Exotic resonances due to η exchange

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ABSTRACT

The meson $X(3872)$ and several related states appear to be in large part hadronic molecules in which a heavy flavored meson (e.g., D^0) is bound to another heavy meson (e.g., $\bar{D}^{*0}$). Although not the only contribution 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 conditions can bind as a result of η 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 $\Lambda_c \bar{D}_s^*$ resonance decaying into $J/\psi \Lambda$.

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The discovery more than a dozen years ago of a very 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 η 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]. We do not estimate detailed binding energies in this brief note, addressing only the utility of η exchange as a signal for molecule formation. We discuss briefly the role of other, shorter-range, exchanges such as η' , $f_0(980)$, and ϕ .

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Table 1: Possible S-wave resonances with two D_s mesons below 4.8 GeV. Only those states with $C = +$, permitted to couple to $J/\psi \phi$, are shown. Here $\Delta M \equiv M - M(J/\psi) - M(\phi)$. Exchanges are labeled “d” for direct ($A\bar{B} \rightarrow A\bar{B}$) and “x” for exchange ($A\bar{B} \rightarrow B\bar{A}$). “Rank” denotes anticipated ease of detection (see text). Allowed J^P values and rank are only shown for those states which can bind via η exchange.

States (J^P)	M (MeV)	ΔM (MeV)	Binding		Allowed J^P	Rank
			by η ?	by $f_0(980)$?		
$D_s^+(0^-) D_s^-(0^-)$	3936.6	-179.8	No	d	—	—
$D_s^+(0^-) D_s^{*-}(1^-)$	4080.4	-36.0	x	d	1^+	1
$D_s^{*+}(1^-) D_s^{*-}(1^-)$	4224.2	107.8	d	d	$0^+, 2^+{}^a$	2
$D_s^+(0^-) D_{s0}^{*-}(2317)(0^+)$	4286.0	169.6	x	d	0^-	2
$D_s^+(0^-) D_{s1}^-(2460)(1^+)$	4427.8	311.4	No ^b	d,x	$[1^-]{}^b$	2
$D_s^{*+}(1^-) D_{s0}^{*-}(2317)(0^+)$	4429.8	313.4	No ^b	d,x	$[1^-]{}^b$	3
$D_s^+(0^-) D_{s1}^-(2536)(1^+)$	4503.4	387.0	No	d,x	—	—
$D_s^+(0^-) D_{s2}^{*-}(2573)(2^+)$	4540.2	423.8	x	d	2^-	2
$D_s^{*+}(1^-) D_{s1}^-(2460)(1^+)$	4571.6	455.2	d,x	d,x	$0^-, 1^-, 2^-$	3
$D_{s0}^{*+}(2317)(0^+) D_{s0}^{*-}(2317)(0^+)$	4635.4	519.0	No	d	—	—
$D_s^{*+}(1^-) D_{s1}^-(2536)(1^+)$	4647.2	530.8	d,x	d,x	$0^-, 1^-, 2^-$	3
$D_s^{*+}(1^-) D_{s2}^{*-}(2573)(2^+)$	4684.0	567.6	d,x	d,x	$1^-, 2^-, 3^-$	3
$D_{s0}^{*+}(2317)(0^+) D_{s1}^-(2460)(1^+)$	4777.2	660.8	x	d	1^+	4

^a $J^P = 1^+$ forbidden by C symmetry.

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

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 $D_s^{*+} D_s^{*-}$ threshold. Both η and ϕ exchange were considered in a work identifying the 4140 MeV state as a $D_s^{*+} D_s^{*-}$ 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 η , σ , and ϕ 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% $D^{*0} \bar{D}^{*0}$, 10% $D^{*+} D^{*-}$, and 80% $D_s^{*+} D_s^{*-}$ [21]. If the $J/\psi \phi$ resonance at 4140 MeV is confirmed, it is likely to be due to a mechanism beyond the η exchange discussed here. For example, in Ref. [22] the 4140 MeV state is dynamically generated in the channels $D_s^{*+} D_s^{*-}$ and $D^* \bar{D}^*$ which are coupled by K^* exchange.

The pseudoscalar η cannot couple to a pair of scalar or pseudoscalar mesons, so some $(c\bar{s})(\bar{c}s)$ channels will receive a contribution to their binding from η exchange, while others will not. Thus no molecule will be expected near $D_s^+ D_s^-$ threshold. (Ref. [23] suggests $X(3915)$ could be such a state.) In Table 1 we summarize possible resonances involving two D_s mesons which can be produced in $B \rightarrow KX$ decays. We take $M(D_s) = 1968.3$ 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. [24]. “Rank” denotes ease of detection (lowest easiest), based on summing assigned scores of 0 for D_s , 1 for D_s^* (missing

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

photon), and 2 for the remaining (P-wave $c\bar{s}$) states. 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 η exchange in some of the lowest-mass channels in which binding is possible.

