The XYZ mesons: what they aren't

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Abstract. I discuss the properties of some representative *XYZ* mesons in the context of the most commonly proposed models for their underlying nature.

1 Some recent history

The study of hadron spectroscopy had enormous success in the latter part of the twentieth century, when the charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) mesons were discovered and it was established that the mass spectra of these states, and many of their properties, could be accurately described by the Quarkonium model, which is based on non-relativistic Quantum Mechanics with a simple potential comprised of a coulombic short-ranged component smoothly coupled to a linearly rising "confining" term at larger distances. Figure 1 shows the status of the charmonium spectrum in 2003, where the established charmonium mesons are colored yellow and the predicted but at that time unassigned states are gray. The assigned mesons all have properties that closely match their model-based expectations. Moreover, exceptions, *i.e.*, $c\bar{c}$ mesons that could not be accommodated by this simple picture, were not seen. At the turn of the century, which coincided with the first operation of the PEPII/BaBar and KEKB/Belle "*B*-factory" experiments, it was generally thought that one of the tasks for early twenty-first century experiments would be the fleshing out some of the remaining unassigned charmonium (and bottomonium) levels.

One of the big surprises from the *B*-factory experiments was the discovery of mesons with decay final states that include a *c*- and a *c̄*-quark that cannot be assigned to any of the remaining unassigned levels of the charmonium spectrum. The first of these *charmoniumlike*[1] states to be observed was the *X*(3872) that was seen by Belle as a distinct narrow peak in the $\pi^+\pi^- J/\psi$ invariant mass distribution in $B \rightarrow K\pi^+\pi^- J/\psi$ decays [2] (see Fig. 2). The J/ψ in its decay final state is a clear indication that the *X*(3872), whatever it is, must contain a *c*- and *c̄*-quark.[2] Although the original Belle report was based on only ∼36 signal events, it established two properties of the *X*(3872) that ruled against its interpretation as a two-quark, $c\bar{c}$ charmonium state:

i) its mass, reported at that time to be $M_{X(3872)} = 3872.0 \pm 0.8$ MeV and shown as a green horizontal line in Fig. 1, was a poor match to expectations for any of the unassigned $c\bar{c}$ charmonium states at that time;

ii) the $\pi^+\pi^-$ invariant mass peaked near the $M_{X(3872)} - m_{J/\psi} \approx 775$ MeV kinematic boundary,

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[1]*Charmoniumlike* is used to designate states that appear to contain a *c*- and *c̄*-quark but have properties that do not match expectations for a $c\bar{c}$ charmonium level.

[2]The large mass of the *c*-quark ensures that the probability for the production of a $c\bar{c}$ pair from the vacuum during the quark to hadron fragmentation process is negligibly small.
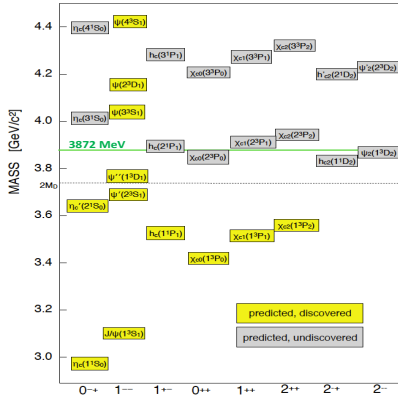
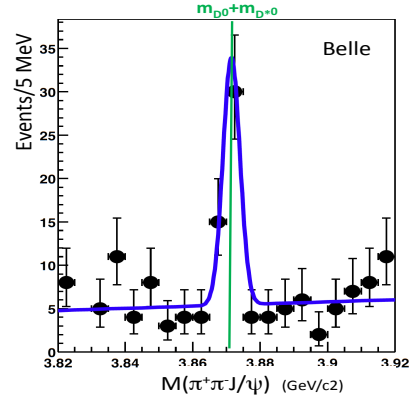**Figure 1.** The charmonium spectrum circa 2003.

Figure 2. The $X(3872)$ signal with all the Belle data [1].

consistent with an $X(3872) \rightarrow \rho J/\psi$, $\rho \rightarrow \pi^+\pi^-$ decay chain. All charmonium states are isoscalars and the ρ-meson is an isovector; if the $X(3872)$ is a charmonium state, its decay to $\rho J/\psi$ would be a suppressed isospin-violating process and an unlikely discovery mode.

