Exotic resonances due to $\eta$ exchange

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ABSTRACT

The meson $X(3872)$ and several related states appear to be, at least in part, hadronic molecules in which a heavy flavored meson (such as $D^0$) is bound to another heavy meson (such as $\bar{D}^*0$). Although not the only effect contributing to the binding, pion exchange seems to play a crucial role in generating the longest-range force between constituents. Mesons without $u$ and $d$ light quarks (such as $D_s$) cannot exchange pions, but under suitable circumstances can bind as a result of $\eta$ exchange. Channels in which this mechanism is possible are identified, and suggestions are made for searches for the corresponding molecular states, including a manifestly exotic baryonic $\Lambda_c\bar{D}^{*0}$ resonance decaying into $J/\psi\Lambda$.

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The discovery more than a dozen years ago of an extremely narrow resonance, $X(3872)$ $[1]$, right at the $D\bar{D}^*$ threshold, inaugurated a flurry of observations of charmonium-like and bottomonium-like resonances similarly correlated with thresholds. A number of these could be identified as possessing a significant “molecular” component, in which a heavy charmed or bottom hadron was bound to an anticharmed or anti-bottom hadron $[2,3]$. When these hadrons possess light quarks, the longest-range force between them is single-pion exchange, in analogy with the deuteron which binds via exchange of pions and other light mesons $[4,9]$. The question then arises as to whether a related mechanism can play a role in binding heavy hadrons which contain no $u,d$ quarks. In this note we identify potential channels in which $\eta$ exchange is the longest-range force, and can thus form bound states with quark content such as $c\bar{s})(\bar{c}s)$. We predict masses based on the proximity to thresholds of charmed-antistrange and anticharmed-strange pairs. Such a proximity is a widespread feature of S-wave structures $[10]$.

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some (special attention to those which can be produced in decays of the form $\eta J/\psi \phi$) below about 4786 MeV. We take the masses others will not. In Table 1 we summarize possible resonances involving two $\eta$ exchange. The large binding energy in these two works is somewhat suspicious. The pseudoscalar $\eta$ cannot couple to a pair of scalar or pseudoscalar mesons. Thus

| States ($J^P$) | $M$ (MeV) | $M - M(J/\psi)$ | Binding by $\eta$? | Allowed $J^P$ |
|----------------|-----------|-------------------|-------------------|---------------|
| $D^+_s(0^-)D^-_s(0^-)$ | 3936.6 | -179.8 | No | – |
| $D^+_s(0^-)D^+_s(1^-)$ | 4080.4 | -36.0 | Yes | 1+ |
| $D^+_s(1^-)D^+_s(1^-)$ | 4224.2 | 107.8 | Yes | 0+, 2+ $^a$ |
| $D^+_s(0^-)D^*_{s0}(2317)(0^+)$ | 4286.0 | 169.6 | Yes | 0- |
| $D^+_s(0^-)D^*_{s1}(2460)(1^+)$ | 4427.8 | 311.4 | No $^b$ | [1-] $^b$ |
| $D^+_s(0^-)D^*_{s2}(2573)(2^+)$ | 4503.4 | 387.0 | No | – |
| $D^+_s(0^-)D^*_{s2}(2573)(2^+)$ | 4540.2 | 423.8 | Yes | 2- |
| $D^+_s(1^-)D^*_{s1}(2460)(1^+)$ | 4571.6 | 455.2 | Yes | 0-, 1-, 2- |
| $D^*_{s0}(2317)(0^+)$ | 4635.4 | 519.0 | No | – |
| $D^*_{s1}(2536)(1^+)$ | 4647.2 | 530.8 | Yes | 0-, 1-, 2- |
| $D^*_{s2}(2573)(2^+)$ | 4684.0 | 567.6 | Yes | 1-, 2-, 3- |
| $D^*_{s0}(2317)(0^+)$ | 4777.2 | 660.8 | Yes | 1+ |
| $D^*_{s1}(2536)(1^+)$ | 4852.8 | 736.4 | Yes | 1+ |
| $D^*_{s2}(2573)(2^+)$ | 4889.6 | 773.2 | No | – |
| $D^*_{s1}(2460)(1^+)$ | 4919.0 | 802.6 | Yes | 0+, 2+ $^a$ |
| $D^*_{s1}(2460)(1^+)$ | 4994.6 | 878.2 | Yes | 0+, 1+, 2+ |

$^a$ $J_P = 1^+$ forbidden by symmetry.

$^b$ Proximity of these two channels may lead to binding. See text.

