The discovery of the $D_{sJ}^*(2860)$ and $D_{sJ}(2460)$ charm-strange mesons three years ago has triggered a strongly renewed interest in heavy-light mesons, and even meson spectroscopy in general. Especially the $D_{sJ}^*(2317)$ has given rise to many different theoretical efforts (see Ref. [3] for a long though still incomplete list of references). The reason is its surprisingly low mass, some 170 MeV below the predictions of standard relativized constituent quark models for the ground-state scalar $car{s}$ meson (see e.g. Ref. [4]), an assignment that has in the meantime been confirmed by experiment [5]. This discrepancy led several model builders to propose alternative explanations for the $D_{sJ}^*(2317)$, such as a tetraquark or a meson molecule. However, in Ref. [6] we showed how the low mass of the $D_{sJ}^*(2317)$ can be quantitatively understood by taking into account its strong coupling to the nearby $S$-wave $Dar{K}$ channel. This explanation was later supported by Refs. [7] and [8]. Similarly, we explained the $D_{sJ}(2460)$ in Ref. [9] via its strong coupling to the $S$-wave $D^*K$ threshold. The coupled-channel model employed in Ref. [6] had previously been used, with essentially the same parameters, to reproduce the $S$-wave $K\pi$ phase shifts and predict the $K^*_s(800)$ (alias $\kappa$) resonance, later confirmed by experiment [10].

Nevertheless, no consensus has been reached so far on the $D_{sJ}^*(2317)$, in part due to the poor experimental status of the very broad partner charm-nonstrange state, listed as $D_{0}^*(2400)$, but first reported at a mass of 2308 MeV [11] and later also at 2407 MeV [12]. Therefore, a more detailed coupled-channel analysis of charmed scalar mesons is very opportune, also in view of new and heavier states that are expected to be found at B factories. Clearly, for a reliable description of higher resonances, additional decay channels must be accounted for. Thus, in the present Letter, we extend the model of Ref. [6] by including all lowest pseudoscalar-pseudoscalar (PP) and vector-vector (VV) two-meson channels that couple to the scalar $c\bar{s}$ and $c\bar{n}$ ($n = u, d$) systems, in an approach very similar to Ref. [14]. In the latter paper, the coupling to all PP channels allowed to fit the properties of the light scalar mesons $\sigma$, $\kappa$, $a_0(980)$, and $f_0(980)$, such as phase shifts, line-shapes, elasticities, and inelastic amplitudes, obtaining an overall good description of these observables, as well as very reasonable pole positions. In the present investigation, the inclusion of the VV channels as well is crucial to study possible radial excitations, as in the $c\bar{n}$ and $c\bar{s}$ sectors the lowest VV channels open at roughly 2.8 GeV and 2.9 GeV, respectively.

We will first discuss the results and finish this Letter with a short description of the mathematics behind the Resonance-Spectrum Expansion (RSE), which is the framework of our model [15]. In Fig. 1 we show, for the $c\bar{s}$ case, the resulting $S$-wave $DK \to DK$ cross sections. The dashed line refers to the case where only PP channels are included, the solid line to the case where also VV channels are accounted for. We will discuss the latter case. A comparison of differences for the two situations is presented below for the $c\bar{n}$ system.

At energies close to threshold (at 2.363 GeV), the cross sections are large due to the presence of the $D_{sJ}^*(2317)$ bound state just below threshold. For higher total invariant mass ($\sqrt{s}$), the cross sections decrease, however not as fast as expected, due to the presence of a scattering-matrix pole, which we find at $2779 - i333$ MeV. At 2.516 GeV one observes the effect of the opening of the $D_{sJ}\eta$ channel, while at about 2.79 GeV the cross sections almost vanish. The first radial excitation of the $D_{sJ}^*(2317)$ is found with a peak mass of 2847 MeV and a width of 47 MeV, and so is a good candidate for the new BABAR state $D_{sJ}(2860)$ [16], which decays to $DK$ and not to $DK^*$. 

