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Hadronic molecule structure of the $Y(3940)$ and $Y(4140)$

Tanja Branz, Thomas Gutsche, and Valery E. Lyubovitskij[*]

Institut für Theoretische Physik, Universität Tübingen, Kepler Center for Astro and Particle Physics,
Auf der Morgenstelle 14, D–72076 Tübingen, Germany

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We report on further evidence that the $Y(3940)$ and the recently observed $Y(4140)$ are heavy hadron molecule states with quantum numbers $J^{PC} = 0^{++}$. The $Y(3940)$ state is considered to be a superposition of $D^{*+}D^{*-}$ and $D^{*0}\overline{D^{*0}}$, while the $Y(4140)$ is a bound state of D_s^{*+} and D_s^{*-} mesons. For the first time we give predictions for the strong $Y(3940) \to J/\psi\omega$, $Y(4140) \to J/\psi\phi$ and radiative $Y(3940)/Y(4140) \to \gamma\gamma$ decay widths in a phenomenological Lagrangian approach. Results for the strong $J/\psi V$ ($V = \omega, \phi$) decays clearly support the molecular interpretation of the $Y(3940)$ and $Y(4140)$. The alternative assignment of $J^{PC} = 2^{++}$ is also tested, giving similar results for the strong decay widths.

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The recent announcement [1] of the narrow state $Y(4140)$ by the CDF Collaboration at Fermilab raises the prospects of possibly uniquely identifying the structure of a meson resonance which does not fit in the conventional quark-antiquark picture. This latest report of a narrow structure with charmoniumlike decay modes is a continuation of previous discoveries of such states [2] which are not easily explained as quark-antiquark configurations. Possible alternative interpretations involve structures such as hadronic molecules, tetraquark states or even hybrid configurations (for recent reviews see e.g. Refs. [3,4]). Now the CDF Collaboration has evidence of a narrow near-threshold structure, termed the $Y(4140)$ meson, in the $J/\psi\phi$ mass spectrum in exclusive $B^+ \to J/\psi\phi K^+$ decays with the mass $m_{Y(4140)} = 4143.0 \pm 2.9(\mathrm{stat}) \pm 1.2(\mathrm{syst})$ MeV and natural width $\Gamma_{Y(4140)} = 11.7^{+8.3}_{-5.0}(\mathrm{stat}) \pm 3.7(\mathrm{syst})$ MeV [1]. As already stressed in [1], the new structure $Y(4140)$, which decays to $J/\psi\phi$ just above the $J/\psi\phi$ threshold, is similar to the previously discovered $Y(3940)$ [5,6], which decays to $J/\psi\omega$ near this respective threshold. The mass and width of the $Y(3940)$ resonance are: $m_{Y(3940)} = 3943 \pm 11(\mathrm{stat}) \pm 13(\mathrm{syst})$ MeV, $\Gamma_{Y(3940)} = 87 \pm 22(\mathrm{stat}) \pm 26(\mathrm{syst})$ MeV (Belle Collaboration [5]), and $m_{Y(3940)} = 3914.6^{+3.8}_{-3.4}(\mathrm{stat}) \pm 2.0(\mathrm{syst})$ MeV, $\Gamma_{Y(3940)} = 34^{+12}_{-8}(\mathrm{stat}) \pm 5(\mathrm{syst})$ MeV (*BABAR* Collaboration [6]). Both observed states, $Y(4140)$ and $Y(3940)$, are well above the threshold for open charm decays. A conventional $c\bar{c}$ charmonium interpretation is disfavored, since open charm decay modes would dominate, while the $J/\psi\phi$ or $J/\psi\omega$ decay rates are essentially negligible [1,4]. Note, current data imply a lower bound of $\Gamma(Y(3940) \to J/\psi\omega) > 1$ MeV [4], which is an order of magnitude higher than typical rates between known charmonium states. This could be a signal for non-conventional structure of the $Y(3940)$. As a first follow-up to the CDF result, it is suggested in [7] that both the $Y(3940)$ and $Y(4140)$ are hadronic molecules (i.e. bound states of mesons induced by the strong interaction). These hadron bound states can have quantum numbers $J^{PC} = 0^{++}$ or 2^{++} whose constituents are the vector charm $D^*(D_s^*)$ mesons:

$$\begin{aligned} |Y(3940)\rangle &= \frac{1}{\sqrt{2}}(|D^{*+}D^{*-}\rangle + |D^{*0}\overline{D^{*0}}\rangle), \\ |Y(4140)\rangle &= |D_s^{*+}D_s^{*-}\rangle. \end{aligned} \qquad (1)$$