$^c$ Cannot be produced in $B \to KX$ because of kinematic mass limit.

There have been observations $^{11-15}$ or failures to observe $^{16-18}$ a $J/\psi \phi$ resonance at 4140 MeV, which does not correspond to any known $D^{*+}D^-_s$ threshold. Both $\eta$ and $\phi$ exchange were considered in a work identifying the 4140 MeV state as a $D^{*+}D^-_s$ molecule $^{19}$, with predicted $J^P = 0^+$ and 2+ masses highly dependent on an arbitrary cutoff parameter. Such a molecule was also considered in Ref. $^{20}$, where the binding was due to $\eta$, $\sigma$, and $\phi$ exchange. The large binding energy in these two works is somewhat suspicious in view of the short range of these potentials. A recent work explains the 4140 MeV state as a mixture of 10% $D^{*0}D^{*0}$, 10% $D^{*+}D^{-s}$, and 80% $D^{*+}D^{-s}$ $^{21}$. If the existence of the $J/\psi \phi$ resonance at 4140 MeV is confirmed, it is likely to be due to an additional mechanism, beyond the $\eta$ exchange discussed here.

The pseudoscalar $\eta$ cannot couple to a pair of scalar or pseudoscalar mesons. Thus some $(c\bar{s})(c\bar{s})$ channels will receive a contribution to their binding from $\eta$ exchange, while others will not. In Table 1 we summarize possible resonances involving two $D_s$ mesons, with special attention to those which can be produced in decays of the form $B \to KX$, i.e., states below about 4786 MeV. We take the masses $M(D_s) = 1968.3$ MeV, $M(D^*_s) = 2112.1$ MeV, $M(D_{s0}^*(2317)) = 2317.7$ MeV, $M(D_{s1}^*(2460)) = 2459.5$ MeV, $M(D_{s1}^*(2536)) = 2535.11$ MeV, $M(D_{s2}^*(2573)) = 2571.9$ MeV, $M(J/\psi) = 3096.92$ MeV, $M(\phi) = 1019.46$ MeV, and $M(f_0) = 990$ MeV from Ref. $^{22}$. Thresholds involving two $D_s$ mesons are compared with the $J/\psi f_0$ and $J/\psi \phi$ thresholds in Fig. 1.
We now discuss the sign of the forces due to $\eta$ exchange in some of the lowest-mass channels in which binding is possible.

(i) $D_s^+ D_s^{-}$: This channel is analogous to $D^0 \bar{D}^{\ast 0}$ if one replaces a $u$ or $\bar{u}$ quark with an $s$ or $\bar{s}$ quark. Hence the binding due to $\eta$ exchange for the $C = +$ combination $(D_s^+ D_s^{-} + D_s^{+}\bar{D}_s^{-})/\sqrt{2}$ should be of the same sign as it is for the $X(3872)$, which is generally acknowledged as having a significant component of the $C = +$ combination $(D_0 \bar{D}_0^{*0} + D^{*0} \bar{D}^0)/\sqrt{2}$. The range, of course, will be smaller by a factor of $m_\pi/m_\eta$ than it is for pion exchange. As the $D_s^+ D_s^{-}$ threshold is 36 MeV below $M(J/\psi) + M(\phi)$, and just below $M(J/\psi) + M(f_0)$, the most one can expect is an enhancement in the $M_{J/\psi \phi}$ and $M_{J/\psi f_0}$ spectra near threshold.

(ii) $D_s^{\ast +} D_s^{-}$: The related channel $D^* \bar{D}^*$ was analyzed in Ref. [9], where it was concluded that the most attractive channel was the one with $I = J = 0$. This was a consequence of the expectation values

$$\langle I_1 \cdot I_2 \rangle = [1/2][I(I + 1) - I_1(I_1 + 1) - I_2(I_2 + 1)] = (-3/4, +1/4) \text{ for } I = (0, 1) , \quad (1)$$
$$\langle J_1 \cdot J_2 \rangle = [1/2][J(J + 1) - J_1(J_1 + 1) - J_2(J_2 + 1)] = (-2, -1, +1) \text{ for } J = (0, 1, 2) , \quad (2)$$

where the most attractive channel for a $q \bar{q}$ interaction is the one with the largest value of $\langle I_1 \cdot I_2 J_1 \cdot J_2 \rangle$. In the present case, in which the isospin factor is absent, the most

Figure 1: Comparison of $D_s^{(*)+} D_s^{(*)-}$ thresholds with those of $J/\psi f_0$ and $J/\psi \phi$. 

