Hadronic Spectrum - Multiquark States

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Abstract

Many newly discovered mesons behave like $c\bar{c}$ charmonium states in that they preferentially decay into final states that contain a $c$- and a $\bar{c}$-quark, but do not fit expectations for any of the unfilled levels of the conventional $c\bar{c}$ spectrum. There is a growing suspicion that at least some of these states are exotic, i.e., have a substructure that is more complex than the quark-antiquark mesons of the classical constituent quark model. Some of these candidate states have a non-zero electric charge and, thus, a minimal quark content of $c\bar{c}u\bar{d}$ or $c\bar{c}d\bar{u}$. In addition, states with similar properties have been observed in the $b$- and $s$-quark sectors. In this report, the experimental situation is briefly reviewed.

Key words: charmonium, exotic mesons, XYZ mesons
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1. Introduction

Quantum Chromodynamics (QCD) suggests the possible existence of hadrons with a substructure that is more complex than the three quark baryons and the quark-antiquark mesons of the Quark Parton Model (QPM). Possibilities for these so-called exotic hadrons include pentaquark baryons ($qq\bar{q}q\bar{q}$), tetraquark mesons ($q\bar{q}q\bar{q}$) and quark-gluon hybrids ($q\bar{q}g$). Although considerable theoretical and experimental effort has gone into identifying exotic states, the situation remains unclear. The interest in this subject is demonstrated by the huge literature related to the purported observation of the $\Theta(1535)$ strangeness=$+1$ pentaquark. According to SPIRES, the experimental paper [1] that claimed first observation of the $\Theta(1530)$ has received over 785 citations.

There has been some recent progress in the identification of what may be exotic mesons. The BaBar and Belle $B$-factory experiments have, somewhat unexpectedly, discovered a...
number of interesting charmonium-like meson states that have defied assignment to any of the unfilled levels of the $c\bar{c}$ spectrum and, thus, remain unclassified. These have come to be known collectively as the "XYZ" mesons, and include: the experimentally well established $X(3872)$ [2] and $Y(4260)$ [3], which decay to $\pi^+\pi^-J/\psi$; the $X(3940)$ [4], seen in $D^*\bar{D}$ [5], and the $X(4160)$ [6] seen in $D^*\bar{D}^*$; the $Y(3940)$ [7,8], seen in $\omega J/\psi$; and the $Y(4350)$ [9] and $Y(4660)$ [10] seen in $\pi^+\pi^-\psi'$. In addition, Belle reported observations of similar states but with non-zero electric charge: the $Z(4430)$ [11] seen in $\pi^+\psi'$ and the $Z_1(4040)$ & $Z_2(4240)$ [12] seen in $\pi^+\chi_{c1}$. These $Z$ states have not yet been confirmed by other experiments and remain somewhat controversial [13]. Table 1 summarizes the abovementioned XYZ candidate states as well as some other states discussed below.

In this report I will briefly review the reasons why these states have eluded conventional $c\bar{c}$ assignments, discuss possible alternative interpretations, and present some evidence for similar states in the $s$- and $b$-quark sectors.

