$D_{sJ}(2860)$ as the First Radial Excitation of $D_{s0}^*(2317)$

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A coupled-channel model previously employed to describe the narrow $D_{s0}^*(2317)$ and broad $D_0^*(2400)$ charmed scalar mesons is generalized so as to include all ground-state pseudoscalar-pseudoscalar and vector-vector two-meson channels. All parameters are chosen fixed at published values, except for the overall coupling constant, which is fine-tuned to reproduce the $D_{s0}^*(2317)$ mass. Thus, the radial excitations $D_{s0}^*(2850)$ and $D_0^*(2740)$ are predicted, both with a width of about 50 MeV. The former state appears to correspond to the new $D_{sJ}(2860)$ resonance decaying to DK announced by *BABAR* in the course of this work. Also, the $D_0^*(2400)$ resonance is roughly reproduced, though perhaps with a somewhat too low central resonance peak.

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The discovery of the $D_{s0}^*(2317)$ [1] and $D_{s1}(2460)$ [2] charm-strange mesons 3 years ago has triggered a strongly renewed interest in heavy-light mesons, and even meson spectroscopy in general. Especially $D_{s0}^*(2317)$ 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 $c\bar{s}$ 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 $D_{s0}^*(2317)$, such as a tetraquark or a meson molecule. However, in Ref. [6], we showed how the low mass of the $D_{s0}^*(2317)$ can be quantitatively understood by taking into account its strong coupling to the nearby S-wave DK channel. This explanation was later supported by Refs. [7,8]. Similarly, we explained $D_{s1}(2460)$ in Ref. [9] via its strong coupling to the S-wave D^*K threshold. The coupled-channel model employed in Ref. [6] had been previously used, with essentially the same parameters, to reproduce the S-wave $K\pi$ phase shifts and predict [10] the $K_0^*(800)$ (alias κ) resonance, later confirmed by experiment [5].

Nevertheless, no consensus has been reached so far on $D_{s0}^*(2317)$, 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 [13] 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 one to fit the properties of the light scalar mesons σ, κ, $a_0(980)$, 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 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, 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 $D_{s0}^*(2317)$ 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 $2779 - i233$ MeV. At 2.516 GeV, one observes the effect of the opening of the $D_s\eta$ channel, while at about 2.79 GeV the cross sections almost vanish. The first radial excitation of $D_{s0}^*(2317)$ 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 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 in Fig. 1, one can judge how well our $D_{s0}^{*\prime}(2850)$ predicts the

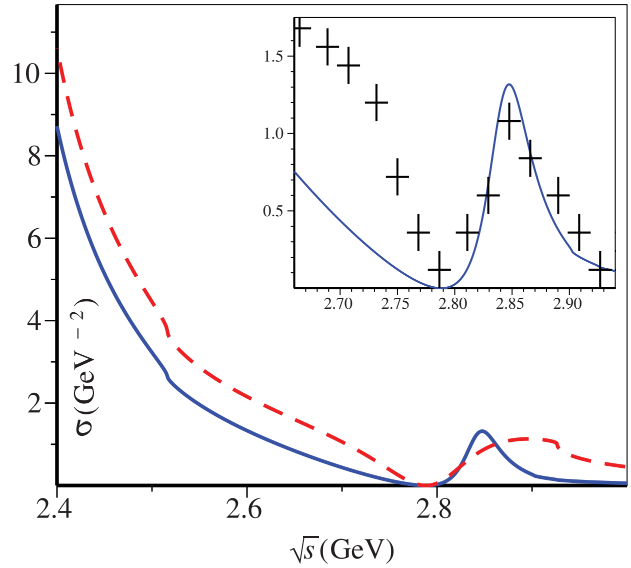

FIG. 1 (color online). The predicted S-wave $DK \to DK$ cross sections. The dashed curve corresponds to PP channels only, the solid curve to $PP + VV$ channels. In the inset, we compare the model results to the data, with arbitrary normalization taken from Ref. [16].

