What’s new with the $XYZ$ mesons? *

Stephen L. OLSEN
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China &
Department of Physics & Astronomy, University of Hawai`i, Honolulu, HI 96822 USA

Abstract I review some of the recent experimental results on the so-called XYZ mesons.

Key words charmonium, multiquark mesons, quark-gluon hybrids

PACS 14.40.Gx, 12.39.Mk, 13.25.Hw

1 Introduction

In addition to carrying out their day jobs of studying CP violation and measuring CKM matrix elements, the B-factory experiments have discovered a number of interesting charmonium-like meson states that are known collectively as the “$XYZ$” mesons. Two of these have been given assignments as charmonium states: the $\eta_c^\prime$ and the $\chi_{c2}$. However, the others have properties that are at odds with expectations of the charmonium model and, as a result, remain unclassified. These latter include the $X(3872)$ and the $Y(4260)$, which decay to $\pi^+\pi^- J/\psi$; the $X(3940)$ seen in $D^+\bar{D}$; the $Y(3940)$ seen in $\omega J/\psi$; and the $Y(4352)$ seen in $\pi^+\pi^-\psi'$.

Proposed assignments for these states have included: multiquark states, either of the (c$\bar{q}, \bar{c}q$) "molecular" type or [c$q, \bar{c}q]$ diquark-antidiquark type (here $c$ represents a charmed quark and $q$ either a $u$, $d$, or $s$-quark); hybrid $c\bar{c}$-gluon mesons; or other missing charmonium states where the masses predicted by potential models are drastically modified by nearby $D^{(*)}\bar{D}^{(*)}$ thresholds. A characteristic that would clearly distinguish a multiquark state from hybrids or charmonia is the possibility to have mesons with non-zero charge (e.g. [c$\bar{c}d\bar{s}$]), strangeness ([c$\bar{c}d\bar{s}$]) or both ([c$\bar{c}d\bar{s}$]).

During the past summer a large number of new results related to the $XYZ$ mesons has been reported, which I will try to summarize in this talk. My focus will be almost entirely experimental.

2 What’s old?

First, I briefly summarize the status before Summer 2007.

$X(3872)$ Measurements at CDF and Belle have favored a $J^{PC} = 1^{++}$ assignment for the $X(3872)$, although $2^{--}$ cannot be completely ruled out. The two charmonium assignments that match these quantum numbers are the $\chi_{c1}^\prime (2^3P_1)$ and the $\eta_{c2}$ ($1^1D_2$). The mass is too low for the $\chi_{c1}^\prime$, especially if Belle’s $\chi_{c2}$ candidate (with $M = 3931$ MeV) has been correctly assigned, and too high for the $\eta_{c2}$.

In addition for either assignment, the decay to the $\pi^+\pi^- J/\psi$ “discovery mode”, which BaBar has shown has a branching fraction that is above 4%, is isospin violating, and should be suppressed. Thus, the consensus opinion is that there is no acceptable charmonium assignment for the $X(3872)$, although this is not an unanimously accepted point of view.

$X(3940)$ The $X(3940)$ was seen by Belle recoiling from the $J/\psi$ in the $e^+e^-$ continuum annihilation process $ee \rightarrow J/\psi DD^\ast$. (In this report, the inclusion of the charge conjugate mode is always implied.) Since the only known charmonium states that are produced this way are the $0^{-+}$ $\eta_c$ and $\eta_c^\prime$, and the $0^{++} \chi_{c0}$, circumstantial evidence suggests that the $X(3940)$ is either a scalar or pseudoscalar. The lack of evidence for a $DD$ decay mode favors the pseudoscalar $0^{-+}$ assignment. The possible charmonium assignment is the $\eta_c^\prime$ ($3^3S_0$). This has some difficulty because the $3^3S_0$ state is the $\psi(4040)$ and its mass is pretty well established at 4040 MeV. So, an $\eta_c^\prime$ assignment for