A third striking feature of the $X(3872)$ that was also noted in ref. [2] is that its mass is indistinguishable from the $D^0\bar{D}^{*0}$ mass threshold, which, in 2003, was known to be $m_{D^0} + m_{D^{*0}} = 3871.1 \pm 1.1$ MeV [3] $[M_{X(3872)} - (m_{D^0} + m_{D^{*0}}) = 0.9 \pm 1.4$ MeV].[3] This suggested that there is a close relationship between the $X(3872)$ and the $D^0\bar{D}^{*0}$ meson system. In fact, two weeks after Belle posted its first (preliminary) $X(3872)$ results in August 2003 [5], Törnqvist posted a note [6] that identified it as a composite deuteronlike $D\bar{D}^*$ state that he had predicted ten years earlier and called a "deuson" [7]. He predicted: its quantum numbers to be $J^{PC} = 0^{-+}$ or 1^{++}; a width of order 50 keV; and a strong decay mode to be $D^0\bar{D}^0\pi^0$ via $D^0\bar{D}^{*0}$. What we now know about the $X(3872)$ aligns well with Törnqvist's predictions: LHCb established its J^{PC} to be unambiguously 1^{++} [8, 9]; Belle placed an upper limit on its width of 1.2 MeV [1]; and both Belle & BaBar have reported that $X(3872) \rightarrow D^0\bar{D}^0\pi^0$ is the dominant decay mode [10–12], with a branching fraction that is greater than 40% [4].

The proximity of $M_{X(3872)}$ to the $D^0\bar{D}^{*0}$ mass threshold and the plausibility of Törnqvist's arguments encouraged us to believe that the $X(3872)$ was the harbinger of a new spectroscopy of open-charmed meson-meson molecules bound by nuclear-physics-like forces, as first advocated in 1976 [13–15]. So, in addition to filling some of the gray boxes in Fig. 1 with bona-fide $c\bar{c}$ states, my colleagues and I expected to spend the first few decades of the twenty-first century establishing a new spectroscopy of deuteron-like $D^{(*)}\bar{D}^{(*)}$ molecular states.

2 What are they? ... or, better, what aren't they?

Sure enough, as the B-factory programs unfolded, and BESIII started up, additional $c\bar{c}$ charmonium states were found,[4] along with a larger number of charmoniumlike states, both neutral and charged, as indicated in Fig. 3. The properties of these states, which are collectively known as the XYZ mesons, have been extensively reviewed (see, for example, ref. [16]) and are generally well known. What is not well known is *what they are*, and this has turned out to be a very challenging issue. Here I address a more modest question: *what aren't they?*

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[3]With 2018 PDG values ($M_{X(3872)} = 3871.69 \pm 0.17$ MeV and $m_{D^0} + m_{D^{*0}} = 3871.70 \pm 0.10$ MeV [4]), $M_{X(3872)}$ and the $D^0\bar{D}^{*0}$ mass threshold are even closer: $[M_{X(3872)} - (m_{D^0} + m_{D^{*0}}) = -0.01 \pm 0.20$ MeV].

[4]The χ'_{c0}, χ'_{c2} and $\psi_2(1^3D_2)$.

Proposed theoretical models for these new states include:

molecules: loosely bound deuteron-like meson-meson structures;

QCD tetraquarks: colored quark ($[cq_i]$) and diantiquark ($[\bar{c}\bar{q}_j]$) configurations ($q_i = u, d, s$) tightly bound by the exchange of colored gluons;

charmonium hybrids: a $c\bar{c}$ pair plus an excited "valence" gluon (and electrically neutral);

threshold effects: enhancements caused by threshold cusps, rescattering processes, etc.;

hadrocharmonium: a colorless hadron cloud of light quarks & gluons, bound to a $c\bar{c}$ charmonium core state via van-der-Waals forces.

