

A Canonical D_s Spectrum

Eric S. Swanson

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA 15260.

E-mail: swansone@pitt.edu

Abstract. Quark mass dependence induced by one loop corrections to the Breit-Fermi spin-dependent one gluon exchange potential permits an accurate determination of heavy-light meson masses. Thus the $D_s(2317)$ is a canonical $c\bar{s}$ meson. Good agreement is also obtained with the properties of two recently announced D_s mesons identified as $D_{s0}(2860) = c\bar{s}(2P)$ and $D_s^*(2700) = c\bar{s}(2S; {}^3S_1)$.

1. Introduction

BaBar's discovery of the $D_s(2317)$ state[1] generated strong interest in heavy meson spectroscopy, chiefly due to its surprisingly low mass with respect to expectations. The $D_s(2317)$ lies some 160 MeV below most model predictions[2], leading to speculation that the state could be a DK molecule[3] or a tetraquark[4]. Such speculation is supported by the isospin violating discovery mode of the $D_s(2317)$ and the proximity of the S-wave DK threshold at 2358-2367 MeV. Other studies have been made with QCD sum rules[5], using heavy quark symmetry to examine decay models[6], or in unitarised chiral models[7].

Although these proposals have several attractive features, it is important to exhaust possible canonical $c\bar{s}$ descriptions of the $D_s(2317)$ before resorting to more exotic models. A simple modification to the standard vector Coulomb+scalar linear quark potential model that maintains good agreement with the charmonium spectrum and agrees remarkably well with the D and D_s spectra was proposed in Ref. [8] and is reviewed here.

2. An Enhanced Quark Model and the D_s Spectrum

The quark model explanation of these states rests on P-wave mass splittings induced by spin-dependent interactions. A common model of spin-dependence is based on the Breit-Fermi reduction of the one-gluon-exchange interaction supplemented with the spin-dependence due to a scalar current confinement interaction. The general form of this potential has been computed by Eichten and Feinberg at tree level using Wilson loop methodology. The result is parameterised in terms of four nonperturbative matrix elements, V_i , which can be determined by electric and magnetic field insertions on quark lines in the Wilson loop. Subsequently, Gupta and Radford[9] performed a one-loop computation of the heavy quark interaction and showed that a fifth interaction, V_5 is present in the case of unequal quark masses. The net result is a quark-antiquark interaction that can be written as:

$$V_{q\bar{q}} = V_{conf} + V_{SD} \quad (1)$$

where V_{conf} is the standard Coulomb+linear scalar form:

$$V_{conf}(r) = -\frac{4}{3} \frac{\alpha_s}{r} + br \quad (2)$$

and

$$\begin{aligned} V_{SD}(r) = & \left(\frac{\sigma_q}{4m_q^2} + \frac{\sigma_{\bar{q}}}{4m_{\bar{q}}^2} \right) \cdot L \left(\frac{1}{r} \frac{dV_{conf}}{dr} + \frac{2}{r} \frac{dV_1}{dr} \right) + \left(\frac{\sigma_{\bar{q}} + \sigma_q}{2m_q m_{\bar{q}}} \right) \cdot L \left(\frac{1}{r} \frac{dV_2}{dr} \right) \\ & + \frac{1}{12m_q m_{\bar{q}}} \left(3\sigma_q \cdot \hat{r} \sigma_{\bar{q}} \cdot \hat{r} - \sigma_q \cdot \sigma_{\bar{q}} \right) V_3 + \frac{1}{12m_q m_{\bar{q}}} \sigma_q \cdot \sigma_{\bar{q}} V_4 \\ & + \frac{1}{2} \left[\left(\frac{\sigma_q}{m_q^2} - \frac{\sigma_{\bar{q}}}{m_{\bar{q}}^2} \right) \cdot L + \left(\frac{\sigma_q - \sigma_{\bar{q}}}{m_q m_{\bar{q}}} \right) \cdot L \right] V_5. \end{aligned} \quad (3)$$

Here $L = L_q = -L_{\bar{q}}$, $r = |r| = |r_q - r_{\bar{q}}|$ is the $\bar{Q}Q$ separation and the $V_i = V_i(m_q, m_{\bar{q}}; r)$ are the Wilson loop matrix elements discussed above.

