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The $D^{*0}\bar{D}^0$ threshold resonance

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Abstract

Tests are discussed to distinguish $c\bar{c}$, hybrid charmonium and molecular interpretations of the narrow Belle resonance at 3872 MeV.

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The Belle Collaboration recently reported the 10.3σ discovery of a resonance at mass $3872.0 \pm 0.6 \pm 0.5$ MeV with a width less than 2.3 MeV in $J/\psi\pi^+\pi^-$ [1]. The resonance, which is denoted here as $X(3872)$, is produced via the decay $B^\pm \to K^\pm X(3872)$ [1].

The most remarkable feature of $X(3872)$ is that it is, within errors, exactly at the $D^{*0}\bar{D}^0$ threshold at 3871.5 ± 0.5 MeV [2]. In fact, $M(X) - M(D^{*0}\bar{D}^0) = 0.5 \pm 0.9$ MeV. The next nearest open charm thresholds are $D^{\pm *}D^{\mp}$, which is 8.0 ± 1.0 MeV above $D^{*0}\bar{D}^0$, and $D_s^{\pm}D_s^{\mp}$, 64.7 ± 1.0 MeV above $D^{*0}\bar{D}^0$ [2]. Based on the mass of $X(3872)$ alone, it is expected that the resonance has a much larger $D^{*0}\bar{D}^0$ component in its wave function than $D^{\pm *}D^{\mp}$, or other, components. Even if $X(3872)$ is hypothesized to be a $c\bar{c}$ state, the degeneracy with the $D^{*0}\bar{D}^0$ threshold leads one to expect that the resonance couples, and mixes, with $u\bar{u}$ more strongly than with $d\bar{d}$ since the D^{*0} and D^0 have quark structure $c\bar{u}$. Hence, the multiquark quark content of the state is dominantly

$$c\bar{c}u\bar{u} = \frac{1}{\sqrt{2}}c\bar{c}\left(\frac{u\bar{u}+d\bar{d}}{\sqrt{2}} + \frac{u\bar{u}-d\bar{d}}{\sqrt{2}}\right) = \frac{1}{\sqrt{2}}\big(|I_s=0\rangle + |I_s=1\rangle\big), \quad (1)$$

which means that the state breaks isospin symmetry maximally. This could turn out to be the largest isospin breaking in the hadronic spectrum to date. Eq. (1) implies that the resonance has no definite isospin, and hence no well-defined G-parity. Isospin symmetry has also been hypothesized to be broken via a similar mechanism for the $f_0(980)$ and $a_0(980)$ states [3,4] and for the $D_s(2.32; 2.46)$ [5].

The observed decay $X(3872) \to J/\psi\pi^+\pi^-$ is not very restrictive for the possible quantum numbers

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of X: it is only possible to show that X cannot be $J^{PC} = 0^{--}$ exotic by conservation of these quantum numbers in QCD.

There are preliminary indications that $X(3872)$ prefers to decay to the high-mass part of the $\pi\pi$ spectrum in $J/\psi\pi^+\pi^-$ [1]. Assuming this is not due to the Adler zero which is known to suppress the low-mass $\pi\pi$ spectrum in $\psi' \to J/\psi\pi\pi$, this could be evidence for the decay $J/\psi\rho^0$. (The $J/\psi\omega$ threshold is 8 MeV above X, so that this mode is negligible). Decay to $J/\psi\rho^0$ means that X decays through its isospin 1 component, and has C-parity positive. The $J/\psi = \rho^0$ threshold is only 6.4 ± 1.1 MeV below the mass of the X [2], so that $X \to J/\psi\rho^0$ should preferably occur in S-wave. If X decays to $J/\psi\rho^0$ it cannot decay to $J/\psi(\pi\pi)_S$, since this final state has negative C-parity. The experimental data are consistent with X not decaying to $J/\psi(\pi^+\pi^-)_S$ [1]. If X indeed decays to $J/\psi\rho^0$, and it is assumed that it is narrow because it couples weakly to the only kinematically allowed open charm threshold ($D\bar{D}$), it follows that either