---

* Talk given at the Belle-BES-CLEO-BaBar Joint Workshop on Charm Physics, Beijing, China November 26-27, 2007
1) E-mail:solsen@ihep.ac.cn
the \(X(3940)\) implies a singlet-triplet mass splitting for radial quantum number \(n = 3\) (\(\gtrsim 100 \text{ MeV}\)) that is larger than that for \(n = 2\) (\(\simeq 50 \text{ MeV}\)). Eichten, Quigg and Lane\cite{12} have shown that this may be due to large admixtures of \(D \bar{D}^*\) and \(D^* \bar{D}^*\) components in the \(\eta_c^*\) and \(\psi(4040)\) wave functions.

\(Y(3940)\) Not much is known about the \(Y(3940)\) other than it must have \(C = +\). If we assume that the branching fraction for \(B \to KY(3940)\) is not larger than \(10^{-3}\), which is typical for factorization-allowed decay modes such as \(B \to K J/\psi\) and \(B \to K \eta_c\), the measured product branching fraction \(B(B \to KY) \times B(Y \to \omega J/\psi) = 7 \pm 3 \times 10^{-5}\) and measured width \(\Gamma = (87 \pm 34) \text{ MeV}\) imply a large value for the partial width \(\Gamma(Y(3940) \to \omega J/\psi) \sim \text{few MeV}\). This is much larger than those seen for hadronic transitions between established charmonium states, which are at most \(\sim 100 \text{ keV}\). Although the \(X(3940)\) (discussed above) is not seen to decay to \(\omega J/\psi\), the upper limit on this branching fraction (\(\leq 26\%\) at 90\% CL) is not stringent enough to rule out the possibility that the \(Y(3940)\) are the same states. If so, the large \(\Gamma(Y(3940) \to \omega J/\psi)\) partial width raises problems with the \(\eta_c^*\) assignment.

\(X(4260)\) The \(Y(4260)\) was discovered by BaBar in a 223 fb\(^{-1}\) data sample as a relatively narrow (\(\Gamma = 88 \pm 24 \text{ MeV}\)) peak near 4260 MeV in the \(\pi^+ \pi^- J/\psi\) invariant mass distribution in the reaction \(e^+ e^- \to \gamma \pi^+ \pi^- J/\psi\), where the \(\gamma\) exhibits the distinct angular behavior of initial state radiation.\cite{23} Since it is clear that this state is produced by radiative-return \(s\)-channel \(e^+ e^-\) annihilation, it must have \(J^{PC} = 1^{--}\). In this case, the \(Y(4260)\) decaying into pairs of open-charm mesons might be seen in the total cross section \(e^+ e^- \to \text{hadrons near } E_{cm} = 4260 \text{ MeV}\). However, this has been measured rather precisely in small \(E_{cm}\) bins (\(\sim 10 \text{ MeV}\)) over this energy region by both the BES\cite{19} and Crystal Ball\cite{20} experiments, and neither group sees evidence for structure in this region. A detailed analysis established a lower limit on the branching fraction for \(Y(4260) \to \pi^+ \pi^- J/\psi\) of 0.6\%.\cite{23} This coupled with the measured resonance width implies that the \(Y(4260)\) has a larger partial decay for \(\pi^+ \pi^- J/\psi\) that is at least an order-of-magnitude larger than those of the established charmonium states. Another problem with a charmonium assignment for the \(Y(4260)\) is the lack of availability of any unoccupied \(1^{--}\) states. The three \(1^{--}\) charmonium states in this mass range, the \(3^0 S_1, 2^3 D_1\) and \(4^3 S_1\) slots have already been assigned to the \(\psi(4040), \psi(4160)\) and \(\psi(4415)\). The properties of these states, including their decay rates to hadrons, match well to charmonium model predictions\cite{16} and there does not seem to be any compelling reasons to alter these assignments.