The authors of Ref. [7] show that binding of the above-mentioned meson configurations can be achieved in the context of meson-exchange potentials generated by the Lagrangian of heavy hadron chiral perturbation theory (HHChPT) [8–10]. Earlier results based on the pion-exchange mechanism already indicated that the $D^*\overline{D^*}$ system can form a bound state [11]. Binding in the $D_s^*\overline{D_s^*}$ channel can be induced by η and ϕ meson exchange [7]. A first QCD sum rule study cannot support the claim that the $D_s^*\overline{D_s^*}$ system binds [12]. This issue remains to be studied.

In this paper we report on a first quantitative prediction for the decay rates of the observed modes $Y(3940) \to J/\psi\omega$ and $Y(4140) \to J/\psi\phi$ assuming the hadronic molecule structures of Eq. (1) with quantum numbers $J^{PC} = 0^{++}$. Results will be shown to be fully consistent with present experimental observations, strengthening the unusual hadronic molecule interpretation. Further predictions are given for the radiative two-photon decays of these states. Finally, we also consider the alternative $J^{PC} = 2^{++}$ assignment for the Y states.

The method of determining the decay rates is based on an effective Lagrangian which includes both the coupling of the molecular-bound state to their hadronic constituents and the coupling of the constituents to other hadrons and photons. In Ref. [13] we developed the formalism for the structural study of other recently observed meson states [like $D_{s0}^*(2317), D_{s1}(2460), X(3872), \ldots$] as hadronic molecules. The composite (molecular) structure of the

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[*] On leave of absence from Department of Physics, Tomsk State University, 634050 Tomsk, Russia

$Y(3940)$ and $Y(4140)$ states is defined by the compositeness condition $Z = 0$ [14–17] (see also Ref. [13]). This condition implies that the renormalization constant of the hadron wave function is set equal to zero or that the hadron exists as a bound state of its constituents. Decay processes are then described by the coupling of the final state particles via one-loop meson diagrams to the constituents of the molecular state (see details in [13]).

For the observed $Y(3940)$ and $Y(4140)$ states we adopt the convention that the spin and parity quantum numbers of both states are $J^{PC} = 0^{++}$. Presently, except for $C = +$, the J^P quantum numbers are not unambiguously determined yet in experiment. For example, the $Y(3940)$ is also discussed as a $J^{PC} = 1^{++}$ charmonium candidate [4], but 0^{++} is not ruled out. Their masses are expressed in terms of the binding energy ϵ_Y as $m_{Y(3940)} = 2m_{D^*} - \epsilon_{Y(3940)}$ and $m_{Y(4140)} = 2m_{D_s^*} - \epsilon_{Y(4140)}$, where $m_{D^*} \equiv m_{D^{*+}} = 2010.27$ MeV and $m_{D_s^*} = m_{D_s^{*+}} = 2112.3$ MeV are the masses of the constituent mesons. Since the observed masses are relatively far from the corresponding thresholds we do not include isospin-breaking effects (i.e. we suppose that charged and neutral nonstrange D^* mesons have the same masses). Following Ref. [7] we consider the $Y(3940)$ meson as a superposition of the molecular $D^{*+}D^{*-}$ and $D^{*0}D^{*0}$ states, while the $Y(4140)$ is a bound state of D_s^{*+} and D_s^{*-} mesons [see Eq. (1)]. The coupling of the scalar molecular states to their constituents is expressed by the phenomenological Lagrangian

$$\mathcal{L}_Y(x) = g_Y Y_{ij}(x) J_{Y_{ij}}(x) \tag{2}$$

where g_Y is the coupling constant; Y_{ij} is the 3×3 matrix containing a nonet of possible hidden and open flavor Y states which can be composed of vector $D^*(D_s^*)$ mesons

$$Y_{ij} = \begin{pmatrix} \frac{Y_\rho^0}{\sqrt{2}} + \frac{Y_\omega}{\sqrt{2}} & Y_\rho^+ & Y_{K^*}^+ \\ Y_\rho^- & -\frac{Y_\rho^0}{\sqrt{2}} + \frac{Y_\omega}{\sqrt{2}} & Y_{K^*}^0 \\ Y_{K^*}^- & \overline{Y_{K^*}^0} & Y_\phi \end{pmatrix}. \tag{3}$$