The first four V_i are order α_s in perturbation theory, while V_5 is order α_s^2 ; for this reason V_5 has been largely ignored by quark modellers. The exceptions are Ref. [10], which examines S-wave masses for a variety of heavy-light mesons in a model very similar to that presented here, and the second of Ref. [9], which does not consider scalar confinement contributions to the spin-dependent interaction.

Here it is proposed to take the spin-dependence of Eqn. 3 seriously and examine its effect on low-lying heavy-light mesons. The model can be described in terms of vector and scalar kernels defined by

$$V_{conf} = V + \quad (4)$$

where $V = -4\alpha_s/3r$ is the vector kernel and $S = br$ is the scalar kernel, and by the order α_s^2 contributions to the V_i , denoted by δV_i . Expressions for the matrix elements of the spin-dependent interaction are then

$$\begin{aligned} V_1 &= -S + \delta V_1 \\ V_2 &= V + \delta V_2 \\ V_3 &= V'/r - V'' + \delta V_3 \\ V_4 &= 2\nabla^2 V + \delta V_4 \\ V_5 &= \delta V_5. \end{aligned} \quad (5)$$

Explicitly,

$$\begin{aligned} V_1(m_q, m_{\bar{q}}, r) &= -br - C_F \frac{1}{2r} \frac{\alpha_s^2}{\pi} \left(C_F - C_A \left(\ln \left[(m_q m_{\bar{q}})^{1/2} r \right] + \gamma_E \right) \right) \\ V_2(m_q, m_{\bar{q}}, r) &= -\frac{1}{r} C_F \alpha_s \left[1 + \frac{\alpha_s}{\pi} \left[\frac{b_0}{2} [\ln(\mu r) + \gamma_E] + \frac{5}{12} b_0 - \frac{2}{3} C_A + \frac{1}{2} \left(C_F - C_A \left(\ln \left[(m_q m_{\bar{q}})^{1/2} r \right] + \gamma_E \right) \right) \right] \right] \\ V_3(m_q, m_{\bar{q}}, r) &= \frac{3}{r^3} C_F \alpha_s \left[1 + \frac{\alpha_s}{\pi} \left[\frac{b_0}{2} [\ln(\mu r) + \gamma_E - \frac{4}{3}] + \frac{5}{12} b_0 - \frac{2}{3} C_A + \right. \right. \\ &\quad \left. \left. + \frac{1}{2} \left(C_A + 2C_F - 2C_A \left(\ln \left[(m_q m_{\bar{q}})^{1/2} r \right] + \gamma_E - \frac{4}{3} \right) \right) \right] \right] \end{aligned}$$

$$V_4(m_q, m_{\bar{q}}, r) = \frac{32\alpha_s\sigma^3 e^{-\sigma^2 r^2}}{3\sqrt{\pi}}$$

$$V_5(m_q, m_{\bar{q}}, r) = \frac{1}{4r^3} C_F C_A \frac{\alpha_s^2}{\pi} \ln \frac{m_{\bar{q}}}{m_q}$$

where $C_F = 4/3$, $C_A = 3$, $b_0 = 9$, $\gamma_E = 0.5772$, and the scale μ has been set to 1 GeV.

The hyperfine interaction (proportional to V_4) contains a delta function in configuration space and is normally ‘smeared’ to make it nonperturbatively tractable. This introduces a new parameter that largely subsumes corrections to the hyperfine interaction such as δV_4 . For this reason we choose not to include δV_4 in the model definition of Eqn. 6. Corrections to the remaining terms are included because they retain their perturbative forms.

Predictions of the new model in the D_s sector are summarised in Table 1.

Table 1. D_s Spectrum.

state	mass (GeV)	expt (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	2.688/2.715 (new)
$D_s^*(3^3S_1)$	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 (new)
$D_{s0}(3^3P_0)$	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	

One sees remarkably good agreement with the known D_s spectrum. Similar good agreement is found for the D spectrum (and the good fit to the charmonium spectrum can be maintained by adjusting parameters slightly). Evidently, the new spin-dependence is capable of describing the open charm mesons as canonical states. Detailed examination of the enhanced model is under way (to determine, for example, the relative importance of the new operator, V_5 , and the logarithmic mass terms).

