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

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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 $D^0\bar D^{*−}$, 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 $Y(3940) \rightarrow J/\psi \omega$, $Y(4140) \rightarrow J/\psi \phi$ and radiative $Y(3940)/Y(4140) \rightarrow \gamma \gamma$ 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 charmonium-like 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 $B^+ \rightarrow J/\psi \phi K^+$ decays with the mass $m_{Y(4140)} = 4143.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst})$ MeV and natural width $\Gamma_{Y(4140)} = 11.7^{+3.3}_{−5.0}(\text{stat}) \pm 3.7(\text{syst})$ 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 $Y(3940)$ [2, 3], which decays to $J/\psi \omega$ near this respective threshold. The mass and width of the $Y(3940)$ resonance are: $m_{Y(3940)} = 3943 \pm 11(\text{stat}) \pm 13(\text{syst})$ MeV, $\Gamma_{Y(3940)} = 87 \pm 22(\text{stat}) \pm 26(\text{syst})$ MeV (Belle Collaboration [5]) and $m_{Y(3940)} = 3914.6^{+3.8}_{−1.4}(\text{stat}) \pm 2.0(\text{syst})$ MeV, $\Gamma_{Y(3940)} = 34^{+12}_{−8}(\text{stat}) \pm 5(\text{syst})$ MeV (BABAR [6]). Both observed states, $Y(4140)$ and $Y(3940)$, are well above the thresholds 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 $\Gamma(Y(3940) \rightarrow J/\psi \omega) > 1$ MeV [3], which is an order of magnitude higher than typical rates between known charmonium states. This could be a signal for nonconventional 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:

\[
|Y(3940)\rangle = \frac{1}{\sqrt{2}}(|D^+ D^−\rangle + |D^0 \bar D^{*−}\rangle),
\]
\[
|Y(4140)\rangle = |D^+_s D^−_s⟩. \quad (1)
\]

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 $D^*\bar D^*$ system can form a bound state [11]. Binding in the $D^*_s\bar D^*_s$ channel can be induced by $\eta$ and $\phi$ meson exchange [7]. A first QCD sum rule study cannot support the claim that the $D^*_s\bar D^*_s$ system binds [12]. This issue remains to be studied.

In this Letter we report on a first quantitative prediction for the decay rates of the observed modes $Y(3940) \rightarrow J/\psi \omega$ and $Y(4140) \rightarrow J/\psi \phi$ 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 con-
stituents and the coupling of the constituents to other
hadrons and photons. In Refs. 13 we developed the for-
malism for the structural study of other recently observed
meson states (like $D_{s0}^*(2317)$, $D_{s1}(2460)$, $X(3872)$, $\cdots$) as hadronic molecules. The composite (molecular) struc-
ture of the $(3940)$ and $(4140)$ states is defined by the
compositeness condition $Z = 0$ (see also Refs. 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 $(3940)$ and $(4140)$ states we adopt
the convention that the spin and parity quantum num-
bers 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 $(3940)$
is also discussed as a $J^{PC} = 1^{++}$ charmonium candidate 13, but $0^{++}$ is not ruled out. Their masses are ex-
pressed in terms of the binding energy $\epsilon_Y$ as $m_Y(3940) =
2m_{D^0} - \epsilon_Y(3940)$ and $m_Y(4140) = 2m_{D^*} - \epsilon_Y(4140)$, where $m_{D^0} \equiv m_{D^*} = 201.27$ MeV and $m_{D^*} = 2112.3$ 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 non-
strange $D^*$ mesons have the same masses). Following
Ref. 7 we consider the $(3940)$ meson as a superposition of the molecular $D^+D^-$ and $D^{*0}D^{*0}$ states, while
the $(4140)$ is a bound state of $D_{s0}^+$ and $D_{s1}^*$ mesons
(see Eq. 11). The coupling of the scalar molecular states
to their constituents is expressed by the phenomenologi-

cal Lagrangian:

$$L_Y(x) = g_Y Y_{ij} (x) J_{ij} (x)$$

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

$$Y_{ij} = \begin{pmatrix} Y^0_{ij} \\ Y^+_{ij} \\ Y^-_{ij} \\ Y^0_{K_s} \\ Y^+_{K_s} \\ Y^-_{K_s} \\ Y^+_{\phi} \\ Y^0_{\phi} \end{pmatrix}.$$  

In addition to the detected $Y_0 = Y(3940)$ and $Y_0 =
Y(4140)$ states, one can propose an isorotilton of non-
strange states $Y_0^+ = (D^{++}D^{*-})$, $Y_0^- = (D^{*-}D^{*+})$, $Y_0^0 = (D^{*0}D^{*0} - D^{*+}D^{*-})/\sqrt{2}$ and two isodoublets