Table 1

| state         | $M$ (MeV) | $\Gamma$ (MeV) $J^{PC}$ | Decay Modes           | Production Modes         | Observed by          |
|---------------|-----------|--------------------------|------------------------|--------------------------|----------------------|
| $Y_1(2175)$   | 2175 ± 8  | 58 ± 26 $1^{--}$         | $\phi J/\psi(980)$ $e^+e^-$ (ISR), $J/\psi \rightarrow \eta Y_1(2175)$ | BaBar, BESII, Belle     |
| $X(3872)$     | 3871.4 ± 0.6 | < 2.3 $1^{++}$ | $\pi^+\pi^-J/\psi, \gamma J/\psi, D\bar{D}^*$ | $B \rightarrow K X(3872), p\bar{p}$ | Belle, CDF, D0, BaBar |
| $Z(3930)$     | 3929 ± 5  | 29 ± 10 $2^{++}$         | $D\bar{D}$ $\gamma\gamma \rightarrow Z(3940)$ | Belle                   |
| $X(3940)$     | 3942 ± 9  | 37 ± 17 $0^{++}$         | $DD^*$ (not $DD$ or $\omega J/\psi$) | $e^+e^- \rightarrow J/\psi X(3940)$ | Belle               |
| $Y(3940)$     | 3943 ± 17 | 87 ± 34 $0^{++}$         | $\omega J/\psi (not\,DD^*)$ | $B \rightarrow KY(3940)$ | Belle, BaBar         |
| $Y(4008)$     | 4008$^{+82}_{-39}$ | 226$^{+97}_{-80}$ $1^{--}$ | $\pi^+\pi^-J/\psi$ | $e^+e^- (ISR)$ | Belle                 |
| $X(4160)$     | 4156$^{+113}_{-85}$ | 139$^{+29}_{-22}$ $0^{++}$ | $D^*\bar{D}^*$ (not $DD$) | $e^+e^- \rightarrow J/\psi X(4160)$ | Belle               |
| $Y(4260)$     | 4264 ± 12 | 83 ± 22 $1^{--}$         | $\pi^+\pi^-J/\psi$ | $e^+e^- (ISR)$ | BaBar, CLEO, Belle |
| $Y(4350)$     | 4361 ± 13 | 74 ± 18 $1^{--}$         | $\pi^+\pi^-\psi'$ | $e^+e^- (ISR)$ | BaBar, Belle         |
| $Y(4660)$     | 4664 ± 12 | 48 ± 15 $1^{--}$         | $\pi^+\pi^-\psi'$ | $e^+e^- (ISR)$ | Belle               |
| $Z_1(4050)$   | 4051$^{+24}_{-23}$ | 82$^{+51}_{-29}$ $?^{++}$ | $\pi^+\chi_{c1}$ | $B \rightarrow K Z_1^+(4050)$ | Belle               |
| $Z_2(4250)$   | 4246$^{+185}_{-45}$ | 177$^{+520}_{-72}$ $?^{++}$ | $\pi^+\chi_{c1}$ | $B \rightarrow K Z_2^+(4250)$ | Belle               |
| $Z(4430)$     | 4433 ± 5  | 45$^{+35}_{-18}$ $?^{++}$ | $\pi^+\psi'$ | $B \rightarrow K Z^+(4430)$ | Belle               |
| $Y_0(10890)$  | 10,890 ± 3 | 55 ± 9 $1^{--}$         | $\pi^+\pi^-T(1,2,3S)$ | $e^+e^- \rightarrow Y_0$ | Belle               |

2. Charmonium possibilities

The $c\bar{c}$ charmonium meson level diagram is shown in Fig. [11]. Here the states that have already been assigned are labeled by their commonly used symbols and measured mass values. The solid lines indicate the measured levels and the broken lines indicate masses derived from QCD-motivated potential model calculations [15]. If any of the XYZ mesons are to be interpreted as simple quark-antiquark states, they must be assigned to one of the figure’s unlabeled levels. All of the states with mass below the $M = 2m_D = 3.73$ GeV “open-charm” threshold (indicated by the horizontal line in Fig. [11]) have already been identified and have properties that are in good agreement with potential model
Fig. 1. The predicted and observed spectrum of $c\bar{c}$ charmonium mesons. Already assigned states and their experimentally measured masses are indicated by solid bars and their commonly used names. The broken lines indicate various theoretical predictions. The horizontal line at 3.73 GeV indicates the mass threshold for decays to $D\bar{D}$ “open charm” final states.

expectations. In addition, all of the 1$^{-+}$ levels above the open charm threshold have been assigned to peaks in the total annihilation cross section for $e^+e^- \rightarrow \text{hadrons}$ [16].

Of the $XYZ$ states listed in Table 1 only the $Z(3930)$ [17] has been convincingly assigned to a charmonium level; there is general agreement that this is the $(2^3P_2)\chi_c^2$.