PACS numbers: 14.40.Lb, 14.40.Ev, 13.25.-k, 12.39.Pn

---

**D$_{sJ}(2860)$ as the first radial excitation of the D**$_{s0}^*$**(2317)**

Eef van Beveren
Centro de Física Teórica, Departamento de Física, Universidade de Coimbra, P-3004-516 Coimbra, Portugal

George Rupf
Centro de Física das Interacções Fundamentais, Instituto Superior Técnico, Edifício Ciência, Piso S, P-1049-001 Lisboa, Portugal

(Dated: June 6, 2018)
$D^*K$, having a mass of 2857 MeV and a width of 48 MeV. In our model it is associated with a resonance pole at 2842 – i23.6 MeV. From the inset of Fig. 1 one can judge how well our $D^*_{s0}(2850)$ predicts the line shape of BABAR’s $D_{sJ}(2860)$. There is furthermore some indication that the data need a broad state as well, which might correspond to our pole at 2779 – i233.

In Fig. 2 we show, for the $c\bar{n}$ case, the resulting $S$-wave $D\pi \rightarrow D\pi$ cross sections. We find the lowest resonance pole at 2149 – i111 MeV (PP) or 2174 – i96.4 MeV (PP+VV), with peak mass at 2180 MeV or 2190 MeV, respectively. This broad resonance should correspond to the $D^0_2(2400)$. Our prediction seems too low, but is not unreasonable in view of the unsettled experimental situation, and also considering our highly dynamical $D^*_0(2400)$ pole, which can travel a long distance with moderate changes in the model’s coupling constant ($\lambda$). For instance, if we reduce $\lambda$ somewhat so as to let the $D^*_{s0}(2317)$ become slightly heavier, still below the $DK$ threshold, it is possible to increase the $D^*_0(2400)$ mass prediction by up to 100 MeV. Nevertheless, we believe it is safer to keep the established $D^*_{s0}(2317)$ in its place, considering the persisting uncertainties regarding the $D^*_0(2400)$. Moreover, the experimental values concern production processes, and not elastic scattering. Furthermore, the analyses rely on a Breit-Wigner shape for the $D^*_2(2460)$ resonance, which has a large contribution to the total signal. In the inset of Fig. 2 we show a comparison of our signal with the data for invariant masses well below the $D^*_2(2460)$ resonance.

Next we look for poles at higher energies. In this situation, we only consider the poles for the full PP+VV system, as several VV channels open above $\sim 2.8$ GeV. Still in the $c\bar{n}$ case, we find a relatively narrow pole at 2737 – i24.0 MeV and a very broad one at 2703 – i228 MeV. The narrow state, with a width of about 50 MeV, corresponds to the first radial excitation of the $c\bar{n}$ system, shifted to complex energy by the coupled channels, while the very broad resonance is the strongly distorted and shifted ground state of the confinement spectrum, also found in Ref. [6], though now with a width of roughly 450 MeV instead of $\approx 200$ MeV. Note that the $D^*_0(2400)$ is a dynamical continuum pole, just as in Ref. [6]. The narrow resonance at about 2.74 GeV predicted here should be observable, though the $S$-wave elastic $D\pi$ cross section is quite small (see Fig. 2 solid curve).

Finally, let us turn to a short description of the model employed in this work. The model’s scattering matrix ($S$) for $N$ two-meson channels (masses $M_{i1}$ and $M_{i2}$, $i = 1, 2, 3, \ldots, N$, orbital angular momentum $l_i$, relative linear momentum $k_i$), all coupled to one quark-antiquark confinement channel (radial confinement spectrum given by $E_0 = \omega (l_{qq} + 3/2) + m_q + m_{\bar{q}}, E_1 = E_0 + 2\omega, E_2 = E_1 + 2\omega, \ldots$), has the following closed form:
where, in the $i$-th channel, the linear momentum $k_i$ and reduced mass $\mu_i$ are related to the total invariant mass $E$ of the system, and to the two meson masses $M_{i1}$ and $M_{i2}$, through

$$E = \sqrt{k_i^2 + M_{i1}^2} + \sqrt{k_i^2 + M_{i2}^2} \quad ,$$

$$E^2 = 2k_i^2 + M_{i1}^2 + M_{i2}^2 + 2E\mu_i \quad .$$

$j_i$ and $h^{(1)}_i$ represent the spherical Bessel and Hankel function of the first kind, respectively.

