/0305025.
[21] E. van Beveren and G. Rupp, arXiv:hep-ph/0305035.
[22] N. Isgur and M. B. Wise, Phys. Rev. Lett. 66, 1130 (1991).
TABLE II: Predictions for partial widths and branching ratios for E1 transitions $2S \rightarrow 1P$ and $1P \rightarrow 2S$ and strong decays in the $D_s$ meson sector. For the $D_{s0}^\ast$ and $D_{s1}^{1/2\ast}$ states we show results for two sets of assumptions. In the first we associate the newly observed $D_{sJ}(2317)$ and $D_{sJ}(2.463)$ with the $D_{s0}^\ast$ and $D_{s1}^{1/2\ast}$ while in the second we show partial widths using the quark model predictions for these state’s masses. For decays involving the $D_{s1}$ states we include the appropriate $\cos^2 \theta$ and $\sin^2 \theta$ factors corresponding to eqn. 3 in the partial widths. The widths are given in keV unless otherwise noted. The masses come from the PDG [22] unless otherwise noted.

| Initial state | Final state | $M_i$ (GeV) | $M_f$ (GeV) | $k$ (MeV) | $\langle 1P|\gamma|nS \rangle$ | Width (keV) | BR |
|---------------|-------------|-------------|-------------|-----------|-------------------|-------------|-----|
| $D_{s0}^\ast(2317)^\pm$ | $D_s^+ \gamma$ | 2.317$^a$ | 2.112 | 196 | 2.17$^b$ | 1.9 | $\sim 16\%$
| | $D_s^0$ | 2.317$^a$ | 1.968 | 297 | $\sim 10$ | $\sim 84\%$
| $D_{s0}^\ast(2466)^+$ | $D_s^+ \gamma$ | 2.466$^c$ | 2.112 | 329 | 2.17$^b$ | 9.0 | $3 \times 10^{-5}$
| | $DK$ | 2.466$^c$ | 289 | $\sim 100\%$
| $D_{s1}^{1/2}(2.463)$ | $D_s^+ \gamma$ | 2.463$^c$ | 2.112 | 326 | 2.18$^b$ | 5.5 | 24%
| | $D_s^0$ | 2.463$^c$ | 1.968 | 297 | $\sim 10$ | 43%
| | $D_s \pi\pi$ | 2.463$^c$ | 1.968 | 297 | $\sim 1.6$ | 7%
| $D_{s1}(2.536)$ | $D_s^+ \gamma$ | 2.536$^c$ | 2.112 | 388 | 2.18$^b$ | 9.2 | $7 \times 10^{-5}$
| | $D^* K$ | 2.536$^c$ | 384 | $\sim 100\%$
| | $D_s^0$ | 2.536$^c$ | 1.968 | 504 | 1.86$^b$ | 9.0 | $7 \times 10^{-5}$
| $D_{s2}^+$ | | 2.574 | 2.112 | 420 | 2.17$^b$ | 19 | $\sim 1.3 \times 10^{-3}$
| $D_{s1}^{1/2}$ | $D_s^+ \gamma$ | 2.535 | 2.112 | 388 | 2.18$^b$ | 5.6 | 1.6%
| | $D^* K$ | 2.535 | 382 | 340$^g$ | 97 %
| | $D_s^0$ | 2.535 | 1.968 | 503 | 1.86$^b$ | 15 | 4.2%
| $D^*(2S)$ | $D_s^+ \gamma$ | 2.714$^c$ | 2.574 | 136 | 2.60$^b$ | 1.5 |
| | $D_s^{3/2}\gamma$ | 2.714$^c$ | 2.535 | 173 | 2.25$^b$ | 0.5 |
| | $D_s^{1/2}(2.536)\gamma$ | 2.714$^c$ | 2.536$^c$ | 172 | 2.25$^b$ | 0.9 |
| | $D_s^{1/2}(2.463)\gamma$ | 2.714$^c$ | 2.463$^c$ | 239 | 2.25$^b$ | 2.3 |
| | $D_s^0\gamma$ | 2.714$^c$ | 2.466$^c$ | 237 | 1.95$^b$ | 0.9 |
| | $D_{s0}\gamma$ | 2.714$^c$ | 2.317$^a$ | 368 | 1.95$^b$ | 3.4 |