\(X(4325)\) The \(Y(4325)\) was discovered by BaBar as a broad enhancement peaking near 4325 MeV in the \(\pi^+ \pi^- J/\psi\) mass distribution for \(e^+ e^- \to \gamma_{ISR}\pi^+ \pi^- J/\psi\) radiative return events in a 298 fb\(^{-1}\) data sample. This peak can neither be fitted with a \(Y(4260)\) line-shape nor does any evidence for it appear in either the \(\pi^+ \pi^- J/\psi\) channel or in the total cross section measurements. Since this also has to have \(J^{PC} = 1^{--}\), there are no unfilled charmonium states that it could be assigned to.

3 What’s new?

3.1 \(X(3872)\) news

This past summer, the Belle group reported the first observation of \(X(3872)\) production in neutral \(B\) meson decays.\cite{24} (BaBar had previously reported a \(\sim 3\sigma\) signal.\cite{25}) The Belle \(X(3872) \to \pi^+ \pi^- J/\psi\) signals from charged and neutral \(B\) decays are shown in Fig. 1.

![Figure 1](image-url)  
Fig. 1. The Belle group’s \(X(3872) \to \pi^+ \pi^- J/\psi\) signals from (top) \(B^+ \to K^+ \pi^+ \pi^- J/\psi\) and (bottom) \(B^0 \to KS \pi^+ \pi^- J/\psi\) decays.

Belle finds consistent mass values for the \(X(3872)\) peaks produced from neutral and charged \(B\) decays.

---

*Here and elsewhere in this report, the first reported error is statistical and the second systematic.*
Their measured mass difference for the two sources is

\[ \Delta M = (0.22 \pm 0.90 \pm 0.27) \text{ MeV}, \]

is consistent with zero and disagrees with a prediction of \((8 \pm 3) \text{ MeV}\) by Maiani et al., which is based on a diquark-antidiquark model for the \(X(3872)\) that has a pair of states with distinct masses.\[12\] Belle also reports a ratio of branching fractions

\[ \frac{B(B^0 \to K^0 X(3872))}{B(B^+ \to K^+ X(3872))} = 0.94 \pm 0.24 \pm 0.10. \]

This is consistent with unity, as one might naively expect based on isospin symmetry. However, in the \(DD^*\) molecular interpretation of the \(X(3872)\), large deviations from unity are possible.\[24\]

A second important \(X(3872)\)-related result reported last summer was the BaBar group’s confirmation of a narrow, near-threshold peak in the \(DD^*\) invariant mass distribution for \(B \to KDD^*\) decays (see Fig. 2).\[22\] The mass of the observed peak \(3875.1^{+0.7}_{-0.5} \pm 0.5 \text{ MeV}\) is 4.5\(\sigma\) higher than that seen for \(X(3872) \to \pi^+\pi^- J/\psi\) decays, which confirms with more significance an earlier result from Belle.\[26\] This difference has been interpreted as being due to threshold effects,\[22\] or as evidence for an \(X(3872)\) partner state as predicted by the diquark-antidiquark model.\[28\]

![Fig. 2. The \(DD^*\) invariant mass distribution for \(B \to KDD^*\) decays (from BaBar).](image)