Here I briefly discuss each of these possibilities, with emphasis on their experimental consequences. I restrict the discussion to six candidate *XYZ* mesons that are experimentally well established and whose J^{PC} values are known: *i.e.,* the isospin zero $X(3872)$, $X(3915)$ [17, 18] and $Y(4220)$ [19],[5] and the isospin one $Z_c(3900)$ [21, 22], $Z_c(4020)$ [23] and $Z(4430)$ [24].
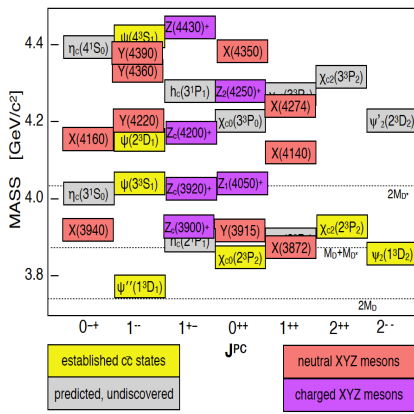

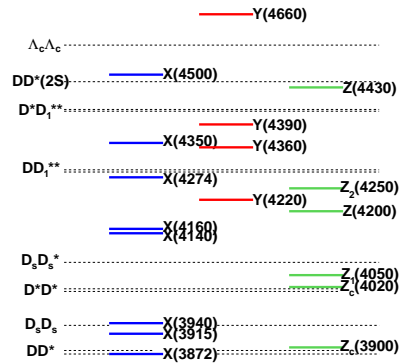**Figure 3.** The above open-charm-threshold charmonium & charmoniumlike spectrum in 2018.

Figure 4. *XYZ* meson masses compared with charmed meson pair thresholds.

2.1 Molecules:

The expected properties of a deuteronlike molecular state are conveniently listed by Karliner and Skwarnicki in the context of remarks about Pentaquarks in the PDG 2018 report [4]:

a) mass near the constituent meson-meson threshold and J^{PC} consistent with an S-wave;

b) narrow despite the large phase-space for $c\bar{c}$ + pion(s) decays;

c) branching fraction for meson-meson "fall-apart" decay larger than that for $c\bar{c}$ + pion(s);

d) not a pseudoscalar-pseudoscalar, for which single-pion exchange is not allowed;

e) wider than either of its constituents.

I take "near the constituent meson-meson threshold," to mean $BE \lesssim m_\pi^2/2\mu \approx 10$ MeV (for reduced mass $\mu \approx m_D/2$), corresponding to an rms meson-meson separation $d_{\mathrm{rms}} \gtrsim m_\pi^{-1}$.

Figure 4 shows how the measured *XYZ* meson masses compare with the charmed-particle/anticharmed particle mass thresholds below 4600 MeV. No clear pattern of *XYZ* states favoring thresholds is evident. The $Z_c(3900)$ and $Z_c(4020)$ are above, but within ~10 MeV, of the $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds, respectively and qualify as unbound, virtual meson-meson states. The $X(3915)$ is ≈ 100 MeV below $2m_{D^*}$ and 18 MeV below $2m_{D_s}$. The

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[5]Commonly known as $Y(4260)$, but whose mass has recently been measured to be 4222 ± 3 MeV by BESIII [20].

binding energy required for $D^*\bar{D}^*$ molecule is too high;[6] $D_s\bar{D}_s$ is a disqualified pseudoscalar-pseudoscalar combination (this is discussed in ref. [26]). Some authors interpret the $Y(4220)$ as an S-wave $D\bar{D}_1(2420)$ molecule, but provide no explanation for the ≈ 65 MeV binding energy this would imply [27]. The mass of the $Z(4430)$, now established to be 4478 ± 18 MeV, is equal within errors to $m_D + M_{D(2600)} \simeq 4480$ MeV, where the $D(2600)$ is a candidate for the $D^*(2S)$ radial excitation of the D^* that was reported by BaBar [28]. However, $\Gamma_{Z(4430)} = 181 \pm 31$ MeV, and $\Gamma_{D(2600)} = 93 \pm 15$ MeV, and one wonders if the concept of molecule applies to objects with such short lifetimes.

2.1.1 The X(3872) as a molecule?

Although the $X(3872)$ is often considered to be the prototypical meson-meson molecule, this may not be the case. Its decay to $D^0\bar{D}^{*0}$ means that its S-wave $D\bar{D}^*$ coupling, $g_{D\bar{D}^*}$, is non-zero and, since its mass is very near $m_{D^0} + m_{\bar{D}^{*0}}$, the effects of $g_{D\bar{D}^*}$ get strongly amplified by the nearly divergent $[M_X - (m_{D^0} + m_{\bar{D}^{*0}}) + k^2/2\mu]^{-1}$ propagator that occurs in coupled-channel calculations. So, whatever its underlying nature may be, the near equality of the $X(3872)$ mass with $m_{D^0} + m_{\bar{D}^{*0}}$ [7] will make it behave like a $D\bar{D}^*$ molecule [29, 30]. Detailed calculations show that coupled-channel effects are more important than meson-meson binding [31].