of strange states $Y_K^+ = (\bar{D}^0D^{*+})$, $Y_0^0 = (D^{*0}D^{*0})$ and $Y_K^- = (D^{*0}D^{*+} - D^{*+}D^{*-})$. We expect
that the masses of the $Y_0^\pm$, $Y_0^0$ states are close
to the $Y(3940)$ mass, while the masses of the other
four states $Y_K^\pm$, $Y_0^0$, $Y_K^\pm$ could be approximately 4040
MeV $\approx m_{D^*} + m_{D_s^*} - 80$ 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 $Y_0^{\pm(0)}(3940)$ and $Y_0^{\pm(0)}(4040)$ 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. $J_{ij}$ of Eq. 2 is the current composed
of the constituents of the respective hadronic molecule
$Y_{ij}$. The simplest form of the hadronic currents $J_{ij}$ is


$$J_{ij} (x) = g_{ij} \int d^4y \Phi(y^2)(H_{ij}(x, y), y)$$

where $J^{\mu\nu}_{ij}(x, y) = D^{\mu\nu}_{ij}(x + \frac{y}{2})D_{ij}^{\nu\tau}(x - \frac{y}{2})$. 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 $\Phi$ is that its Fourier
transform vanishes at a sufficient rate in the ultraviolet
region of Euclidean space to render the Feynman dia-
grams ultraviolet finite. We use a Gaussian form of
$\Phi(y^2)$: $\Phi(\frac{y^2}{4}) \equiv \exp(-\frac{y^2}{4})$, where $p_E$ is
the Euclidean Jacobi momentum. Here $\Lambda_Y$ is a size pa-

ter with a value of about 2 GeV – a typical scale for
the masses of the constituents of the $Y$ states. The
coupling constants $g_{ij}$ are determined by the composit-
ness condition 13]: $Z_Y = 1 - \Sigma_Y(m_Y^2) = 0$, where
$\Sigma_Y(m_Y^2) = d\Sigma_Y(p^2)/dp^2|_{p=m_Y^2}$ is the derivative of the mass operator $\Sigma_Y$ generated by $L_Y(x)$.

To determine the strong $Y \rightarrow J/\psi V$ and two-photon
$Y \rightarrow \gamma\gamma$ decays we have to include the couplings
of $(D^{*}(D_S^*))$ mesons to vector mesons ($J/\psi$, $\omega$, $\phi$) and to photons. The couplings of $J/\psi$, $\omega$, $\phi$ to vector $D^*(D_s^*)$ mesons are taken from the HHChPT Lagrangian 8-10:

$$\mathcal{L}_{D^{*}} = ig_{D^{*}\omega} \bar{\psi} \gamma_5 \omega \psi + ig_{D^{*}\phi} \bar{\psi} \gamma_5 \phi \psi - \bar{\psi} \gamma_5 \omega \psi$$

$$\mathcal{L}_{D^{*}\alpha} = ig_{D^{*}\omega} \bar{\psi} \gamma_5 \omega \psi + ig_{D^{*}\phi} \bar{\psi} \gamma_5 \phi \psi - \bar{\psi} \gamma_5 \omega \psi$$

$$\mathcal{L}_{D^{*}\alpha} = ig_{D^{*}\omega} \bar{\psi} \gamma_5 \omega \psi + ig_{D^{*}\phi} \bar{\psi} \gamma_5 \phi \psi - \bar{\psi} \gamma_5 \omega \psi$$

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$$\mathcal{L}_{D^{*}\alpha} = ig_{D^{*}\omega} \bar{\psi} \gamma_5 \omega \psi + ig_{D^{*}\phi} \bar{\psi} \gamma_5 \phi \psi - \bar{\psi} \gamma_5 \omega \psi$$

where $\bar{\psi} \gamma_5 \omega \psi + \bar{\psi} \gamma_5 \phi \psi = A \bar{\omega} B - \bar{\phi} B A$, $i, j$ are flavor indices; $V_{ij} = \text{diag}(\omega/\sqrt{2}, \omega/\sqrt{2}, \phi)$ is the diagonal matrix containing $\omega$ and $\phi$ mesons (we omit the $\rho$ and $K^*$ mesons); $D_\xi = (D^{*0}, D^{*+}, D^{*-})$ is the triplet of vector $D^*$
mesons containing light antiquarks $\bar{u}$, $\bar{d}$ and $\bar{s}$, respec-
tively. The chiral couplings $g_{D^{*}\omega}, g_{D^{*}\phi}$ and $f_{D^{*}\omega}$ are
fixed as 8-10: $g_{D^{*}\omega} = 0.5\sqrt{2}$, $f_{D^{*}\omega} = m_{D^*} m_{V_{ij}} / \sqrt{2}$, $g_{D^{*}\phi} = (m_{D} - m_{J/\psi})/(m_{D} f_{J/\psi})$, where $f_{J/\psi} = 416.4$ MeV is the $J/\psi$ leptonic decay constant;
\( g_\nu \approx 5.8 \) and \( \beta \approx 0.9 \) are fixed using vector dominance; the parameter \( \lambda = 0.56 \text{ GeV}^{-1} \) is extracted by matching \( \text{HHChPT} \) to lattice QCD and light cone sum rules (see details in [1]). The leading-order process relevant for the strong decays \( Y(3940) \rightarrow J/\psi \omega \) and \( Y(4140) \rightarrow J/\psi \phi \) is the diagram of Fig.1 involving the vector mesons \( D^* \) or \( D_{s}^* \) in the loop.