**3.2 The \(Y(3940)\) is confirmed by BaBar**

This summer the BaBar group reported a study of \(B \to K\omega J/\psi\) decays with a data sample containing 383 million \(B\bar{B}\) meson pairs.\[29\] In this sample, the \(\omega J/\psi\) invariant mass spectrum, shown in Fig. 3, exhibits a near-threshold enhancement that is qualitatively similar to the \(Y(3940)\) reported earlier by Belle.\[12\] The two groups agree on the product branching fraction \(B(B^+ \to K^+ Y(3940)) \times B(Y(3940) \to \omega J/\psi)\): BaBar finds \((4.9 \pm 1.0 \pm 0.5) \times 10^{-5}\) while Belle finds \((7.1 \pm 3.1 \pm 3.1) \times 10^{-5}\). (The Belle result is an average of the neutral & charged \(B\) samples.) However, there is some disagreement about the mass and width values: BaBar reports \(M = (3914.6^{+3.8}_{-3.4} \pm 1.9) \text{ MeV}\) and \(\Gamma = (33^{+12}_{-12} \pm 5) \text{ MeV}\), which are both smaller than Belle’s values of \(M = (3943 \pm 11 \pm 13) \text{ MeV}\) and \(\Gamma = (87 \pm 22 \pm 26) \text{ MeV}\). There are some differences between the two analyses: BaBar’s uses smaller \(M(\omega J/\psi)\) bin sizes than Belle’s: 10 MeV in the region of the peak versus 40 MeV. In addition, BaBar exploits the distinctive Dalitz-plot distribution of \(\omega \to \pi^+\pi^-\pi^0\) decays by introducing an event-by-event weighting factor. However, preliminary results from a reanalysis of Belle data with smaller bin sizes and consideration of the 3\(\pi\) Dalitz plot distribution do not resolve the mass and width discrepancies between the two experiments.

![Fig. 3. The \(\omega J/\psi\) invariant mass distribution for \(B^+ \to K^+ \omega J/\psi\) decays (from BaBar). Below 4.0 GeV, the data are plotted in 10 MeV mass bins; above 4 GeV, the bin size is 40 MeV.](image)

### 3.3 A new one recoiling from the \(J/\psi\): \(X(4160) \to D^* D^*\)

In a continuation of their analyses of \(D^{(*)}\bar{D}^{(*)}\) systems recoiling from a \(J/\psi\) in the \(e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}\) annihilation process at \(E_{cm} \approx 10.6 \text{ GeV}\), Belle confirmed\[22\] with higher statistics and better precision their previously reported signal for \(X(3940) \to D^* D^*\) (see Figs. 4(b) and (c)). With a 693 fb\(^{-1}\) data sample they report \(M = (3942^{+7}_{-6} \pm 6) \text{ MeV}\) and \(\Gamma = (37^{+25}_{-25} \pm 8) \text{ MeV}\). In addition they report a 5.5\(\sigma\) significance signal for a new state seen in \(D^{*+} D^{*-}\) decays, (see Fig. 4(d)) that they call the \(X(4160)\). The fitted mass and width are \(M = (4156^{+25}_{-20} \pm 15) \text{ MeV}\) and \(\Gamma = (139^{+111}_{-61} \pm 21) \text{ MeV}\). Although the masses and widths of the \(X(4160)\) and the well established \(\psi(4160)\) \(1^-\) charmonium state are consistent with each other (within errors), they have opposite charge conjugation and, thus, must be distinct. Neither \(X(3940)\) nor \(X(4160)\) signals are evident in the \(D\bar{D}\) invariant mass distribution for \(e^+ e^- \to J/\psi D\bar{D}\) annihilations, which is shown in Fig. 4(a). Here instead,
there is a broad enhancement above background that peaks around 3880 MeV. Although the excess above background is significant, the data are not sufficient to establish a resonance shape.

As mentioned above, the \(X(3940)\) is a candidate for the \(\eta_c''\) even though its mass is somewhat lower than theoretical expectations. In contrast, the \(X(4160)\) mass is higher than \(\eta_c''\) expectations, and much too low to be the \(\eta_c''\), which is expected to have a mass near 4400 MeV. Thus, although it is conceivable that either the \(X(3940)\) or the \(X(4160)\) could be a standard \(\bar{c}c\) meson, it seems very unlikely that they both could be assigned to charmonium states.