2.2 QCD tetraquarks

Since the diquark and diantiquark in a QCD tetraquark are bound by the color confining force, the binding energies are technically infinite and strong mass affinities for meson-meson thresholds are not expected; just about any mass and many J^{PC} values can be accommodated. Thus, in the absence of a specific model, any charmoniumlike meson state with quantum numbers consistent with a $[cq_i][\bar{c}\bar{q}_j]$ arrangement can be explained as a QCD tetraquark. On the other hand, since the QCD color force is flavor blind and the same for $[cu]$, $[cd]$ and $[cs]$ diquarks (and diantiquarks), QCD tetraquarks should form $SU(3)$ nonets [32]. However, other than the $Z_c(3900)$ and $Z_c(4020)$ isospin partners, none of the expected nonet partner states have been seen. This may reflect a lack of experimental sensitivity, but, in cases where experimentally verifiable predictions have been made [32, 33], the expected partner particles have not been found [1, 34].

The $X(3915)$, which is an unlikely candidate for a molecule (see above) and too light to be a charmonium hybrid (see below), is, by default, a candidate for an $[cs][\bar{c}\bar{s}]$ QCD tetraquark state [35]. In this case, its quark content would be better matched to $\eta\eta_c$ than to $\omega J/\psi$,[8] and one would naïvely expect the partial decay width for $X(3915) \to \eta\eta_c$ to be substantially larger than that for the $X(3915) \to \omega J/\psi$ discovery channel. A Belle search for $X(3915) \to \eta\eta_c$ saw no signal and set a upper limit $\Gamma_{X\to\eta\eta_c} < 1.5 \times \Gamma_{X\to\omega J/\psi}$ [38], which is not encouraging for a QCD tetraquark assignment.

2.3 Charmonium hybrids

Of the six XYZ mesons that we are considering, only the $X(3872)$, $X(3915)$ and $Y(4260)$ are electrically neutral and viable candidates for $c\bar{c}$-gluon charmonium hadrons. The strongest positive indication of a charmonium hybrid would be exotic spin-parity quantum numbers,

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[6]In ref. [25], the $X(3915)$ is interpreted as a (mostly) $D^*\bar{D}^*$ system tightly bound by vector-meson exchange and a vector-vector contact term. However, there is no independent evidence for the existence of the proposed binding mechanism, and the predicted accompanying 1^{+-} and 2^{++} mesons have not been seen.

[7]It is not known if this near equality is the result of some dynamics or just a coincidence.

[8]The η's $|s\bar{s}>$ and $|u\bar{u} + d\bar{d}> / \sqrt{2}$ contents are nearly equal [36]; the ω's $|s\bar{s}>$ content is nearly zero [37].

e.g., J^{PC} values that cannot be accessed by a fermion-antifermion pair, but could be formed by a $c\bar{c}$-gluon system. Examples would be $J^{PC} = 0^{--}$, 0^{+-}, 1^{-+} or 2^{+-} mesons. However, all *XYZ* meson candidates reported to date have non-exotic J^{PC} values. Another charmonium hybrid characteristic would be a preference to decay to a $D^{(*)}\bar{D}^{**}$ pair, *i.e.,* an S-wave $c\bar{q}_i$ meson plus P-wave $\bar{c}q_j$ antimeson ($q_i = u, d$), or vice-versa [39]. However the only distinctively narrow and relevant P-wave $c\bar{q}$ meson is the $D_1(2420)$, and the $D\bar{D}_1(2420)$ decay channel is energetically inaccessible to all three states.

The Hadron Spectrum Collaboration (HSC) reported charmonium and charmonium-hybrid mass values calculations performed on two lattice volumes with a pion mass $\approx$400 MeV [40]. Their lightest 1^{++} hybrid mass value is $\approx$4400 MeV, more than 500 MeV too high for an $X(3872)$ assignment, and their lightest 0^{++} hybrid mass is $\approx$4480 MeV, an equally poor match to the $X(3915)$. On the other hand, their mass value for the lightest 1^{--} hybrid is $\approx$4380 MeV, and consistent with the $Y(4220)$ mass within the $\sim$100 MeV precision that characterizes their calculation.[9] Thus, although there is no other strong evidence to back a charmonium-hybrid assignment for the $Y(4220)$, there is nothing that rules it out.