(1) The resonance has unnatural parity $0^-, 1^+, 2^-, 3^+, \ldots$, which cannot couple to $D\bar{D}$ by conservation of J^P. Together with positive C-parity this gives its $J^{PC} = 0^{-+}, 1^{++}, 2^{-+}, 3^{++}, \ldots$. Only 1^{++} can decay to $J/\psi\rho^0$ in S-wave;
(2) The resonance is in the J^{PC} exotic sequence $0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$, which cannot decay to $D\bar{D}$ by conservation of CP. Together with positive C-parity X should be $1^{-+}, 3^{-+}, \ldots$. Such states cannot decay to $J/\psi\rho^0$ in S-wave;
(3) The resonance decays to $D\bar{D}$, which is ~ 138 MeV below the X, in a very high wave. Resonances in the sequence $J^P = 3^-, 4^+, \ldots$, can decay to $D\bar{D}$ in F-wave and higher. Incorporating positive C-parity $J^{PC} = 3^{-+}, 4^{++}, \ldots$. These states cannot decay to $J/\psi\rho^0$ in S-wave.
(4) The decay of the resonance to $D\bar{D}$ is suppressed dynamically. An example of such a selection rule is that charmonium hybrid meson decay to $D\bar{D}$ is exactly zero in non-relativistic models with spin-1 pair creation [6]. Also, a large $D^*\bar{D}$ molecule will have suppressed decays to $D\bar{D}$, because the decay is proportional to the wave function at the origin $|\psi(0)|^2, |\psi'(0)|^2, \ldots$, in a non-relativistic formalism appropriate for large molecules.

The detection of $X(3872)$ in $J/\psi\pi^+\pi^-$ indicates that the state contains $c\bar{c}$ pairs. Various possibilities for the interpretation of the state arise, keeping in mind that naive expectations will be skewed by the mass coincidence with the $D^*\bar{D}$ threshold. In particular, as discussed above, the $D^{*0}\bar{D}^0$ + c.c. component will contain both isospins even though the state may have "originated" as isospin 0 conventional or hybrid charmonium. The possibilities are now listed starting with the more conservative ones. These possibilities can be distinguished experimentally by measuring the J^{PC} of the state.

Conventional charmonium. There are 3S, 2P, 1D and 1F charmonia predicted in the relevant mass region, of which 2^{--} can be narrow, if, as is expected, it is below the DD^* threshold. However, the 2^{--} possibility may already be excluded by potential models [1]. Within the realm of $C = +$ it is immediate from (1) and (3) that 3S charmonia are probably 0^{-+}, 2P charmonia are likely to be 1^{++}, that 1D charmonia should be 2^{-+}, and that 1F charmonia are probably 3^{++} or 4^{++}. The 3S and 1F levels are predicted to be at ~ 4.1 GeV, which is higher than the 2P and 1D levels, and less likely to explain the mass of X.

Although the 2P 2^{++} state does couple to $D\bar{D}$, it does so in D-wave, and an estimate suggests that the open charm width below $D^*\bar{D}$ threshold for this state is 0–4 MeV [7]. Such a state is consistent with the measured width of X, and can decay to $J/\psi\rho^0$ in S-wave.

Hybrid charmonium. The X mass region is somewhat lower than the region around 4.3 GeV where the lightest hybrid charmonia are located according to lattice QCD and models. The lightest hybrid charmonia in lattice calculations are the TE hybrids with $J^{PC} = (0, 1, 2)^{-+}$ and 1^{--}. The 0^{-+} and 2^{-+} do not couple to $D\bar{D}$ from (1), the 1^{-+} not due to (2), and 1^{--} has a suppressed coupling to $D\bar{D}$ from (4).

The X may be a conventional or hybrid charmonium state that strongly couples to the $D^*\bar{D}$ threshold, shifting it to the threshold, where it acquires molecular character. In this case no isospin partner of the X is expected.