In addition to the detected $Y_\omega = Y(3940)$ and $Y_\phi = Y(4140)$ states, one can propose an isotriplet of nonstrange states $Y_\rho^+ = (D^{*+}\overline{D^{*0}})$, $Y_\rho^- = (D^{*-}D^{*0})$, $Y_\rho^0 = (D^{*0}\overline{D^{*0}} - D^{*+}D^{*-})/\sqrt{2}$ and two isodoublets of strange states $Y_{K^*}^+ = (\overline{D^{*0}}D_s^{*+})$, $Y_{K^*}^0 = (D^{*-}D_s^{*+})$ and $Y_{K^*}^- = (D^{*0}D_s^{*-})$, $\overline{Y_{K^*}^0} = (D^{*+}D_s^{*-})$. We expect that the masses of the $Y_\rho^\pm$, Y_ρ^0 states are close to the $Y(3940)$ mass, while the masses of the other four states $Y_{K^*}^\pm$, $Y_{K^*}^0$, $\overline{Y_{K^*}^0}$ could be approximately $4040 \text{ MeV} \simeq m_{D^*} + m_{D_s^*} - 80$ MeV [a typical value for the binding energy, as in the case for the $Y(3940)$ and $Y(4140)$ states]. In analogy with the $Y(3940)$ and $Y(4140)$ states, we suggest that the new hypothetical states $Y_\rho^{\pm(0)}(3940)$ and $Y_{K^*}^{\pm(0)}(4040)$ can decay into $J/\psi\rho$ and $J/\psi K^*$ pairs, respectively. Note, we use the notation Y_V for the nonet of Y states since it decays into $J/\psi V$ pairs. $J_{Y_{ij}}$ of Eq. (2) is the current composed of the constituents of the respective hadronic molecule Y_{ij}. The simplest form of the hadronic currents $J_{Y_{ij}}$ is given by $J_{Y_{ij}}(x) = g_{\mu\nu}\int d^4y \Phi(y^2) J_{ij}^{\mu\nu}(x,y)$, where $J_{ij}^{\mu\nu}(x,y) = D_i^{*\mu}(x + \frac{y}{2}) \times D_j^{*\nu\dagger}(x - \frac{y}{2})$. Here $\Phi(y^2)$ is the correlation function describing the distribution of the constituents inside the molecular states Y. For simplicity we adopt a universal equivalent function for all states. A basic requirement for the choice of an explicit form of the correlation function Φ is that its Fourier transform vanishes at a sufficient rate in the ultraviolet region of Euclidean space to render the Feynman diagrams ultraviolet finite. We use a Gaussian form of $\Phi(y^2)$ $\Phi(y^2)$: $\tilde{\Phi}(p_E^2/\Lambda_Y^2) \doteq \exp(-p_E^2/\Lambda_Y^2)$, where p_E is the Euclidean Jacobi momentum. Here, Λ_Y is a size parameter with a value of about 2 GeV—a typical scale for the masses of the constituents of the Y states. The coupling constants g_Y are determined by the compositeness condition [13–17] $Z_Y = 1 - \Sigma_Y'(m_Y^2) = 0$, where $\Sigma_Y'(m_Y^2) = d\Sigma_Y(p^2)/dp^2|_{p^2=m_Y^2}$ is the derivative of the mass operator Σ_Y generated by $\mathcal{L}_Y(x)$.

To determine the strong $Y \to J/\psi V$ and two-photon $Y \to \gamma\gamma$ decays we have to include the couplings of $D^*(D_s^*)$ mesons to vector mesons (J/ψ, ω, ϕ) and to photons. The couplings of J/ψ, ω, ϕ to vector $D^*(D_s^*)$ mesons are taken from the HHChPT Lagrangian [8,10]