The model parameters representing quark masses ($m_n = 0.406$ GeV, $m_s = 0.508$ GeV, $m_c = 1.562$ GeV) and the radial spacings in the bare confinement spectrum ($\omega = 0.19$ GeV) are kept identical to the ones originally optimized in Ref. [17], and also used in Ref. [14]. Moreover, the parameter $r_{q\bar{q}}$, which stands for the average radius of $^3P_0$ quark-pair creation, is identical to the value $r_{sn} = 3.2$ GeV$^{-1}$ used in Ref. [11], but scaled with the reduced quark mass in order to impose flavor symmetry of our equations [12][18], i.e.,

$$r_{cn} = \frac{m_n(m_c+m_n)}{m_c(m_n+m_s)} r_{sn} = 2.24 \text{ GeV}^{-1} \quad ,$$

$$r_{cs} = \frac{m_n(m_c+m_n)}{m_c(m_n+m_s)} r_{sn} = 1.88 \text{ GeV}^{-1} \quad .$$

The overall decay coupling constant $\lambda$ is fine-tuned to reproduce the mass of the now very well established $D_{s0}^*(2317)$. Yet, also $\lambda$ turns out to be close to the values used in the light scalar sector [14], owing to the referred flavor-symmetric mass scaling. This yields the values $\lambda = 2.854$ GeV$^{-3/2}$ when only PP channels are included, and $\lambda = 2.617$ GeV$^{-3/2}$ with PP as well as VV channels. Note that the former value of $\lambda$ is fully compatible with the values found for the light scalars in Ref. [14], which analysis was also restricted to PP channels. The change in $\lambda$ from the VV channels amounts to a reduction by less than 10%.

The channels included in the present work are summarized in Table I, their relative couplings to the $q\bar{q}$ channels in Table II.

The pseudoscalar $\eta-\eta'$ mixing angle $\Theta_{PS}$ we choose at the recently found experimental value $\Theta_{PS} = -13.5^\circ$ [20] (octet-singlet basis). However, we also verify our results for another frequently used value, i.e., $\Theta_{PS} = -17.3^\circ$ [14], which turns out to change the predictions by only a few MeV. We force the damping of closed scattering channels with subthreshold form factors, which are a standard tool in modern multichannel phase-shift analyses:

$$g_t^2(n) \to g_t^2(n) e^{-\alpha k_t^2} \quad \text{for} \quad \Im k_t^2 < 0 \quad . \quad (2)$$
We choose the value $\alpha = 4 \text{ GeV}^{-2}$, which is the same as used in the analysis of the light scalars. Such a suppression, in addition to the one resulting from our kinematically relativistic Schrödinger formalism, can be justified from relativistic covariance, offshellness, self-energies, and other effects not accounted for in the present model. These contributions are, of course, very difficult to rigorously evaluate in our nonperturbative scheme. However, even if we were to completely switch off subthreshold damping, our $D_{s0}^*(2850)$ pole would only shift to $2864 - i \times 15 \text{ MeV}$, after a readjustment of $\lambda$ so as to reproduce again the $D_{s0}^*(2317)$ mass.

Having now fixed all parameters in formula (1), we can search our amplitudes for resonance poles. We predict the first radial excitations of the $D_{s0}^*(2317)$ and $D_{0}^*(2400)$ to come out as $D_{s0}^*(2850)$ and $D_{0}^*(2740)$, respectively. We furthermore predict the very broad states $D_{s0}^*(2780)$ and $D_{s}^*(2700)$, which might show up in a more pronounced way in production experiments than in elastic scattering.

Note added in proof: after completion of this work, the BABAR collaboration posted a preprint confirming the announcement of the $D_{sJ}(2860)$ in Ref. [10]. Furthermore, three theoretical papers on this new state have appeared in the meantime, the first one favoring a $3^-(1^3D_3)$ assignment, the second a $0^+(2^3P_0)$ like we do, and the third admitting either possibility. Clearly, the non-observation so far of the $D^*K$ decay mode, forbidden for a scalar meson, favors the $0^+$ option, although the $D_{s\eta}$ mode, not observed either, is allowed in both the $0^+$ and $3^-$ scenarios. It is also interesting that Ref. [22], which makes out a case for the $3^-$ assignment, predicts branching ratios $D_{sJ}(2860) \rightarrow D^*K/DK = 0.39$ for $3^-$, and $D_{sJ}(2860) \rightarrow D_{s\eta}/DK = 0.34$ for $0^+$. We predict a value of 0.30 for the latter branching ratio, if we include all PP+VV channels. Anyhow, experiment will have the final word on interpreting the $D_{sJ}(2860)$ beyond any doubt, by observing either $D_{s\eta}$ or $D^*K$.