$D^*\bar{D}$ molecule. Due to the nearness of the resonance to the $D^*\bar{D}$ threshold, this is a natural interpretation. A $D^*\bar{D}$ molecule was previously predicted [8–10]. If the resonance is below $D^*\bar{D}$ threshold, it would be natural to assume that it has the D^* and $\bar{D}$ in rela-

tive S-wave, since there is no evidence for other molecular states nearby in mass. Such a state can be 1^{+-} or 1^{++}, although the latter possibility is preferred by (1). Note that the recently discovered $D_s(2460)$ is probably also 1^{++} and may be similar to the X. Because $M(X) - M(D^{*0}\bar{D}^0) = 0.5 \pm 0.9$ MeV, the binding should be $\lesssim 0.4$ MeV, so that

$$r_{\text{r.m.s.}} \gtrsim \frac{1}{\sqrt{2\mu E_{\text{binding}}}} = 7 \text{ fm}, \tag{2}$$

larger than the size Eq. (2) gives for the deuteron (4 fm for the deuteron binding energy of 2.22 MeV). Here μ is the reduced mass of D^{*0} and $\bar{D}^0$. Because the constituents in the molecule are separated by nuclear distances, two implications obtain: (1) The binding is likely to be strongly influenced by long-distance π^0 exchange, which is known to be attractive [10], and (2) the constituents move non-relativistically with momentum $p \lesssim 1/r_{\text{r.m.s.}} = 30$ MeV. Because of the deuteron-like character of this loosely bound two-meson molecule, the term "deuson" was suggested to discriminate such states from molecules in atomic physics [9]. t-channel π^0 exchange can happen via $\bar{D}^0 \to \bar{D}^{*0}\pi^0$ and $D^{*0}\pi^0 \to D$. Interestingly, π exchange will not happen for a $D\bar{D}$ bound state, since the $\pi D\bar{D}$ vertex is zero by parity conservation. This explains why $1^{++}\bar{D}D^*$ molecules can exist without the existence of $0^+ D\bar{D}$ molecules.

Tornqvist has argued [9] that in the positive charge conjugation $I_s = 0$ there is a strong attraction arising from the spin–isospin factor associated with π exchange, giving a "relative binding number" (RBN [9]) of $-3/2$ (attraction, $I_s = 0$) and $+1/2$ (repulsion, $I_s = 1$). Thus there is one 1^{++} bound state in this limit. To see what happens as $m_d \gg m_u$ it is instructive first to see how the RBN arise by enumerating the individual contributions of the various π charge states. The particles with their quark contents are $D^+(c\bar{d})$, $D^0(-c\bar{u})$, $\bar{D}^0(u\bar{c})$, $D^-(d\bar{c})$, $\pi^+(u\bar{d})$ and $\pi^-(-d\bar{u})$. (We use D to represent D or D^*.) The π^0 is $(u\bar{u} - d\bar{d})/\sqrt{2}$ in the isospin limit, and $u\bar{u}$ when $m_d \to \infty$. There are four contributions in a specific time ordering, i.e., $D^0\bar{D}^0 \to D^0\bar{D}^0$ (with t-channel π^0 exchange through its $u\bar{u}$ component), $D^0\bar{D}^0 \to D^+D^-$ (π^- exchange), $D^0\bar{D}^0 \to D^+D^-$ (π^+ exchange) and $D^+D^- \to D^+D^-$ (π^0 exchange through its $d\bar{d}$ component). By inserting the quark contents, the amplitudes in the isospin limit are proportional to $-1/2, 1, 1$ and $-1/2$ for the four contributions, respectively. In the limit $m_d \to \infty$ they behave as $-1, 1, 1$ and 0, respectively. In the isospin limit

$$|I_s = 0\rangle = \frac{D^0\bar{D}^0 - D^+D^-}{\sqrt{2}},$$
$$|I_s = 1\rangle = \frac{D^0\bar{D}^0 + D^+D^-}{\sqrt{2}}, \tag{3}$$

the amplitude for the states in Eq. (3) become proportional to $(-1/2-1-1-1/2)/2 = -3/2 (I_s = 0$ state) and $(-1/2+1+1-1/2)/2 = +1/2 (I_s = 1$ state), as expected. When $m_d \to \infty$ the isospin basis is broken leaving two states, an infinitely heavy D^+D^- and a light $D^0\bar{D}^0$. The exchange amplitudes are then driven by the $u\bar{u}$ exchange only. The D^+D^- state experiences no splitting (fourth contribution). In the same normalisation as above, the state $D^0\bar{D}^0$ has an amplitude of -1 (first contribution).