2.4 Threshold effects

In coupled channel systems that involve an S-wave meson-meson system (the "elastic channel"), cusp-like peaks can be produced in other channels by purely kinematic effects [41–43] or by rescattering processes with internal triangular loops [44, 45] that become singular when the internal particles go on the mass shell [46]. These peaks occur at masses just above the relevant threshold and have narrow, but non-zero widths. The $Z_c(3900)$, seen as S-wave $\pi J/\psi$ and $D\bar{D}^*$ mass peaks just above the $D\bar{D}^*$ threshold, is a candidate for this kind of effect, as is the $Z_c(4020)$, which is seen as πh_c and $D^*\bar{D}^*$ mass peaks just above the $D^*\bar{D}^*$ threshold.[10] An analysis of the $Z_c(3900)$ [47] concluded that while a kinematic cusp just above the $D\bar{D}^*$ threshold can be produced in the $\pi J/\psi$ mass distribution, this effect cannot produce a similarly narrow peak in the elastic $D\bar{D}^*$ channel. Thus, according to ref. [47], BESIII's narrow $Z_c(3900) \rightarrow D\bar{D}^*$ signal [48] establishes the presence of a genuine meson-like pole in the $D\bar{D}^*$ S-matrix. Similar considerations obtain for the $Z_c(4020)$ and its $D^*\bar{D}^*$ decay mode [49]. A more general discussion of the theoretical issues is provided in ref. [50].

2.5 Hadrocharmonium

For conventional charmonium states that are above the open-charmed meson pair threshold, branching fractions for "fall-apart" decays to charmed meson pairs are 2 or 3 orders of magnitude higher than decays to hidden charm states. On the other hand, most of the *XYZ* mesons were discovered via their hidden charm decay modes, which, in contrast to ordinary charmonium states, have branching fractions that are within one order of magnitude of those for fall-apart modes. The hadrocharmonium mode was proposed to account for this. In this model, a compact color-singlet $c\bar{c}$ charmonium core state is embedded in a spatially extended "blob" of light hadronic matter. These two components interact via a QCD version of the van der Waals force [51]. In the case of the $Y(4220)$, this core state was taken to be the J/ψ. Since the J/ψ is present in its constituents, the $Y(4220)$ naturally prefers to decay to final states that include it, such as the $Y(4220) \rightarrow \pi^+\pi^- J/\psi$ discovery mode.

Precision BESIII measurements of $\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)$, shown in Fig. 5, revealed two peaks in the $\sqrt{s} = 4260$ MeV region: the $Y(4220)$ and $Y(4320)$ [20]. Measurements of

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[9]The HSC-calculated masses for the χ'_{c0} and χ'_{c2} charmonium states are also high by about 100 MeV.

[10]The $Z_b(10, 610)$ and $Z_b(10, 650)$ "bottomoniumlike" mesons are seen as $\pi\Upsilon(nS)$ ($n = 1, 2, 3$), $\pi h_b(mP)$ ($m = 1, 2$) and $B^{(*)}\bar{B}^*$ mass peaks just above the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds.
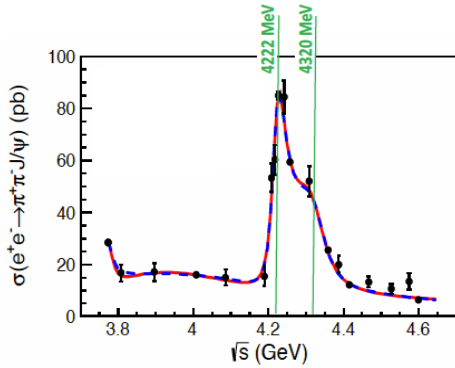
Figure 5. BESIII $\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)$ measurements [20] that show that the $Y(4260)$ is actually two peaks with masses 4222 ± 3 MeV and 4320 ± 13 MeV. The $Y(4220) \rightarrow \pi^+\pi^- J/\psi$ peak cross section is 85 ± 6 pb.
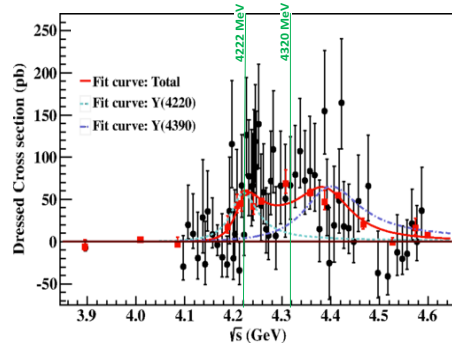
Figure 6. BESIII $\sigma(e^+e^- \rightarrow \pi^+\pi^- h_c)$ measurements [52]. Here there is a strong $Y(4220)$ signal but the $Y(4320)$ is absent. The $Y(4220) \rightarrow \pi^+\pi^- h_c$ peak cross section is 55 ± 9 pb.