Acknowledgments

This work was presented at the QNP06 conference in Madrid, unknowing of the simultaneous experimental release at the CHARM06 conference in Beijing. We are indebted to S. Tosi for drawing our attention to the brand-new data. This work was supported in part by the Fundação para a Ciência e a Tecnologia of the Ministério da Ciência, Tecnologia e Ensino Superior of Portugal, under contract POCI/FP/63437/2005.

* Electronic address: gep@teor.fis.uc.pt
† Electronic address: george@ist.utl.pt

[1] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 90, 242001 (2003) arXiv:hep-ex/0304021.
[2] D. Besson et al. [CLEO Collaboration], Phys. Rev. D 68, 032002 (2003) arXiv:hep-ex/0305100.
[3] E. van Bevelen, J. E. G. N. Costa, F. Kleefeld, and G. Rupp, Phys. Rev. D 74, 037501 (2006) arXiv:hep-ph/0509351.
[4] S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985).
[5] W. M. Yao et al. [Particle Data Group], J. Phys. G 33, 1 (2006).
[6] E. van Bevelen and G. Rupp, Phys. Rev. Lett. 91, 012003 (2003) arXiv:hep-ph/0305035.
[7] D. S. Hwang and D. W. Kim, Phys. Lett. B 601, 137 (2004) arXiv:hep-ph/0408154.
[8] Yu. A. Simonov and J. A. Tjon, Phys. Rev. D 70, 114013 (2004) arXiv:hep-ph/0409361.
[9] E. van Bevelen and G. Rupp, Eur. Phys. J. C 32, 493 (2004) arXiv:hep-ph/0306051.
[10] Eef van Bevelen and George Rupp, Eur. Phys. J. C 22, 493 (2001) arXiv:hep-ex/0106077.
[11] K. Abe et al. [Belle Collaboration], Phys. Rev. D 69, 112002 (2004) arXiv:hep-ex/0307021.
[12] J. M. Link et al. [FOCUS Collaboration], Phys. Lett. B 586, 11 (2004) arXiv:hep-ex/0312000.
[13] E. van Bevelen and G. Rupp, Multichannel calculation of the very narrow $D_{sJ}(2317)$ and the very broad $D_{sJ}(2300-2400)$, parallel talk given by G. Rupp on 6 June 2006 at the IVth Intern. Conf. on Quarks and Nuclear Physics, 5–10 June 2006, Madrid, Spain.
[14] E. van Bevelen, D. V. Bugg, F. Kleefeld and G. Rupp, Phys. Lett. B 641, 265 (2006) arXiv:hep-ph/0606022.
[15] E. van Bevelen and G. Rupp, Int. J. Theor. Phys. Group Theor. Nonlin. Opt. 11, 179 (2006) arXiv:hep-ph/0304105.
[16] A. Palano, New Spectroscopy with Charm quarks at B factories, plenary talk given on 7 June 2006 at the Charm2006 Intern. Workshop, 5–7 June 2006, Beijing, China; Silvano Tosi, private communication.
[17] E. van Bevelen, G. Rupp, T. A. Rijken, and C. Dullemond, Phys. Rev. D 27, 1527 (1983).
[18] E. van Bevelen and G. Rupp, Mod. Phys. Lett. A 19, 1949 (2004) arXiv:hep-ph/0409232.
[19] D. Besson, F. Kleefeld, and E. van Bevelen, AIP Conf. Proc. 756 (2005) 360 arXiv:hep-ph/0412078; F. Kleefeld, AIP Conf. Proc. 717, 332 (2004) arXiv:hep-ph/0310320.
[20] E. van Bevelen, Z. Phys. C 21, 291 (1984) arXiv:hep-ph/0602247.
[21] B. Aubert et al. [BABAR Collaboration], arXiv:hep-ex/0607082.
[22] P. Colangelo, F. De Fazio and S. Nicotri, arXiv:hep-ph/0607245.
[23] F. E. Close, C. E. Thomas, O. Lakhina and E. S. Swanson, arXiv:hep-ph/0608139.
[24] B. Zhang, X. Liu, W. Z. Deng and S. L. Zhu, arXiv:hep-ph/0609013.
[25] In the one-PP-channel calculations of Ref. [3] and Ref. [13] (3rd paper), the $D_{s0}^*(2850)$ pole was estimated at 2923 $– i\times 157 \text{ MeV}$ and 2928 $– i\times 120 \text{ MeV}$, respectively. Here, with a restriction to the three PP channels only, the pole comes out at 2804 $– i\times 159.9 \text{ MeV}$.