![Graphs](Fig. 4. (a) The \(DD\) invariant mass distribution for \(e^+e^- \rightarrow J/\psi DD\) annihilations. Here one \(D\) is detected and the other is inferred from kinematics. Panels (b) and (c) show the \(D\bar{D}\) invariant mass distribution for \(e^+e^- \rightarrow J/\psi D\bar{D}\). In (b), the \(D\) is detected and the \(D^*\) is inferred; in (c), the \(D^*\) is detected and the \(D\) is inferred. Panel (d) shows the \(D^+D^*\) invariant mass distribution for \(e^+e^- \rightarrow J/\psi D^+D^*\), where one \(D^*\) is detected and the other inferred. (From Belle.)
)

### 3.4 News on the \(1^-\) states

The top panel of Fig. 5 shows recently reported Belle results for the \(\pi^+\pi^- J/\psi\) invariant mass distribution from a 548 fb\(^{-1}\) sample of \(e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi\) radiative return events. The mass distribution shows a distinct peak with mass and width of \(M = (4247\pm12^{+17}_{-32})\) MeV and \(\Gamma = (108\pm19\pm10)\) MeV; results that confirm BaBar’s \(Y(4260)\). In addition, there is an accumulation of events at lower masses that is significantly higher than the sideband-determined background level. A fit of a resonance shape to this enhancement gives mass and width values of \(M = (4008\pm40^{+14}_{-24})\) MeV and \(\Gamma = (226\pm44\pm87)\) MeV. Although the mass of this second peak is consistent with that of the \(\psi(4040)\) charmonium state, the fitted width value is much larger than the world average value for the \(\psi(4040)\) (80\pm10) MeV. Currently, it is not clear whether or not this is another \(XYZ\) state, a threshold effect, or the \(\psi(4040)\).

![Graphs](Fig. 5. The \(\pi^+\pi^- J/\psi\) (top) and \(\pi^+\pi^- \psi'\) (bottom) invariant mass distributions for \(e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi\) (\(\pi^+\pi^- \psi'\)) events in Belle.
)

The bottom panel of Fig. 5 shows the \(\pi^+\pi^- \psi'\) invariant mass distribution for the \(e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- \psi'\) events in a 617 fb\(^{-1}\) data sample. Although the data points are consistent with those measured by BaBar, Belle’s larger data sample allows them to distinguish two distinct enhancements: one at \(M = (4361\pm9\pm9)\) MeV & \(\Gamma = (74\pm15\pm10)\) MeV with a significance of more than 8\(\sigma\), and another at \(M = (4664\pm11\pm5)\) MeV & \(\Gamma = (48\pm15\pm3)\) MeV with a significance of 5.8\(\sigma\). Neither peak has parameters consistent with those of the \(Y(4260)\) nor is there any evident signal for them in the \(\pi^+\pi^- J/\psi\) channel. In addition, there are no signs of peaking behavior at these masses in either the total cross section for \(e^+e^- \rightarrow \text{hadrons}\) or in the exclusive cross sections for \(e^+e^- \rightarrow DD, D\bar{D}\), \(D\bar{D}^*\), \(D^*\bar{D}^*\) or \(DD\pi\). This indicates that the \(\pi^+\pi^- \psi'\) partial widths are at the \(\sim\)MeV level and much larger than those measured for established charmonium states (i.e., \(\Gamma(\psi' \rightarrow \pi^+\pi^- J/\psi) = (106\pm4)\) keV.
and $\Gamma(\psi(3770) \to \pi^+\pi^-J/\psi) = (49 \pm 8) \text{ keV}^{[32]}$.

Since all of the $1^{--}$ charmonium states have already been assigned, the three (or four, if the 4008 MeV peak is included) $1^{--}$ structures have no available charmonium assignment. It has been suggested that coupled-channel effects and rescattering between pairs of charmed mesons may be playing a role.\textsuperscript{[33]} However, the peak masses do not overlap with any of the $D^{(*)}D^{(*)}$ or $D_s^{(*)}D_s^{(*)}$ thresholds (see Fig. 6).