Thus in this extreme there is a weakened binding at the $D^{*0}\bar{D}^0$ relative to the isospin limit and no effect at the charged threshold. An intermediate scenario where $m_u < m_d < \infty$ should give repulsion of the one level and attraction of the other. In general, there is only one attractive state. This starts out as $I_s = 0$ in the isospin limit and goes over into the $D^{*0}\bar{D}^0$ in the $m_d \to \infty$ limit. The conclusion is that there is only one molecular state bound by the pion associated with the $D^*\bar{D}$ threshold.

If the resonance X is above the $D^{*0}\bar{D}^0$ threshold, the D^{*0} and $\bar{D}^0$ are expected to be in a relative L-wave, with $L > 1$, since this will lead to an angular momentum barrier suppressing the constituents from annihilating, as the decay will at least be proportional to $|\psi'(0)|^2$. In addition, the potential must have a form which enables the wave function to be localized, so that it does not "fall-apart" to D^{*0} and $\bar{D}^0$.

If X is indeed a molecule, its D^{*0} component should decay with a width equal to that of D^{*0} (known to be < 2.1 MeV [2], and likely smaller than the width of the D^{*+}, which is $96 \pm 4 \pm 22$ keV [2]). This is consistent with the experimental bounds on the width of the state. Also, these decay modes of the state should derive from the decay modes of the D^{*0}, i.e., the state should be seen in $\bar{D}^0(D^0\pi^0)$ and $\bar{D}^0(D^0\gamma)$, and charge conjugates. It is hence predicted that when these modes are studied a signal will be seen at Belle, BaBar and CLEO. The relative strength

of the $\bar{D}^0(D^0\pi^0)$ and $\bar{D}^0(D^0\gamma)$ modes should be similar to the relative branching ratios of the D^{*0}, i.e., $(61.9 \pm 2.9\%)/(38.1 \pm 2.9\%)$ [2], because the D^{*0} in the molecule is almost on-shell.

In addition to the decay modes of the state mentioned above, there will be dissociation modes where the D^{*0} and $\bar{D}^0$ come together at the origin, rearranging the quarks to $c\bar{c}$ and $u\bar{u}$ pairs which evolve to a charmonium and light meson. (Modes involving a $c\bar{c}$ and two light quark pairs should be suppressed since an extra pair creation is required, and are not considered further here. Also, the radiative decay mode $c\bar{c}\gamma$ is not expected to be competitive as it requires not only a rearrangement of the molecule to $c\bar{c}u\bar{u}$, but also electromagnetic suppression. This is consistent with the non-observation of $X \to \chi_{c1}\gamma$ by Belle [1]. Further, note that this mode will be forbidden if $C(X) = +$, as advocated here.) The dissociation decay widths will be proportional to $|\psi(0)|^2$ for an S-wave molecule, and $|\psi'(0)|^2$ for a P-wave molecule. For light mesons such calculations in the case of the S-wave molecules ($f_0(980)$ and $a_0(980)$) can generate widths of order 100 MeV [11], while for P-wave molecules the widths are smaller [11]. In the likely scenario where the state is an S-wave 1^{++} molecule, these modes will dominate those mentioned in the previous paragraph. The modes allowed by phase space for a such a molecule are $\eta_c(\pi\pi)_S$, $J/\psi\rho^0$, $\chi_{c0}\pi^0$, $\chi_{c1}\pi^0$, $\chi_{c1}(\pi\pi)_S$, $\chi_{c2}\pi^0$ and $\chi_{c2}(\pi\pi)_S$.

If X is molecular in origin, there will also be short-range interactions. These interactions can be further t- or u-channel processes, or s-channel processes. The latter are particularly interesting when the $D^*\bar{D}$ threshold lies between two resonances. These resonances will interact with the threshold between them. The contribution to the potential for D^* scattering with $\bar{D}$ through an s-channel resonance is of the form

$$\frac{g^2_{R_1 DD^*}}{q^2 - m^2_{R_1}} + \frac{g^2_{R_2 DD^*}}{q^2 - m^2_{R_2}}, \tag{4}$$

neglecting the effect of widths. Here g_{RDD^*} is the coupling of the resonance R to D and D^*, and m_R is the mass of the resonance. If the D^* scattering with $\bar{D}$ is calculated at $q^2 = m^2_X$, and $m_{R_1} < m_X < m_{R_2}$, it is possible for the two terms to approximately cancel each other. This may well be the case for the Belle resonance, as the binding energy of this resonance is so small compared to other molecular candidates like the $f_0(980)$, $a_0(980)$ and $D_s(2.32; 2.46)$ whose binding is usually explained by assuming that either R_1 does not exist, or that it couples weakly. For example, if X is 1^{++}, the first resonance would be the 1P charmonium and the second one the 2P charmonium.