2.1. The $X(3872)$

The experimentally preferred $J^{PC}$ value for the $X(3872)$ is 1$^{++}$, although 2$^{-+}$ has not been conclusively ruled out [18]. The only unfilled 1$^{++}$ level in Fig. 1 is the $\chi'_c$, the $2^3P_1$ $c\bar{c}$ state. As mentioned above, the $J = 2$ triplet partner state for this level has been identified as the $Z(3930)$ with a mass of 3929 ± 5 MeV. A $\chi'_c$ assignment for the $X(3872)$ would imply a $\chi'_c \chi'_c$ mass splitting for radial quantum number $n = 2$ (i.e. $\delta m \sim 57$ MeV) that is larger than that for the $n = 1$ splitting ($\delta m \sim 46$ MeV), contrary to potential model expectations. A bigger difficulty with this assignment is the fact that the $X(3872) \rightarrow \rho J/\psi$ discovery mode would be an isospin violating transition that should be strongly suppressed compared to the $X(3872) \rightarrow \gamma J/\psi$ mode; the latter is measured to be much smaller than the former [19]. Using the 2$^{-+}$ assignment does not help; in this case the $\pi^+\pi^- J/\psi$ transition would also be isospin violating, and the $\gamma J/\psi$ transition, which would be a $\Delta L = 2$ transition, would be unmeasurably small, which it isn’t.

2.2. The $X(3940)$ and $X(4160)$

The $X(3940)$ is seen in the $DD^*$ system recoiling from the $J/\psi$ in exclusive $ee \rightarrow J/\psi DD^*$ annihilations; the $X(4160)$ is seen in the $D^*D^*$ system in $J/\psi$ in $ee \rightarrow J/\psi D^*D^*$. 


Neither are seen in the experimentally more accessible $D\bar{D}$ channel. The only known charmonium states that are seen recoiling from the $J/\psi$ in $e^+e^- \rightarrow J/\psi X$ processes have $J = 0$. This, plus the absence of the $D\bar{D}$ mode, provides circumstantial evidence that favors $J^{PC} = 0^{-+}$ assignments for both states, which for charmonium would be the η''c and η'''c. Such an assignment has difficulty with the measured masses: the predicted η''c mass is about 4050 MeV, over 100 MeV too high for the $X(3940)$; the predicted η'''c is around 4400 MeV, more than 200 MeV higher than the $X(4160)$.

2.3. The $Y(3940)$

The $Y(3940)$ was first seen by Belle as a near-threshold peak in the $\omega J/\psi$ invariant mass spectrum in exclusive $B \rightarrow K\omega J/\psi$ decays [7]. It was subsequently confirmed by BaBar [8], although there remain some ($\sim 2\sigma$) discrepancies between the Belle & BaBar measurements of the mass and width.

It is unlikely that the $Y(3940)$ (seen in $\omega J/\psi$) and the $X(3940)$ (seen in $D\bar{D}^*$) are different decay modes of the same state. Belle has searched for $Y(3940) \rightarrow D\bar{D}^*$ in $B \rightarrow K D\bar{D}*$ decays and finds a 90% CL lower limit of $B(Y \rightarrow \omega J/\psi)/B(Y \rightarrow D\bar{D}^*) > 0.71$ [20] that contradicts a 90% CL upper limit from a search for $X(3940) \rightarrow \omega J/\psi$ in $e^+e^- \rightarrow J/\psi J/\psi\omega$ annihilations: $B(X \rightarrow \omega J/\psi)/B(X \rightarrow D\bar{D}^*) < 0.58$ [4].

Possible charmonium assignments for the $Y(3940)$ are the η''c (0−+) — although its mass is a little low — and the $\chi_{c0}'$ (0++) for which its mass is too high. The primary difficulty with a charmonium assignment for the $Y(3940)$ is its large partial width to $\omega J/\psi$, which reasonable estimates put above 1 MeV [21] and which may in fact be quite a bit higher. This is well above the measured partial widths for any of the observed hadronic transitions between charmonium states.

2.4. The $J^{PC} = 1^{--} Y$ states

The $Y(4260)$ was first seen by BaBar as a peak in the $\pi^+\pi^- J/\psi$ mass spectrum in the initial-state-radiation (ISR) process $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$. The $Y(4350)$ and $Y(4660)$ are seen in the $\pi^+\pi^-\psi'$ mass spectrum in the $ee \rightarrow \pi^+\pi^-\psi'$ ISR process. (Belle also sees a broad $Y(4008)$ peak in $\pi^+\pi^- J/\psi$ [22], but this has not been confirmed by BaBar [23].) Since these states are produced via ISR, their $J^{PC}$ has to be $1^{--}$.