| 5000 MeV | $D_s D_s' (2460)$ |
| 4800 MeV | $D_s D_s' (2317)$ |
| 4600 MeV | $D_s D_s' (2573)$ |
| 4400 MeV | $D_s D_s' (2317)$ |
| 4200 MeV | $D_s D_s' (2317)$ |
| 4000 MeV | $D_s D_s' (2317)$ |

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Thresholds involving two $D_s$ mesons

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$J/\psi \phi$ threshold

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$J/\psi f_0$ threshold

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one $\eta$ exchange possible

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one $\eta$ exchange not possible
attractive channel will be that with $J = 2$. Thus, $\eta$ exchange between $D_{s}^{*+}$ and $D_{s}^{*-}$ should give rise to a $J^P = 2^+$ resonance near 4224 MeV decaying to $J/\psi \phi$.

(iii) $D_{s}^{+} D_{s0}^{*-}(2317)$: The forces due to $\eta$ exchange will be equal and opposite for eigenstates of the matrix

$$ V \sim \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} $$

in the channels $[D_{s}^{+} D_{s0}^{*-}(2317), D_{s0}^{*0}(2317) D_{s}^{*-}]$ (cf. the discussion of $D D^*$ in Ref. [9]). The eigenstates have positive and negative $C$, and thus $J^{PC} = 0^{-\mp}$. The attractive channel, with $C = +$, can decay to $J/\psi \phi$. One would then see a resonance near 4286 MeV with $J^{PC} = 0^{-+}$ decaying to $J/\psi \phi$. Indeed, the CDF Collaboration has $3.1\sigma$ evidence for a state at $4274^{+8.4}_{-6.7} \pm 1.9$ MeV decaying to $J/\psi \phi$ [12], identified as a $D_{s}^{+} D_{s0}^{*-}(2317)$ molecule in Refs. [23] and [24].

(iv) $D_{s}^{+} D_{s1}^{+}(2460)$ and $D_{s}^{*+} D_{s0}^{*-}(2317)$: The proximity of these two channels means that mixing between them due to $\eta$ exchange may be possible, with an interaction of the form (3). One should then expect a $J^P = 1^{-}$ resonance near 4429 MeV decaying to $J/\psi \phi$. The mixing will produce two eigenstates of opposite $C$, with $V$ attractive in the $C = +$ channel.

(v) We have included $D_{s2}^{*}(2573)$ in the discussion even though it is not as narrow as the other states, having a width of $17 \pm 4$ MeV. Any resonance involving it will be at least as broad, such as the predicted state around 4540 MeV with $J^P = 2^-$. The potential is again of the form (3), with the lower-lying eigenstate having $C = +$.

(vi) Arguments similar to those in (iii) may be applied to states near 4572, 4647, 4684, and 4777 MeV. In each case $\eta$ exchange gives an attractive force in one or more channels with $C = +$, giving resonances which can decay to $J/\psi \phi$.

If it turns out that $\eta$ exchange can indeed lead to $D_s D_s^*$ resonances, then analogous meson-baryon resonances should also exist, by the same reasoning as in [9]. A prerequisite is that both the meson and the baryon must be heavy, and at least one of them should not couple to pions. The simplest example is a $\Lambda_c D_s^*$ resonance, with quark content $c\bar{c}sud$. The relevant threshold is at 4398.6 MeV.

If such a $\Lambda_c D_s^*$ resonance does exist, its best chance of being formed is in $\Lambda_b$ decay. The decay $\Lambda_b \rightarrow \Lambda_c D_s^*$ is Cabibbo favored. The mass of $\Lambda_b$ is 5619.5 MeV, so approximately 1221 MeV needs to be carried off, e.g., by an extra $\pi^+\pi^-$ pair or, as recently suggested [25], by an $\eta$. The $\Lambda_c D_s^*$ resonance can decay through quark rearrangement to $J/\psi \Lambda$, with $Q$-value of approximately 186 MeV. The most promising discovery channel is then

$$ \Lambda_b \rightarrow J/\psi \Lambda \left( \pi^+\pi^- \text{ or } \eta \right) $$

where one looks for a $J/\psi \Lambda$ resonance around 4400 MeV.

When $u, d$ quarks are absent, $\eta$ exchange indeed seems to be the longest-range single-particle-exchange force available to form hadronic molecules of two systems containing heavy quarks. It will be interesting to see if the dynamics of this formation is sufficiently sensitive to $\eta$ exchange that the predicted states are observed.

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