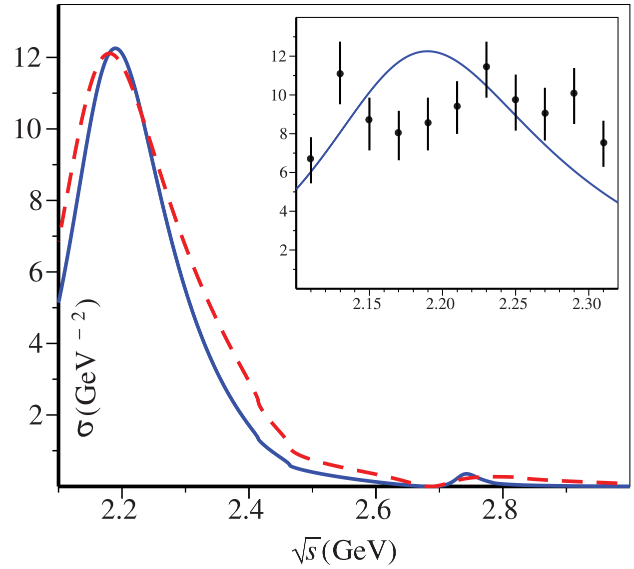

FIG. 2 (color online). The predicted elastic S-wave $D\pi$ cross sections. The dashed curve correspond to PP channels only, the solid curve to $PP + VV$ channels. In the inset, we compare the model results to the data, with arbitrary normalization taken from Ref. [11].

line shape of *BABAR*'s $D_{sJ}(2860)$. There is furthermore some indication [16] that the data need a broad state as well, which might correspond to our pole at $2779 - i233$ MeV.

In Fig. 2, we show, for the $c\bar{n}$ case, the resulting S-wave $D\pi \to D\pi$ 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 or 2190 MeV, respectively. This broad resonance should correspond to $D_0^*(2400)$. Our prediction seems too low but is not unreasonable in view of the unsettled experimental situation [5] and also considering our highly dynamical $D_0^*(2400)$ pole [6], which can travel a long distance with moderate changes in the model's coupling constant (λ). For instance, if we reduce λ somewhat so as to let $D_{s0}^*(2317)$ become slightly heavier, though 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 $D_0^*(2400)$. 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 in Fig. 2, we show a comparison of our signal with the data [11], for invariant masses well below the $D_2^*(2460)$ resonance.

Next we look for poles at higher energies. In this situation, we consider only the poles for the full $PP + VV$ system, as several VV channels open above ~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 instead of ≈200 MeV. Note that $D_0^*(2400)$ 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 $E_0 = \omega(\ell_{q\bar{q}} + 3/2) + m_q + m_{\bar{q}}$, $E_1 = E_0 + 2\omega$, $E_2 = E_1 + 2\omega, \ldots$], has the following closed form [15]:

$$S_{ij}(E) = \delta_{ij} - 2i \frac{2\lambda^2 r_{q\bar{q}} \left\{\sum_{n=0}^{\infty} \frac{g_i(n) g_j(n)}{E - E_n}\right\} \sqrt{\frac{\mu_i \mu_j}{k_i k_j}} k_i k_j j_{\ell_i}(k_i r_{q\bar{q}}) j_{\ell_j}(k_j r_{q\bar{q}})}{1 + 2i\lambda^2 r_{q\bar{q}} \sum_{m=1}^{N} \left\{\sum_{n=0}^{\infty} \frac{|g_m(n)|^2}{E - E_n}\right\} \mu_m k_m j_{\ell_m}(k_m r_{q\bar{q}}) h_{\ell_m}^{(1)}(k_m r_{q\bar{q}})}, \quad (1)$$

where, in the ith channel, the linear momentum k_i and reduced mass μ_i are related to the total invariant mass E of the system and to the two meson masses M_{i1} and M_{i2}, through

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

j_ℓ and $h_\ell^{(1)}$ represent the spherical Bessel and Hankel functions 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. [10] but scaled with the reduced quark mass in order to impose flavor symmetry of our equations [3,18], i.e.,

$$r_{cn} = \frac{m_s(m_c + m_n)}{m_c(m_s + m_n)} r_{sn} = 2.24 \text{ GeV}^{-1},$$
$$r_{cs} = \frac{m_n(m_c + m_s)}{m_c(m_n + m_s)} r_{sn} = 1.88 \text{ GeV}^{-1}.$$