There are no unassigned $1^{--}$ slots for any of these states in the $M < 4.4$ GeV spectrum of Fig. [1]. Moreover, no hint of any of them in seen in any of the $D^{(*)}D^{(*)}$ channels [24]. This implies that their $\pi^+\pi^- J/\psi(\psi')$ decay widths must be quite large. In the case of the $Y(4260)$, the $\pi^+\pi^- J/\psi$ has been established to be more that 1.6 MeV [25]. This is much too large for charmonium, where allowed $\pi^+\pi^- J/\psi$ transitions have measured partial widths of 100 keV or less.

2.5. The charged $Z$ particles

Belle reported a peak with a $\sim 6.5\sigma$ statistical significance near 4430 MeV in the $\pi^\pm\psi'$ channel in exclusive $B \rightarrow K\pi^\pm\psi'$ decays [11]. A peak at the observed $\pi\psi'$ invariant mass value cannot be produced by reflections from the $K\pi$ system. However, BaBar did not confirm this peak, finding at most a signal of $\sim 1.7\sigma$ significance [13]. A subsequent
full Dalitz-plot analysis (see Fig. 2 left) of the Belle $B \to K\pi^\pm\psi'$ sample confirms their original mass and significance determinations [26]. Belle also reported two peaks with greater than 5σ statistical significance in the $\pi^\pm\chi_{c1}$ channel, the $Z_{1}(4050)$ & $Z_{2}(4250)$, in exclusive $B \to K\pi^\pm\chi_{c1}$ decays, again from a Dalitz-plot analysis (Fig. 2 right). If these peaks are interpreted as meson states, they must have a minimal tetraquark $c\bar{c}ud$ substructure and there are no possible charmonium or charmonium hybrid assignments.

Fig. 2. Left: $(B \to K\pi^\pm\psi')$ The points with errors are data and the histograms show fits to a Dalitz-plot projection that has the $K^*$ bands removed with & without the inclusion of the $Z(4430)$ resonance in the $\pi^\pm\psi'$ channel. Right: $(B \to K\pi^\pm\chi_{c1})$ A similar Dalitz-plot projection for data & fits with & without the inclusion of two resonances in the $\pi^\pm\chi_{c1}$ channel.

3. Exotic possibilities

In this section I discuss the possible interpretations of the $XYZ$ peaks as $c\bar{c}q\bar{q}$ tetraquark states or $c\bar{c}$-gluon hybrid states.

3.1. Tetraquarks

Two very distinct types of tetraquark mesons have been proposed: molecular states, which are relatively loosely bound structures comprised of deuteron-like mesons-antimeson bound states [27], and diquark-diantiquark mesons in which the two quarks form an anticolor triplet state that binds tightly to a color triplet that is formed from the two antiquarks [28]. These two types of structures have very different phenomenologies.

3.1.1. Molecules

A molecular state is expected to have a mass that is slightly below the sum of the masses of its meson-antimeson constituents and exhibit large isospin violations. The $X(3872)$, with a mass that is within errors of the $m_D + m_{D^*}$ mass threshold and has decay rates to $\pi^+\pi^-J/\psi$ and $\pi^+\pi^-\pi^0J/\psi$ that are nearly equal [29]. Thus, this is a nearly ideal candidate for a $DD^*$ molecular state, either real [30,31,32,33] or virtual [34]. On the other hand, its proximity to the $DD^*$ threshold has also led to speculation that it is some kind of a threshold effect [35,36,37,38]. In these latter schemes, mixing with the $\chi'_{c1}$ charmonium state can play an important role.

5
A new piece of experimental information, the significance of which has yet to be commented on by any theorist, is a study of $X(3872)$ production in exclusive $B \rightarrow K\pi X(3872)$ decays [35]. The left panel of Fig. 3 shows the $K\pi$ invariant mass distribution, where it is evident that non-resonant $K\pi$ production dominates, and the $K^*(890)$ contribution is small and of marginal significance. This is in contrast to what is seen in all other $B \rightarrow K\pi+$charmonium decays in which the $K^*(890)$ contribution dominates; for example, the right panel of Fig. 3 shows the $M(K\pi)$ distribution for $B \rightarrow K^-\pi^+\chi_{c1}$ decays [39], where a prominent $K^*(890)$ signal is clearly evident.