$$\begin{aligned} \mathcal{L}_{D^*D^*J_\psi} &= ig_{D^*D^*J_\psi} J_\psi^\mu (D_{\mu i}^{*\dagger} \overleftrightarrow{\partial}_\nu D_i^{*\nu} + D_{\nu i}^{*\dagger} \overleftrightarrow{\partial}^\nu D_{\mu i}^* \\ &\quad - D_i^{*\dagger\nu} \overleftrightarrow{\partial}_\mu D_{\nu i}^*), \\ \mathcal{L}_{D^*D^*V} &= ig_{D^*D^*V} V_{ij}^\mu D_{\nu i}^{*\dagger} \overleftrightarrow{\partial}_\mu D_j^{*\nu} + 4if_{D^*D^*V}(\partial^\mu V_{ij}^\nu \\ &\quad - \partial^\nu V_{ij}^\mu) D_{\mu i}^* D_j^{*\dagger\nu} \end{aligned} \tag{4}$$

where $A\overleftrightarrow{\partial}B \equiv A\partial B - B\partial A$; i, j are flavor indices; $V_{ij} = \text{diag}\{\omega/\sqrt{2}, \omega/\sqrt{2}, \phi\}$ is the diagonal matrix containing ω and ϕ mesons (we omit the ρ and K^* mesons); $D_i^* = (D^{*0}, D^{*+}, D_s^{*+})$ is the triplet of vector D^* mesons containing light antiquarks $\bar{u}$, $\bar{d}$, and $\bar{s}$, respectively. The chiral couplings $g_{D^*D^*J_\psi}$, $g_{D^*D^*V}$, and $f_{D^*D^*V}$ are fixed as [8–10] $g_{D^*D^*V} = \beta g_V/\sqrt{2}$, $f_{D^*D^*V} = m_{D^*}\lambda g_V/\sqrt{2}$, $g_{D^*D^*J_\psi} = (m_{D^*}m_{J_\psi})/(m_D f_{J_\psi})$, where $f_{J_\psi} = 416.4$ MeV is the J/ψ leptonic decay constant; $g_V \approx 5.8$ and $\beta \approx 0.9$ are fixed using vector dominance; the parameter $\lambda = 0.56\ \text{GeV}^{-1}$ is extracted by matching HHChPT to lattice QCD and light cone sum rules (see details in [9]). The leading-order process relevant for the strong decays $Y(3940) \to J/\psi\omega$ and $Y(4140) \to J/\psi\phi$ is the diagram of Fig. 1 involving the vector mesons D^* or D_s^* in the loop.

The coupling of the charged $D^{*\pm}(D_s^{*\pm})$ mesons to photons is generated by minimal substitution in the free Lagrangian of these mesons. The corresponding electromagnetic Lagrangian reads as

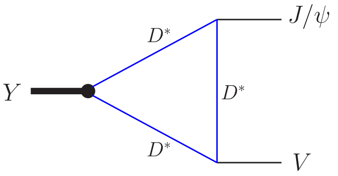

FIG. 1 (color online). The diagram describes the $Y \to J/\psi V$ decay.

$$\mathcal{L}_{\rm em} = eA_\alpha(g^{\alpha\nu}D^{*-}_\mu i\partial^\mu D^{*+}_\nu - g^{\mu\nu}D^{*-}_\mu i\partial^\alpha D^{*+}_\nu + \text{H.c.}) + e^2 D^{*-}_\mu D^{*+}_\nu(A^\mu A^\nu - g^{\mu\nu}A^\alpha A_\alpha). \tag{5}$$

This Lagrangian results in the two relevant diagrams displayed in Figs. 2(a) and 2(b). In order to fulfill electromagnetic gauge invariance the strong interaction Lagrangian $\mathcal{L}_Y$ also has to be modified. As outlined in Ref. [18] and extensively used in Refs. [13,17], each charged constituent meson field $H^\pm$ in $\mathcal{L}_Y$ is multiplied by the gauge field exponential $H^\pm(y) \to e^{\mp ieI(y,x,P)}H^\pm(y)$, where $I(x,y,P) = \int_y^x dz_\mu A^\mu(z)$. Expanding $e^{\mp ieI(y,x,P)}$ up to second order in the electromagnetic field, the two additional diagrams of Figs. 2(c) and 2(d) are generated, which are necessary to guarantee full gauge invariance. The contribution of these additional processes is significantly suppressed (of the order of a few percent) compared to the leading diagram of Fig. 2(a).