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

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

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 \( H^k \) in \( \mathcal{L}_Y \) is multiplied by the gauge field exponential: \( H^\pm \rightarrow e^{\mp ieI(y,x,P)}H^\pm \), where \( I(x,y,P) = \int_y^z dz_A^\alpha A^\alpha(z) \). 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:

\[
M_{\mu\nu}(Y \rightarrow J/\psi V) = g_{\mu\nu} g_{YJ\psi V} + v_1 v_2 f_{YJ\psi V},
\]

\[
M_{\mu\nu}(Y \rightarrow \gamma\gamma) = (g_{\mu\nu} q_1 q_2 - g_{\mu\nu} q_1 q_2) g_{Y\gamma\gamma}, \tag{6}
\]

where \( v_1(q_1) \) and \( v_2(q_2) \) are the 4-velocities (momenta) of \( J/\psi \) 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. [13] 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:

\[
\Gamma(Y \rightarrow J/\psi V) = \frac{3P^*}{8\pi m_Y^2} g_{YJ\psi V}^2 \left( 1 + \beta + 2\omega \beta + 3r^2 \beta^2 \right),
\]

\[
\Gamma(Y \rightarrow \gamma\gamma) = \frac{\pi \alpha^2}{4} m_Y^3 g_{Y\gamma\gamma}^2, \tag{7}
\]

where

\[
r = \frac{f_{YJ\psi V}}{g_{YJ\psi V}}, \quad \beta = \frac{1}{3} \left( \frac{P^* m_Y}{m_j m_V} \right)^2, \quad \omega = v_1 v_2
\]

and \( \alpha \) is the fine structure constant. Here \( P^* \) is the corresponding three-momentum of the decay products.

Our numerical results for the quantities characterizing the strong \( J/\psi V \) \((V = \omega, \phi) \) 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 [3] and the CDF [5] 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 \( g_Y^W = \sqrt{32\pi m_D^3} \epsilon_{YV}^{1/4} \). This formula

### Table I: Decay properties of \( Y(3940) \) and \( Y(4140) \) states

| Quantity | \( Y(3940) \)        | \( Y(4140) \)        |
|----------|----------------------|----------------------|
| \( g_\nu \), GeV | \( 14.08 \pm 0.30 \) | \( 13.20 \pm 0.26 \) |
| \( g_{YJ\omega V} \), GeV | \( 1.72 \pm 0.03 \) | \( 1.46 \pm 0.03 \) |
| \( f_{YJ\omega V} \), GeV | \( 1.64 \pm 0.01 \) | \( 1.84 \pm 0.01 \) |
| \( \Gamma(Y \rightarrow J/\psi V) \), MeV | \( 5.47 \pm 0.34 \) | \( 3.26 \pm 0.21 \) |
| \( g_{Y\gamma\gamma} \times 10^3 \), GeV\(^{-1} \) | \( 1.15 \pm 0.01 \) | \( 1.46 \pm 0.01 \) |
| \( \Gamma(Y \rightarrow \gamma\gamma) \), keV | \( 0.33 \pm 0.01 \) | \( 0.63 \pm 0.01 \) |
| \( R = \frac{\Gamma(Y \rightarrow \gamma\gamma)}{\Gamma(Y \rightarrow J/\psi V)} \times 10^4 \) | \( 0.61 \pm 0.06 \) | \( 1.93 \pm 0.16 \) |
represents the leading term of an expansion in powers of the binding energy $\epsilon$. 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 $k^\mu k^\nu/m_D^2$, of the constituent vector meson propagator is neglected. The numerical results for $g_W^{Y(3940)} = 9.16\text{ GeV}$ and $g_Y^{W(4140)} = 8.91\text{ GeV}$ are in good agreement with nonlocal results of $g_Y^{(3940)} = 14.08\text{ GeV}$ and $g_Y^{(4140)} = 13.20\text{ GeV}$.

The predictions of $\Gamma(Y(3940) \to J/\psi\omega) = 5.47\text{ MeV}$ and $\Gamma(Y(4140) \to J/\psi\phi) = 3.26\text{ MeV}$ 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 $\Gamma(Y(3940) \to J/\psi\omega)$ 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 chiral interpretation the $J/\psiV$ decays are strongly suppressed by the Okubo, Zweig and Iizuka rule [4]. In addition to the possibility of binding the $D^*D^*$ and $D^*_sD^*_s$- systems [4], present results on the $J/\psiV$ 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 $Y_{\mu
u;i,j}$ to the two-meson constituent current $J_{ij}^{\mu}$ is set up as

$$\mathcal{L}_{Y}(x) = g_{Y} Y_{\mu
u;i,j}(x) \int d^4 y \Phi(y^2) J_{ij}^{\mu}(x, y). \quad (8)$$

Proceeding as outlined before we obtain

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

Since the results for the strong $J/\psi$ 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 $D^*_sD^*_s$ systems and iii) theory and experiment to consider the open charm decay modes, such as $D\bar{D}$, $D\bar{D}^*$, $D\bar{D}^*\gamma$, 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 $D^*_s\bar{D}^*_s$ system binds for $J^{PC} = 0^{++}$, hence give further support to the interpretation presented here.

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