Babar[11] and Belle[12] have recently announced the discovery of two new D_s resonances. The first has a mass of $M(D_{sJ}(2860)) = 2856.6 \pm 1.5 \pm 5.0$ MeV and a width of $48 \pm 7 \pm 10$ MeV and was seen in the DK decay mode. The second was found in B decays in the DK final state and has a Breit-Wigner mass and width of $M = 2715 \pm 11^{+11}_{-14}$ MeV and $\Gamma = 115 \pm 20^{+36}_{-32}$. Note

that the BaBar collaboration also saw a structure in this channel at 2690 MeV. The new states have been assigned to the excited vector and scalar D_s states predicted in the model. Again, the agreement is quite good.

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. [13]. Here we focus on the new states with the results given in Table 2. The predicted total widths are in good agreement with experiment, given the rather large errors. However, the $D_s(2700)$ has not been detected in the D^*K decay mode, which is difficult to understand given its large predicted partial width.

Table 2. Strong Partial Widths for Candidate D_s States.

state (mass)	decay mode	partial width (MeV)	expt (MeV)
$D_s^*(2S)(2688)$	DK	22	
	D^*K	78	
	$D_s\eta$	1	
	$D_s^*\eta$	2	
	total	103	115
$D_{s0}(2P)(2857)$	DK	80	
	$D_s\eta$	10	
	total	90	48

Radiative decays are also useful probes of internal structure. Certainly, the decay vertex is established and the impulse approximation has a long history of success. Unfortunately, the predictions are sensitive to the use of the zero recoil approximation and whether a nonrelativistic reduction of the photon vertex spinors is made. Direct computation shows that nonzero recoil effects can be surprisingly large.

4. Other Open Flavour States

It is, of course, possible to apply the model to other open flavour sectors. Predictions for the lowest mass B , B_s , and B_c states are shown in Table 3.

The bottom flavoured meson spectra of Table 3 have been obtained with the ‘average’ extended model parameters and $m_b = 4.98$ GeV. As with the open charm spectra, a flavour-dependent constant was fit to each pseudoscalar. The second row reports recently measured P-wave B meson masses[14]; these are in reasonable agreement with the predictions of the first row.

A popular model of the D_s mesons is based on an effective lagrangian description of mesonic fields in the chiral and heavy quark limits[15]. Deviations from these limits induce mass splittings which imply that the axial-vector and scalar-pseudoscalar mass differences are the same. Since the premise of this idea has been questioned in Refs. [2, 16], it is of interest to consider this

Table 3. Low Lying Bottom Meson Masses (MeV)

flavour	0^-	1^-	0^+	1^+	1^+	2^+
B	5279	5322	5730	5752	5753	5759
expt	5279	5325	—	$5724 \pm 4 \pm 7$	—	5748 ± 12
B_s	5370	5416	5776	5803	5843	5852
expt	5369.6	5416.6	—	—	—	—
B_c	6286	6333	6711	6746	6781	6797
expt	6286	—	—	—	—	—

mass difference in the present model. As shown in Table 1, these splittings are predicted to be within 1 MeV of each other. The same is also found in the D spectrum. Nevertheless, the near equivalence of these mass differences must be regarded as an accident. Indeed, the B masses given in Table 3 indicate that this relationship no longer holds. It would thus be of interest to find P-wave open bottom mesons (especially scalars). These data will distinguish chiral multiplet models from the model presented here and from more traditional constituent quark models. For example, Godfrey and Isgur claim that the B_0 meson lies between 5760 and 5800 MeV, the B_{s0} mass is 5840-5880 MeV, and the B_{c0} mass is 6730-6770 MeV. Of these, our B_{s0} mass is predicted to be 65-105 MeV lower than the Godfrey-Isgur mass.

Finally, the work presented here may explain the difficulty in accurately computing the mass of the D_{s0} in lattice simulations. If the extended quark model is correct, it implies that important mass and spin-dependent interactions are present in the one-loop level one-gluon-exchange quark interaction. It is possible that current lattice computations are not sufficiently sensitive to the ultraviolet behaviour of QCD to capture this physics. The problem is exacerbated by the nearby, and presumably strongly coupled, DK continuum; which requires simulations sensitive to the infrared behaviour of QCD. Thus heavy-light mesons probe a range of QCD scales and make an ideal laboratory for improving our understanding of the strong interaction.