Not all of the $XYZ$ states fit the molecule picture. For example the $X(3940)$, $Y(3940)$ and $Y(4660)$ are not near any $D^*(\bar{D}^*)$ mass threshold. (Note that $\pi$-exchange, the dominant binding term in molecular models, is absent in $D^*(\bar{D}^*)$ systems.)

3.1.2. Diquark-diantiquarks

Essentially all of the observed $XYZ$ states can be accommodated by the diquark-diantiquark model. However, in this picture, each of the assigned state is expected to have an associated flavor-$SU(3)$ multiplet of states. One prediction of this model is that there should be two $X(3872)$ states — $X_u = cu\bar{u}$ and $X_d = cd\bar{c}$ — with a mass difference of $8 \pm 3$ MeV. No evidence for such a pairing has been found [20,38]. In addition, in this model one expects a charged isospin partner of the $X(3872)$ to be produced in $B$ decays. BaBar searched for such an $X^+(3872) \rightarrow \rho^+J/\psi$ state in neutral $B$ meson decays and set an upper limit that is well below isospin-based expectations [40]. No isospin partners of any of the other $XYZ$ states have been reported.

3.2. Hybrids

The lattice QCD expectation for the mass of the lowest-lying charmonium hybrid is around 4.3 GeV and the relevant open-charm threshold is 4.29 GeV, the $D^{**}\bar{D}$ mass threshold, where $D^{**}$ denotes the lowest mass $P$-wave charmed meson with mass 2.42 GeV. Since the $Y(4260)$ mass is near the LQCD value and below the $D^{**}\bar{D}$ mass threshold — which would explain its relatively strong decay rate to $\pi^+\pi^-J/\psi$ as opposed to open charm states — a charmonium hybrid interpretation is attractive. However, the $Y(4260)$ is broad and $D^{**}\bar{D}$ decays are accessible from its high mass side, but there is no sign of a...
lineshape distortion that might be expected when a dominant new decay channel opens up. Moreover, the $Y(4350)$ & $Y(4660)$ are both well above all $D^{*+}\bar{D}$ thresholds and no open charm decays have been seen. So, while the hybrid interpretation might work for the $Y(4260)$, it does not seem to apply to the other $1^{--}$ ISR-produced states.

4. Evidence for $XYZ$-like states in the $s$- and $b$-quark sectors

An obvious question is whether or not there are counterparts in the $s$- and $b$-quark sectors. Recent results suggest that there are. In a BaBar study of the ISR process $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-\phi$, where the $\pi^+\pi^-$ comes from $f_0(980) \rightarrow \pi^+\pi^-$, a distinct $\pi^+\pi^-\phi$ mass peak is seen at 2175 MeV [41]. This peak was confirmed in an ISR measurement by Belle [42] (left panel of Fig. 4) and seen in $J/\psi \rightarrow \eta f_0\phi$ decays by BES [43]. Although a conventional $s\bar{s}$ assignment cannot be ruled out [44], this state has properties similar to what one would expect for an $s$-quark sector counterpart of the $Y(4260)$.

The Belle group recently reported measurements of the energy dependence of the $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$ ($n = 1, 2 & 3$) cross section around $E_{cm} \sim 10.9$ GeV and found peaks in all three channels at 10.899 GeV (right panel of Fig. 4) [45]. The peak mass and width value are quite distinct from those of the nearby $\Upsilon(5S)$ bottomonium ($b\bar{b}$) state, and the cross section values are more than two-orders-of-magnitude above expectations for a conventional $b\bar{b}$ system. One interpretation for this peak is that it is a $b$-quark sector equivalent of the $1^{--}Y$ states seen in the $c$-quark sector [46].

5. Summary

There is a growing body of evidence for a new type of hadron spectroscopy involving pairs of $c$-quarks that neither fits well to classic Quark Parton Model expectations nor QCD-motivated extensions. A recurring feature of these new state are large partial widths for decays to charmonium plus light hadrons. There is some evidence for similar structures in the $s$- and $b$-quark sectors.
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