A popular interpretation for these $1^{--}$ states is that they are $cc$-gluon hybrids.\textsuperscript{[36]} Lattice-QCD says that the lowest mass should be about 4.2 GeV. In addition, decays to $D^{(*)}D^{(*)}$ are expected to be suppressed and the relevant open charm threshold is $m_D + m_{D^{(*)}} \simeq 4285$ MeV, which is higher than the peak mass of the $Y(4260)$. However, both the $Y(4360)$ and the $Y(4660)$ are well above this threshold, as is a large part of the high mass tail of the $Y(4260)$. Thus, the absence of any sign of these states in the total cross section for $e^+e^- \to$ hadrons is a problem for the hybrid interpretation.

4 The $Z^+(4430)$

All of the original $XYZ$ meson candidates were electrically neutral. This changed in Summer 2007, when Belle reported the observation of a distinct peak in the $\pi^+\psi'$ mass distribution produced in $B \to K\pi^+\psi'$ decays (see Fig. 7). A fit to this distribution with an $S$-wave Breit Wigner resonance line-shape gives resonance parameters of $M = (4433 \pm 4 \pm 2)$ MeV & $\Gamma = (45_{-13}^{+18} \text{ (stat)} \pm 30 \text{ (syst)})$ MeV with a signal significance of $6.5\sigma$.\textsuperscript{[33]}

In the three-body decay $B \to K\pi\psi'$, the $M(\pi\psi')$ values are strongly correlated with $\cos\theta_\pi$, where $\theta_\pi$ is the angle between the $\pi$ meson and the $\psi'$ directions in the $K\pi$ restframe. Thus, interference between different partial waves in the $K\pi$ system that produce peaks in $\cos\theta_\pi$ will produce corresponding structures in the $M(\pi\psi')$ distribution. From the $M(K\pi)$ distribution for these decays, strong contributions from $S$-wave and $P$-wave $K\pi$ partial waves are evident. In addition, there is some evidence for the $D$-wave $K\pi$ resonance state. However, the fitted peak mass value of 4433 MeV corresponds to $\cos\theta_\pi \simeq 0.25$, and it is not possible to produce a peak at this value of $\cos\theta_\pi$ with only $S$- $P$- and $D$-waves, without producing additional, more dramatic structures at other $M(\pi\psi')$ values. Since no such additional structures are evident in the $M(\pi\psi')$ distribution shown in Fig. 7, Belle concludes that the peak they observe is inherent to the $\pi\psi'$ system and not a reflection of interference effects between different $K\pi$ partial waves.

Fig. 7. The $M(\pi^+\psi')$ distribution for $B \to K\pi^+\psi'$ decays (from Belle.)

If the $Z(4430)$ peak is interpreted as a meson, it cannot be a $cc$ charmonium or a $cc$-gluon hybrid because these are necessarily electrically neutral. The remaining possibility is a tetraquark state. Some authors have proposed that it is a $D^*D_1^{-*}$ molecule\textsuperscript{[38]} and others have advocated a diquark-antidiquark interpretation (e.g. a $cu\bar{c}\bar{d}$ combination).\textsuperscript{[39]} The $Z(4430)$ bears some similarities to the $Y(4360)$ and $Y(4660)$ in that they are in the same mass range, have similar widths and are observed to decay to $\psi'$ and not $J/\psi$. If, in fact, they are related, this would cause trouble with the hybrid interpretation for the $Y(4360)$ and $Y(4660)$, as well as with the $D^*D_1^{-*}$ molecule picture for the $Z(4430)$.
5 Are the corresponding states in the $s$- and $b$-quark sectors?

The proliferation of meson candidates that are strongly coupled to $c\bar{c}$ quark pairs but not compatible with a conventional charmonium assignment leads one naturally to question whether or not similar states exist that are strongly coupled to $s\bar{s}$ or $b\bar{b}$ quark pairs. There is some evidence that this, in fact, may be the case.