(i) $D_s^+ D_s^{*-}$: This channel is analogous to $D^0 \bar{D}^{*0}$ if one replaces a u or $\bar{u}$ quark with an s or $\bar{s}$ quark. Hence the binding due to η exchange for the $C = +$ combination $(D_s^+ D_s^{*-} + D_s^{*+} D_s^-)/\sqrt{2}$ 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 $(D^0 \bar{D}^{*0} + D^{*0} \bar{D}^0)/\sqrt{2}$. The range, of course, will be smaller by a factor of m_π/m_η 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) $D_s^{*+} D_s^{*-}$: The related channel $D^* \bar{D}^*$ was analyzed in Ref. [9], where it was concluded that the most attractive channel was the one with $I = J = 0$. (See also [25].) 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 $\langle I_1 \cdot I_2 \ J_1 \cdot J_2 \rangle$ [4]. In the present case, in which the isospin factor is absent, the most attractive channel will be that with $J = 2$. Thus, η 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 η exchange will be equal and opposite for eigenstates of the matrix

$$V \sim \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} \quad (3)$$

in the channels $[D_s^+ D_{s0}^{*-}(2317), D_{s0}^+(2317) D_s^{*-}]$ (cf. the discussion of $D\bar{D}^*$ in Ref. [9]). The eigenstates have positive and negative C , and thus $J^{PC} = 0^{-\pm}$. 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 3.1σ evidence for a state at $4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV decaying to $J/\psi \ \phi$ [12], identified as a $D_s^+ D_{s0}^{*-}(2317)$ molecule in Refs. [26] and [27].

(iv) $D_s^+ D_{s1}^{*-}(2460)$ and $D^{*+} D_{s0}^{*-}(2317)$: The proximity of these two channels means that mixing between them due to η 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 ± 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 η exchange gives an attractive force in one or more channels with $C = +$, giving resonances which can decay to $J/\psi \ \phi$.

The dominance of the long-range interaction by η exchange is much less certain than for pion exchange, as other states with $s\bar{s}$ content (notably η' , f_0 , and ϕ) have only about twice the η mass. However, this is a significant effect, as hadronic molecules tend to be large, with radii of order 1 fm or more. The larger the molecule, the more η exchange will be expected to dominate over the other exchanges, thanks to the exponential form of the Yukawa potential.

One should interpret Table 1 as an initial guide to whether η exchange can provide a quick signal of molecule formation. The “rank” assigned in Table 1 to various channels can help to indicate which of them are most likely to provide early information. If some signals are observed but not others, the pattern of “direct” ($A\bar{B} \rightarrow A\bar{B}$) vs. “exchange” ($A\bar{B} \rightarrow B\bar{A}$) contributions may provide valuable systematic information. For example, the exchange of the scalar meson $f_0(980)$ is allowed for all direct processes. In some processes

η exchange contributes only to exchange channels, while $f_0(980)$ exchange contributes only to direct channels. In other processes both direct and exchange contributions are allowed for both 0^- and 0^+ exchange.

If it turns out that η exchange can indeed lead to $D_s \bar{D}_s^*$ 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 $\Lambda_c \bar{D}_s^*$ resonance, with quark content $c\bar{c}sud$. The relevant threshold is at 4398.6 MeV. As in the case of the 4140 MeV meson, Ref. [28] finds that coupled channels contribute to dynamical generation of exotic baryon resonances.

If such a $\Lambda_c \bar{D}_s^*$ resonance does exist, its best chance of being formed is in Λ_b decay. The decay $\Lambda_b \rightarrow \Lambda_c \bar{D}_s^*$ is Cabibbo favored. The mass of Λ_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 [29], by an η . The $\Lambda_c \bar{D}_s^*$ resonance can decay through quark rearrangement to $J/\psi \Lambda$, with Q -value of approximately 186 MeV. The most promising discovery channel is then

$$\Lambda_b \rightarrow J/\psi \Lambda (\pi^+\pi^- \text{ or } \eta) \quad (4)$$

where one looks for a $J/\psi \Lambda$ resonance around 4400 MeV. Slightly different considerations have led the authors of Ref. [30] to expect a $J/\psi \Lambda$ resonance around 4650 MeV.

When u, d quarks are absent, η 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 η exchange that the predicted states are observed.

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