The overall decay coupling constant λ is fine-tuned to reproduce the mass of the now very well established $D_{s0}^*(2317)$. Yet, λ also 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 λ 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 λ 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 η-η' mixing angle Θ_{PS} we choose at the recently found experimental value $\Theta_{PS} = -13.5°$ [20] (octet-singlet basis). However, we also verify our results for another frequently used value, i.e., $\Theta_{PS} = -17.3°$ [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:

$$g_i^2(n) \to g_i^2(n)e^{\alpha k_i^2} \quad \text{for Re}k_i^2 < 0. \qquad (2)$$

We choose the value $\alpha = 4$ GeV^{-2}, which is the same as used in the analysis of the light scalars [14]. 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 $2864 - i \times 15$ MeV, after a readjustment of λ so as to reproduce again the $D_{s0}^*(2317)$ mass.

Having now fixed all parameters in Eq. (1), we can search our amplitudes for resonance poles. We predict the first radial excitations of $D_{s0}^*(2317)$ and $D_0^*(2400)$ to come out as $D_{s0}^{*\prime}(2850)$ [25] and $D_0^{*\prime}(2740)$, respectively. We furthermore predict the very broad states $D_{s0}^*(2780)$ and $D_0^*(2700)$, which might show up in a more pronounced way in production experiments than in elastic scattering.

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Note added.—Recently, the *BABAR* Collaboration posted a preprint [21] confirming the announcement of the $D_{sJ}(2860)$ in Ref. [16]. Furthermore, three theoretical papers on this new state have appeared in the meantime,

TABLE I. The various meson-meson channels included in this analysis and their threshold energies.

Charm-Nonstrange Channels (waves)	Thresh. (GeV)	Charm-Strange Channels (waves)	Thresh. (GeV)
$D\pi$ (S)	2.004	DK (S)	2.363
$D\eta$ (S)	2.415	$D_s\eta$ (S)	2.516
$D\eta'$ (S)	2.825	$D_s\eta'$ (S)	2.926
D_sK (S)	2.464		
$D^*\rho$ (S, D)	2.784	D^*K^* (S, D)	2.902
$D^*\omega$ (S, D)	2.791	$D_s^*\phi$ (S, D)	3.132
$D_s^*K^*$ (S, D)	3.006		

TABLE II. The relative couplings (four-fermion recombination coefficients [19]) for the various meson-meson channels included in this analysis (in the same order as in Table I), to $J^{PC} = 0^{++}$ $c\bar{n}$ and $c\bar{s}$ in S or D waves. For the relative couplings to higher radial excitations n, one has $g(n) = \sqrt{(n+1)}g(0)/2^n$ for S and $g(n) = \sqrt{(2n+5)}g(0)/(5 \times 2^n)$ for D waves. The symbols x and y stand for $\cos\Theta_{PS}$ and $\sin\Theta_{PS}$, respectively.

Charm-Nonstrange	Charm-Strange
$\sqrt{1/16}$	$\sqrt{1/12}$
$x\sqrt{1/144} - y\sqrt{1/72}$	$-y\sqrt{1/72} - x\sqrt{1/36}$
$y\sqrt{1/144} + x\sqrt{1/72}$	$x\sqrt{1/72} - y\sqrt{1/36}$
$\sqrt{1/24}$	
$\sqrt{1/48}$, $\sqrt{5/12}$	$\sqrt{1/36}$, $\sqrt{5/9}$
$\sqrt{1/144}$, $\sqrt{5/36}$	$\sqrt{1/72}$, $\sqrt{5/18}$
$\sqrt{1/72}$, $\sqrt{5/18}$	

the first one [22] favoring a 3^- (1^3D_3) assignment, the second [23] a 0^+ (2^3P_0) like we do, and the third [24] admitting either possibility. Clearly, the nonobservation 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 a case for the 3^- assignment, predicts branching ratios $D_{sJ}(2860) \to D^*K/DK = 0.39$ for 3^- and $D_{sJ}(2860) \to D_s\eta/DK = 0.34$ 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.

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