5.1 The $Y(2175)$

In 2006, the BaBar group reported a resonance-like structure in the $f_0(980)\phi$ invariant mass distribution produced in $e^+e^-\rightarrow\gamma_{ISR}f_0(980)\phi$ radiative-return events. They report resonance parameters of $M = (2170\pm10\pm15)$ MeV & $\Gamma = (58\pm16\pm20)$ MeV. They see no signal for this peak in a sample of $K^*(892)K\pi$ events that has little kinematic overlap with $f_0(980)\phi$, and conclude that this structure, which they call the $Y(2175)$, has a relatively large branching fraction for $f_0(980)\phi$.

![Fig. 8. The $M(f_0(980)\phi)$ distribution for $J/\psi\rightarrow\eta f_0(980)\phi$ decays in BESII.](image)

The similarities with the $Y(4260)$, both in production and decay properties, led them to speculate that the $Y(2175)$ might be an $s\bar{s}$ analogue of the $Y(4260)$, i.e. it is the "$Y_s'(2175)$". On the other hand, there is no compelling evidence against it being a conventional $3^3S_1$ or $2^3D_1$ $s\bar{s}$ "strangeonium" state. The study of the $Y(2175)$ in other production and decay modes would be useful for distinguishing between different possibilities.

The BESII group made a first step in this program by finding an $f_0(980)\phi$ mass peak with similar parameters produced in $J/\psi\rightarrow\eta f_0(980)\phi$ decays (see Fig. 8). The BESII fit yields a mass and width of $M = (2186\pm10\pm6)$ MeV & $\Gamma = (65\pm23\pm17)$ MeV, which are in good agreement with BaBar’s measurements.

The next steps will be finding it in other decay modes and searching for counterpart states with quantum numbers other than $1^{--}$ that, perhaps, decay into final states containing an $\eta'$. This will be an important task for BESIII.

5.2 Anomalous $\pi^+\pi^-\Upsilon(nS)$ production at the $\Upsilon(5S)$

Using a sample of 236 million $\Upsilon(4S)$ mesons, BaBar observed 167 $\pm$ 19 and 97 $\pm$ 15 event signals for $\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ and $\pi^+\pi^-\Upsilon(2S)$, respectively, from which they infer partial widths $\Gamma(\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S)) = (1.8\pm0.4)$ keV. $\Gamma(\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(2S)) = (2.7\pm0.8)$ keV. Belle, with a sample of 464 million $\Upsilon(4S)$ events reported a 44 $\pm$ 8 event signal for the transition $\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S)$, from which they infer a partial width $\Gamma(\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S)) = (3.65\pm0.67\pm0.65)$ keV. These partial widths are comparable in magnitude to those measured for $\pi^+\pi^-$ transitions between the $\Upsilon(3S)$, $\Upsilon(2S)$ and $\Upsilon(1S)$.

In 2006, Belle had a one-month-long run at $e^+e^-$ c.m. energy of 10.87 GeV, which corresponds to the peak mass of the $\Upsilon(5S)$. The total data sample collected was 21.7 fb$^{-1}$ and the number of $\Upsilon(5S)$ events collected was 6.3 million. Much to their surprise, they found large numbers of $\pi^+\pi^-\Upsilon(4S)$ events in this data sample: 325 $\pm 20$ $\pi^+\pi^-\Upsilon(1S)$ events and 186 $\pm 15 \pi^+\pi^-\Upsilon(2S)$ events (see Figs. 9a and 9b). (The $\Upsilon(2,3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ signals in Fig. 9a are produced by radiative-return transitions $e^+e^-\gamma_{ISR}\Upsilon(2,3S)$.)