The invariant matrix elements of the strong and two-photon transitions (when all initial and final particles are on their mass shell) are given by

$$\begin{aligned} M_{\mu\nu}(Y \to J/\psi V) &= g_{\mu\nu}g_{YJ_\psi V} + v_{2\mu}v_{1\nu}f_{YJ_\psi V}, \\ M_{\mu\nu}(Y \to \gamma\gamma) &= (g_{\mu\nu}q_1q_2 - q_{2\mu}q_{1\nu})g_{Y\gamma\gamma}, \end{aligned} \tag{6}$$

where $v_1(q_1)$ and $v_2(q_2)$ are the 4-velocities (momenta) of J_ψ and V. The effective strong couplings $g_{YJ_\psi V}$ and $f_{YJ_\psi V}$ have dimension of mass, while the electromagnetic coupling $g_{Y\gamma\gamma}$ has dimension of inverse mass. The matrix element of the two-photon transition has a full gauge-invariant structure. The constants $g_{YJ_\psi V}$ and $f_{YJ_\psi V}$ are products of the coupling g_Y, the chiral couplings in Eq. (4), and the generic D^* meson loop structure integral (see Fig. 1). In terms of these effective couplings $g_{YJ_\psi V}$, $f_{YJ_\psi V}$, and $g_{Y\gamma\gamma}$ the corresponding decay widths are calculated according to the expressions

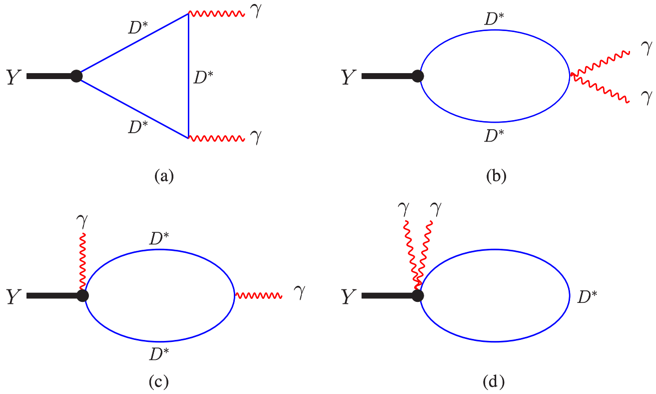

FIG. 2 (color online). The diagrams shows contributions to the $Y \to \gamma\gamma$ decay.

$$\begin{aligned} \Gamma(Y \to J/\psi V) &= \frac{3P^*}{8\pi m_Y^2}g^2_{YJ_\psi V}(1 + \beta + 2wr\beta + 3r^2\beta^2), \\ \Gamma(Y \to \gamma\gamma) &= \frac{\pi}{4}\alpha^2 m_Y^3 g^2_{Y\gamma\gamma}, \end{aligned} \tag{7}$$

where

$$r = \frac{f_{YJ_\psi V}}{g_{YJ_\psi V}}, \qquad \beta = \frac{1}{3}\left(\frac{P^* m_Y}{m_{J_\psi}m_V}\right)^2, \qquad w = v_1v_2$$

and α is the fine structure constant. Here P^* is the corresponding 3-momentum of the decay products.

Our numerical results for the quantities characterizing the strong $J/\psi V$ ($V = \omega$, ϕ) and radiative two-gamma decays of $Y(3940)$ and $Y(4140)$ are contained in Table I. For the masses of the Y states we use the values extracted by the *BABAR* [6] and the CDF [1] Collaborations. The error bars correspond to the ones of the experimental mass values of the Y states.

The predictions for the couplings g_Y of the Y states to their meson constituents are consistent with a trivial estimate using the Weinberg formula. It was originally derived for the deuteron as based on the compositeness condition [14] with $g_Y^W = \sqrt{32\pi}m_{D^*}^{3/4}\epsilon_Y^{1/4}$. This formula represents the leading term of an expansion in powers of the binding energy ϵ. Note that this expression can be obtained in the local limit [i.e. the vertex function approaches the limit $\Phi(y^2) \to \delta^4(y)$] and when the longitudinal part $k^\mu k^\nu/m^2_{D^*}$ of the constituent vector meson propagator is neglected. The numerical results for $g^W_{Y(3940)} = 9.16$ GeV and $g^W_{Y(4140)} = 8.91$ GeV are in good agreement with nonlocal results of $g_{Y(3940)} = 14.08$ GeV and $g_{Y(4140)} = 13.20$ GeV.