Acknowledgments

This manuscript is based on talks presented at the Second Workshop of the Topical Group on Hadronic Physics (Nashville) and the Fourth International Conference on Quarks and Nuclear Physics (Madrid). I am grateful to my colleagues, F. Close, O. Lakhina, and C. Thomas for discussions. This work was supported by the U.S. Department of Energy under contract DE-FG02-00ER41135.

References

- [1] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **90**, 242001 (2003);
- [2] For recent reviews of open charm states see E. S. Swanson, Phys. Rept. **429**, 243 (2006) [arXiv:hep-ph/0601110]; P. Colangelo, F. De Fazio and R. Ferrandes, Mod. Phys. Lett. A **19**, 2083 (2004) [arXiv:hep-ph/0407137].
- [3] T. Barnes, F. E. Close and H. J. Lipkin, Phys. Rev. D **68**, 054006 (2003) [arXiv:hep-ph/0305025]. See also A. P. Szczepaniak, Phys. Lett. B **567**, 23 (2003) [arXiv:hep-ph/0305060].
- [4] E. van Beveren and G. Rupp, Phys. Rev. Lett. **91**, 012003 (2003) [arXiv:hep-ph/0305035]; K. Terasaki, Phys. Rev. D **68**, 011501 (2003) [arXiv:hep-ph/0305213]; T. E. Browder, S. Pakvasa, and A. A. Petrov, Phys. Lett. B **578**, 365 (2004) [arXiv:hep-ph/0307054]; L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. Lett. **93**, 212002 (2004) [arXiv:hep-ph/0407017]; Y. Q. Chen and X. Q. Li, Phys. Rev. Lett. **93**, 232001 (2004) [arXiv:hep-ph/0407062]; D. S. Hwang and D. W. Kim, Phys. Lett. B **601**, 137 (2004) [arXiv:hep-ph/0408154]; L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D **71**, 014028 (2005); U. Dmitrasinovic, Phys. Rev. Lett. **94**, 162002 (2005).
- [5] S. Narison, Phys. Lett. B **605**, 319 (2005); Phys. Lett. B **210**, 238 (1988).

- [6] P. Colangelo and F. De Fazio, Phys. Lett. B **570**, 180 (2003) [arXiv:hep-ph/0305140].
- [7] F. K. Guo, P. N. Shen, H. C. Chiang and R. G. Ping, arXiv:hep-ph/0603072; E. E. Kolomeitsev and M. F. M. Lutz, Phys. Lett. B **582**, 39 (2004) [arXiv:hep-ph/0307133].
- [8] O. Lakhina and E. S. Swanson, arXiv:hep-ph/0608011; F. E. Close, C. E. Thomas, O. Lakhina and E. S. Swanson, arXiv:hep-ph/0608139.
- [9] S. N. Gupta and S. F. Radford, Phys. Rev. D **24**, 2309 (1981). J. T. Pantaleone, S. H. H. Tye and Y. J. Ng, Phys. Rev. D **33**, 777 (1986).
- [10] S. N. Gupta, S. F. Radford and W. W. Repko, Phys. Rev. D **28**, 1716 (1983).
- [11] B. Aubert *et al.* [BaBar Collaboration] hep-ex/0607082.
- [12] K. Abe *et al.* [Belle Collaboration], "Observation of a new DsJ meson in B+ $\rightarrow$ D0-bar D0 K+ decays", arXiv:hep-ex/0608031.
- [13] F. E. Close and E. S. Swanson, Phys. Rev. D **72**, 094004 (2005) [arXiv:hep-ph/0505206]. See also S. Godfrey, Phys. Lett. B **568**, 254 (2003) [arXiv:hep-ph/0305122].
- [14] I. Bertram, G. Borissov, M. Doidge, P. Ratoff [DØ Collaboration], "Study of excited B mesons", DØ note 4517 (1 Aug 2004).
- [15] M.A. Nowak, M. Rho, and I. Zahed, Phys. Rev. **D48**, 4370 (1993); W.A. Bardeen and C.T. Hill, Phys. Rev. **D49**, 409 (1994).
- [16] P. Bicudo, "Quark model evidence against D/s*(2317) and D/s*(2460) as chiral partners of standard D/s," arXiv:hep-ph/0512041.