$\sigma(e^+e^- \rightarrow \pi^+\pi^- h_c)$ (Fig. 5) [52], show that the $Y(4220) \rightarrow \pi^+\pi^- h_c$ decay branching fraction is comparable to that for $\pi^+\pi^- J/\psi$. Since the $c\bar{c}$ is in a spin-singlet state in the h_c and a spin triplet state in the J/ψ, the $c\bar{c}$ core in the hadrocharmonium version of the $Y(4220)$ should be one or the other, but not a mixture of the two. However, the $Y(4220)$ itself could be a mixture of two hadrocharmonium states, one with an h_c core and the other with a J/ψ core [53]. This implies the existence of two $Y(4220)$-like states with orthogonal h_c-J/ψ mixtures. The obvious candidate for the second state is the $Y(4360)$ [20], but there is no sign of it in the $\sigma(e^+e^- \rightarrow \pi^+\pi^- h_c)$ measurements shown in Fig. 6,[11] as would be expected for a J/ψ-h_c mixture orthogonal to the $Y(4220)$. Even though hadrocharmonium was originally proposed as an explanation for the properties of the $Y(4220)$, it has trouble explaining BESIII's $Y(4220)rt\pi^+\pi^- J/\psi$ and $\pi^+\pi^- h_c$ measurements. Recently, BESIII reported observation of $X(3872) \rightarrow \pi^0\chi_{c1}$ with a (preliminary) branching fraction that is $(0.9 \pm 0.3) \times \mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi)$ [54]. This implies a similar dilemma for a hadrocharmonium interpretation for the $X(3872)$.

3 No single size fits all

Table 1 summarizes the above discussion, where the red entries indicate assignments that are ruled out and the blue ones designate the best of the remaining possibilities for each meson under consideration. Possiblities that the Z_c states may be threshold effects are indicted in olive (and not red) because, in spite of the arguments in ref. [47], the match between the properties of these states (and the similar Z_b states) and expectations for kinematically induced peaks (*i.e.*, masses just above threshold, similar widths, not seen in *B*-meson decays, etc.) is so uncanny, I think more information is needed before they can be conclusively ruled out. The black question marks reflect my lack of knowledge.

While red entries indicate assignments that I consider ruled out for reasons given above, blue entries are blue mainly by default. Other than that for the $X(3872)$, blue assignments are not strongly supported by experimental evidence, but are not ruled out either. Establishing what the *XYZ* mesons *are* will require more experimental and theoretical investigation.

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[11]The second peak in Fig. 6 is at 4392 ± 7 MeV and quite distinct from the 4320 MeV structure in Fig. 5.

Table 1. Comparison of meson properties with model expectations. The text describes the color code.

state	molecule?	tetraquark?	charmonium hybrid?	kinematic effect?	hadro-charmonium?
$X(3872)$	coupled-channel system; not a deuson	partner states not found	m≈500 MeV too low	width too narrow	decays to $\gamma J/\psi$ & $\gamma\chi_{c1}$
$X(3915)$	π-exchange forbidden	$\eta\eta_c$ decay not seen	m≈500 MeV too low	no nearby threshold	???
$Y(4220)$	$D\bar{D}_1(2420)$ BE≈65 MeV -too high-	???	possible	no nearby threshold	decays to $\pi^+\pi^- J/\psi$ & $\pi^+\pi^- h_c$
$Z_C(3900)$	$D\bar{D}^*$ virtual state?	???	Isospin=1	possible?	???
$Z_c(4020)$	$D^*\bar{D}^*$ virtual state?	???	Isospin=1	possible?	???
$Z(4430)$	too wide for a $D\bar{D}^*(2P)$ molecule?	???	Isospin=1	too wide	???

I conclude that no single one of the models addressed above can satisfactorily explain all the results. If we are ever to have a coherent, comprehensive understanding of the *XYZ* particles, a new idea is needed. Otherwise we will be left with an (unsatisfactory) menu of different models with column A for some states, column B for others, etc.

4 Acknowledgements

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