$^a$From Babar Ref. [2].
$^b$Obtained using the wavefunctions generated from Ref. [3].
$^c$Masses taken from Ref. [2] with the modification that the predictions have been adjusted downward by 18 MeV to give better agreement with the measured masses. The masses in Ref. [2] were rounded to 10 MeV. Here we round to 1 MeV.
$^d$Obtained by rescaling the result of Ref. [3] by phase space.
$^e$From CLEO Ref. [3].
$^f$Based on the PDG total width for the $D_{sJ}(2573)^\pm$ [22].
$^g$The PDG gives $\Gamma < 2.3$ MeV 90% C.L. We used the width given by Ref. [3] rescaled for phase space.

TABLE III: Comparison of 90% C.L. limits on radiative transitions obtained by CLEO [3] with the predictions given in Table II. The BR’s are with respect to the decay $D_{s0}^\ast(2317) \rightarrow D_s \pi^0$ for the $D_{sJ}^{1/2}(2317)$ and with respect to the decay $D_{s1}^{1/2}(2.463) \rightarrow D_s^+ \pi^0$ for the $D_{sJ}(2463)$.

| Transition | Predicted | CLEO [3] |
|------------|-----------|-----------|
| $D_{sJ}^{1/2}(2317) \rightarrow D_s^+ \gamma$ | 0.19 | < 0.059 |
| $D_{sJ}(2317) \rightarrow D_s^+ \gamma$ | 0 | < 0.052 |
| $D_{sJ}(2.463) \rightarrow D_s^+ \gamma$ | 0.55 | < 0.16 |
| $D_{sJ}(2.463) \rightarrow D_s^+ \gamma$ | 0.62 | < 0.49 |
| $D_{sJ}(2.463) \rightarrow D_{sJ}^{1/2}(2317) \gamma$ | $1.2 \times 10^{-3}$ | < 0.58 |

[23] E. J. Eichten, C. T. Hill and C. Quigg, Phys. Rev. Lett. 71, 4116 (1993) [arXiv:hep-ph/9308337].
[24] Particle Data Group, K. Hagiwara et al., Phys. Rev. D66, 010001 (2002).
[25] A. J. Siegert, Phys. Rev. 52, 787 (1937).
[26] R. McClary and N. Byers, Phys. Rev. D 28, 1692 (1983).
[27] P. Moxhay and J. L. Rosner, Phys. Rev. D 28, 1132 (1983).
[28] J.L. Goity and W. Roberts, Phys. Rev. D 64, 094007 (2001).
[29] P. L. Cho and M. B. Wise, Phys. Rev. D 49, 6228 (1994) [arXiv:hep-ph/9401301].
[30] M. B. Voloshin, Sov. J. Nucl. Phys. 43, 1011 (1986); M. B. Voloshin and V. I. Zakharov, Phys. Rev. Lett. 45, 688 (1980).
[31] B.L. Ioffe and M.A. Shifman, Phys. Lett. **95B**, 99 (1980); V.A. Novikov and M.A. Shifman, Z. Phys. **C8**, 43 (1981); M.B. Voloshin, [hep-ph/0302261](http://arxiv.org/abs/hep-ph/0302261).

[32] Y. P. Kuang and T. M. Yan, Phys. Rev. **D24**, 2874 (1981); T. M. Yan, Phys. Rev. **D22**, 1652 (1980); Y. P. Kuang, S. F. Tuan and T. M. Yan, Phys. Rev. **D37**, 1210 (1988).

[33] P. Ko, Phys. Rev. **D52**, 1710 (1995).

[34] See also Ref. [19] and Ref. [14].

[35] A discussion about uncertainties in these decay models appears in H.G. Blundell and S. Godfrey Phys. Rev. **D53**, 3700 (1996).

[36] For a discussion of this puzzle see S. Godfrey and J. Napolitano, Rev. Mod. Phys. **71**, 1411 (1999) [arXiv:hep-ph/9811410](http://arxiv.org/abs/hep-ph/9811410).

[37] K. Abe et al., [Belle Collaboration], contributed paper to the XXXI International Conference on High Energy Physics (24 - 31 July 2002, Amsterdam, The Netherlands) BELLE-CONF-0235.