The predictions of $\Gamma(Y(3940) \to J/\psi\omega) = 5.47$ MeV and $\Gamma(Y(4140) \to J/\psi\phi) = 3.26$ MeV for the observed decay modes are sizable and fully consistent with the upper limits set by present data on the total widths. The result for

TABLE I. Decay properties of $Y(3940)$ and $Y(4140)$ states.

Quantity	$Y(3940)$	$Y(4140)$
g_Y, GeV	14.08 ± 0.30	13.20 ± 0.26
$g_{YJ_\psi V}$, GeV	1.72 ± 0.03	1.46 ± 0.03
$f_{YJ_\psi V}$, GeV	1.64 ± 0.01	1.84 ± 0.01
$\Gamma(Y \to J/\psi V)$, MeV	5.47 ± 0.34	3.26 ± 0.21
$g_{Y\gamma\gamma} \times 10^2$, GeV^{-1}	1.15 ± 0.01	1.46 ± 0.01
$\Gamma(Y \to \gamma\gamma)$, keV	0.33 ± 0.01	0.63 ± 0.01
$R = \frac{\Gamma(Y\to\gamma\gamma)}{\Gamma(Y\to J/\psi V)} \times 10^4$	0.61 ± 0.06	1.93 ± 0.16

$\Gamma(Y(3940) \to J/\psi\omega)$ is also consistent with the lower limit of about 1 MeV [4]. Values of a few MeV for these decay widths naturally arise in the hadronic molecule interpretation of the $Y(3940)$ and $Y(4140)$, whereas in a conventional charmonium interpretation the $J/\psi V$ decays are strongly suppressed by the Okubo, Zweig, and Iizuka rule [4]. In addition to the possibility of binding the $D^*\overline{D^*}$ and $D_s^{*+}D_s^{*-}$ systems [7], present results on the $J/\psi V$ decays give further strong support to the interpretation of the Y states as heavy hadron molecules. Further tests of the presented scenario concern the two-photon decay widths, which we predict to be of the order of 1 keV.

Finally we also test the $J^{PC} = 2^{++}$ assignment not yet ruled out experimentally. The coupling of the molecular tensor field $Y_{\mu\nu;ij}$ to the two-meson constituent current $J_{ij}^{\mu\nu}$ is set up as

$$\mathcal{L}_{Y_T}(x) = g_{Y_T} Y_{\mu\nu;ij}(x) \int d^4y \Phi(y^2) J_{ij}^{\mu\nu}(x, y). \tag{8}$$

Proceeding as outlined before we obtain

$$\begin{aligned} \Gamma(Y(3940) \to J/\psi\omega) &= 7.48 \pm 0.27 \text{ MeV}, \\ \Gamma(Y(4140) \to J/\psi\phi) &= 4.41 \pm 0.16 \text{ MeV}, \\ \Gamma(Y(3940) \to \gamma\gamma) &= 0.27 \pm 0.01 \text{ keV}, \\ \Gamma(Y(4140) \to \gamma\gamma) &= 0.50 \pm 0.01 \text{ keV}. \end{aligned} \tag{9}$$

Since the results for the strong J/ψ decays are quite similar to the 0^{++} case, a 2^{++} scenario cannot be ruled out and is also consistent within a molecular interpretation of the Y states.

A full interpretation of the $Y(3940)$ and $Y(4140)$ states requires: i) an experimental determination of the J^{PC} quantum numbers, ii) a consistent and hopefully converging study of binding mechanisms in the $D_{(s)}^*\overline{D_{(s)}^*}$ systems, and iii) theory and experiment to consider the open charm decay modes, such as $D\overline{D}$, $D\overline{D^*}$, $D\overline{D^*}\gamma$, etc., which are also naturally fed in a charmonium picture. Ultimately, only a full understanding of the decay patterns of the $Y(3940)$ and $Y(4140)$ can lead to a unique structure interpretation, yet present results clearly support the notion of the establishment of hadronic molecules in the meson spectrum.

After submission of this manuscript, calculations both in the potential model approach [19] and in QCD sum rules [20] were presented, which support the original claim that the $D_s^*\overline{D_s^*}$ system binds for $J^{PC} = 0^{++}$, hence give further support to the interpretation presented here.

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