As is evident for the discussion of the molecular origin of X, it cannot be viewed in isolation: since interactions with charmonium states occur, that implies that the effect of $D^*\bar{D}$ on charmonium states should also be considered. Specializing to the case of two charmonium resonances, R_1 and R_2, with $m_{R_1} < m_{D^*\bar{D}} < m_{R_2}$, this mixing is expected to shift the R_2 and R_1 masses. The shift in the $D^*\bar{D}$ threshold can be analysed with the dynamics outlined around Eq. (4). The charmonium states will acquire $D^*\bar{D}$ components. If X is 1^{++}, then R_1 is the $\chi_{c1}(3510)$. Mixing with the $D^*\bar{D}$ threshold will induce a $c\bar{c}n\bar{n}$ ($n\bar{n} = (u\bar{u} + d\bar{d})/\sqrt{2}$) component in the χ_{c1} wave function within isospin symmetry. Since the $D^{*0}\bar{D}^0$ threshold is nearer to the χ_{c1} mass than the $D^{*\pm}D^{\mp}$ threshold, the $c\bar{c}u\bar{u}$ component will dominate the $c\bar{c}d\bar{d}$ component, leading to isospin violating decays like $\chi_{c1} \to \rho^{\pm}\pi^{\mp}$ and $\pi\pi = K^+K^- > \pi\pi K^0\bar{K}^0$, which should be searched for experimentally. The $c\bar{c}n\bar{n}$ component will lead to an additional contribution to $\eta_c(\pi\pi)_S$ (and $\eta_c\pi\pi$), and light hadron modes of χ_{c1}. In the former case this is because $c\bar{c}n\bar{n}$ can decay via OZI allowed diagrams with one pair creation, while the conventional $c\bar{c} \to c\bar{c}$ (light hadrons) requires the light hadrons to be created via two pair creations from two gluons violating the OZI rule. It is known that $c\bar{c}$ components of χ_{cJ} cannot describe their decays, both inclusively and exclusively [12]. The light hadron modes of χ_{c1} coming from its $c\bar{c}$ component going via OZI forbidden two-gluon annihilation is suppressed by Yang's theorem. A $c\bar{c}n\bar{n}$ component can have $c\bar{c}$ annihilation into a colour octet gluon, yielding light hadrons via OZI allowed diagrams. An additional contribution to measured final states like $2(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$ and $K^0_S K^+\pi^-$ is hence expected. It is noted in passing that threshold mixing with other narrow states should also be important, e.g., mixing of χ_{c0}, χ_{c2} and $\psi(2S)$ with the $D\bar{D}$ threshold.

In summary, of the $c\bar{c}$, hybrid and molecular possibilities considered the $J^{PC} = 1^{++}$ assignment for X seems most promising, because it allows an S-wave

interaction between the D^0 and D^{*0}, *and* it couples to $J/\psi\rho^0$. This resonance can be a 2P resonance shifted by a threshold, of genuine molecular origin, or is generated by a "shepherd state" scenario [5] where the two-meson continuum is driven into a bound state just below threshold. A 1^{++} resonance should be weakly produced in $\gamma\gamma$ collisions by Yang's theorem.

It is suggested that BES and CLEO-III search for $e^+e^- \to X$, as observation will signal 1^{--} quantum numbers not expected here. Also, discovery of X in $p\bar{p} \to X$ at FNAL will indicate whether X is J^{PC} exotic or not, as J^{PC} exotic quantum numbers cannot be produced. Central production in, e.g., $pp \to pXp$ at high energy by double Pomeron exchange would confirm $C = +$, since the Pomeron has $C = +$. The azimuthal angular distribution for production of X will have a characteristic dependence on J^P [13].

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While this work was in preparation, a discussion of the molecular possibility with similar conclusions to ours has appeared [14].

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