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Exotic resonances due to η 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 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 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 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].

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Table 1: Possible S-wave resonances with two D_s mesons below 5 GeV.

States (J^P)	M (MeV)	$M - M(J/\psi)$ $-M(\phi)$	Binding by η?	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]
$D_s^{*+}(1^-)\ D_{s0}^{*-}(2317)(0^+)$	4429.8	313.4	No[b]	$[1^-]$ [b]
$D_s^+(0^-)\ D_{s1}^-(2536)(1^+)$	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	$0^-, 1^-, 2^-$
$D_{s0}^{*+}(2317)(0^+)\ D_{s0}^{*-}(2317)(0^+)$	4635.4	519.0	No	–
$D_s^{*+}(1^-)\ D_{s1}^-(2536)(1^+)$	4647.2	530.8	Yes	$0^-, 1^-, 2^-$
$D_s^{*+}(1^-)\ D_{s2}^{*-}(2573)(2^+)$	4684.0	567.6	Yes	$1^-, 2^-, 3^-$
$D_{s0}^{*+}(2317)(0^+)\ D_{s1}^-(2460)(1^+)$	4777.2	660.8	Yes	1^+
$D_{s0}^{*+}(2317)(0^+)\ D_{s1}^-(2536)(1^+)$	4852.8[c]	736.4	Yes	1^+
$D_{s0}^{*+}(2317)(0^+)\ D_{s2}^{*-}(2573)(2^+)$	4889.6[c]	773.2	No	–
$D_{s1}^+(2460)(1^+) D_{s1}^-(2460)(1^+)$	4919.0[c]	802.6	Yes	$0^+, 2^+$ [a]
$D_{s1}^+(2460)(1^+) D_{s1}^-(2536)(1^+)$	4994.6[c]	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 $D_s^{*+} D_s^{*-}$ 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 existence of the $J/\psi\,\phi$ resonance at 4140 MeV is confirmed, it is likely to be due to an additional mechanism, beyond the η exchange discussed here.

The pseudoscalar η cannot couple to a pair of scalar or pseudoscalar mesons. Thus some $(c\bar{s})(\bar{c}s)$ channels will receive a contribution to their binding from η 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.

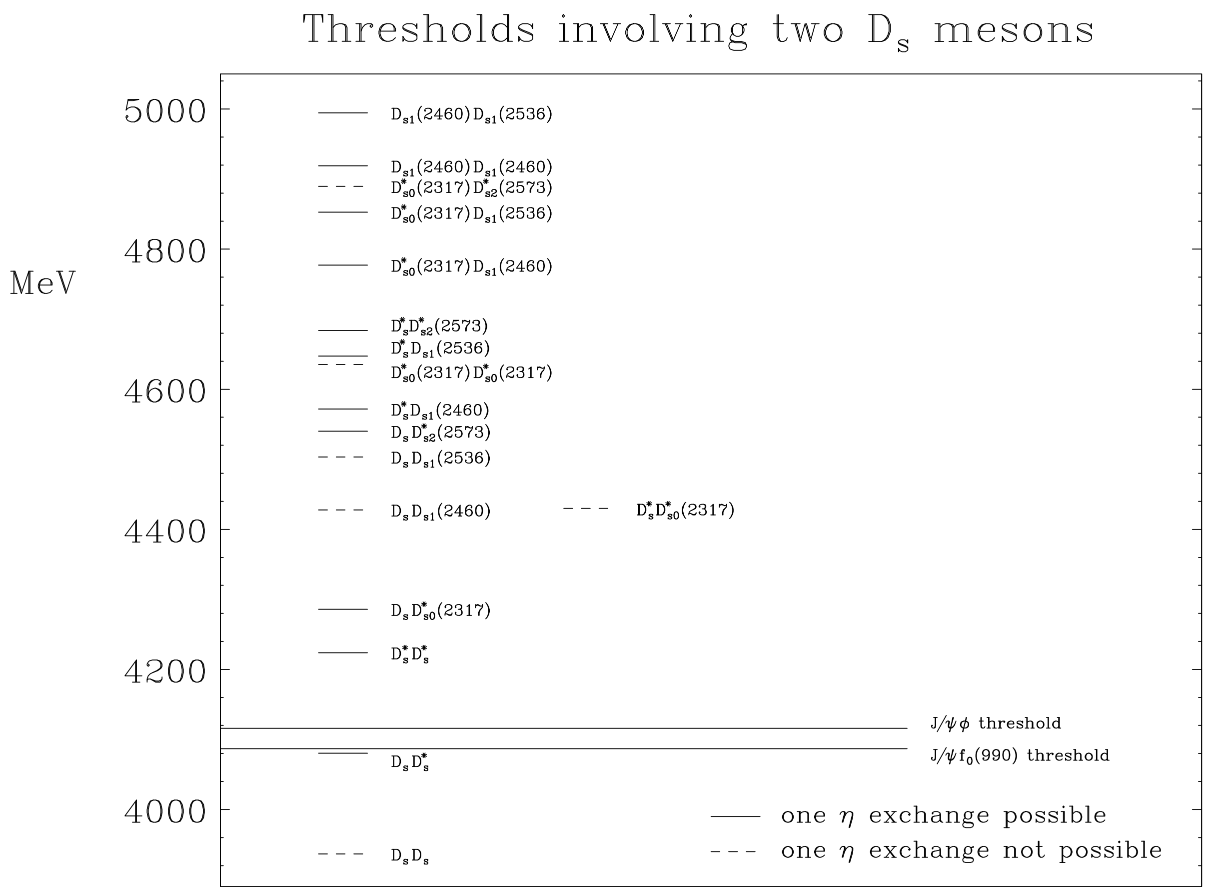

Figure 1: Comparison of $D_s^{(*)+} D_s^{(*)-}$ thresholds with those of $J/\psi\, f_0$ and $J/\psi\, \phi$.

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 $I = J = 0$. 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

$$V \sim \left[\begin{array}{cc} 0 & -1 \\ -1 & 0 \end{array} \right] \tag{3}$$

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. [23] and [24].

(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 $J/\psi\ \phi$.

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.

If such a $\Lambda_c\bar{D}_s^*$ resonance does exist, its best chance of being formed is in Λ_b decay. The decay $\Lambda_b \to \Lambda_c\bar{D}_s^*$ 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 [25], 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

$$\Lambda_b \to J/\psi\,\Lambda\,(\pi^+\pi^- \text{ or } \eta) \tag{4}$$

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