![Fig. 9. Belle’s $M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$ mass difference distributions for events with (a) $M(\mu^+\mu^-) = \Upsilon(1S)$ and (b) $M(\mu^+\mu^-) = \Upsilon(2S)$. Vertical dashed lines show the expected locations for $\Upsilon(nS)\rightarrow\pi^+\pi^-\Upsilon(1,2S)$ transitions.](image)

If one assumes that these events are coming from $\Upsilon(5S)\rightarrow\pi^+\pi^-\Upsilon(nS)$ transitions, the inferred partial widths are huge: $\Gamma(\Upsilon(5S)\rightarrow\pi^+\pi^-\Upsilon(1S)) = (590 \pm 40\pm90)$ keV. $\Gamma(\Upsilon(5S)\rightarrow\pi^+\pi^-\Upsilon(2S)) = (850 \pm 70\pm90)$ keV.

The study of the $\Upsilon(5S)$ in other production and decay modes would be useful for distinguishing between different possibilities. The BESIII group made a first step in this program by finding an $f_0(980)\phi$ mass peak with similar parameters produced in $J/\psi\rightarrow\eta f_0(980)\phi$ decays (see Fig. 8). The BESII fit yields a mass and width of $M = (2186\pm10\pm6)$ MeV & $\Gamma = (65\pm23\pm17)$ MeV, which are in good agreement with BaBar’s measurements.
160) keV, more than two orders-of-magnitude higher than corresponding transitions from the $\Upsilon(4S)$.

A likely explanation for these unexpectedly large partial widths (and, in fact, the motivation for Belle’s pursuit of this subject) is that there is a \textit{“Y”}, \textit{i.e.}, a $b\bar{b}$ counterpart of the $\Upsilon(4260)$, that is overlapping the $\Upsilon(5S)$, and this state is producing the $\pi^+\pi^-\Upsilon(1,2S)$ events that are seen. To test this possibility, Belle performed an energy scan to map the $\pi^+\pi^-\Upsilon(1,2S)$ cross section in the cm energy region around 10.87 GeV during December 2007. Results from this scan will be reported in the near future.

6 Summary

A large (and growing) number of candidate charmonium-like meson states have been observed that do not seem to fit into the quark-antiquark classification scheme of the constituent quark model. Some of the salient properties of the states discussed in this report are summarized in Table 1, which is modeled after the one shown by Eichten at QWG2007.

These states exhibit a number of peculiar features:

• Many of them have partial widths for decays to charmonium + light hadrons that are at the \textasciitilde MeV scale, which is much larger than is typical for established $c\bar{c}$ meson states.

• They are relatively narrow although many of them are well above relevant open-charm thresholds.

• There seems to be some selectivity: states seen to decay to final states with a $\psi'$ are not seen in the corresponding $J/\psi$ channel, and \textit{vice versa}.

• The new $1^{--}$ charmonium states are not apparent in the $e^+e^- \rightarrow$ charmed-meson-pair or the total hadronic cross sections.

• There are no evident changes in the properties of these states at the $D^*D^{**}$ mass threshold.

• Although some states are near mass thresholds for pairs of open charmed mesons, this is not a universal feature (see Fig. 9).

• There is some evidence that similar states exist in the $s$- and $b$-quark sectors.

Attempts to explain these states theoretically have usually been confined to subsets of the observed states. For example, the $X(3872)$ and $Z(4430)$ have been attributed to bound molecular states of $DD^*$ and $D^*D^{**}$ mesons, or as diquark-antidiquark tetraquark states, the $Y(4260)$ as a $cc$-gluon hybrid, etc. However, no single model seems able to deal with the whole system and their properties in a compelling way. In general, the predictions of the various models have had limited success.

This continues to be a data-driven field, with an increasingly large number of new results continuing to come out from BaBar, Belle and BES. Hopefully, this deluge of information will eventually lead to a more unified and clearer picture of what is going on.

Table 1. Summary of the candidate $XYZ$ mesons discussed in the text.

| state   | $M$ (MeV)     | $\Gamma$ (MeV) | $J^{PC}$ | Decay Modes | Production Modes | Observed by:             |
|---------|---------------|----------------|----------|-------------|------------------|-------------------------|
| $Y_4(2175)$ | 2175 $\pm 8$ | 58 $\pm 26$ | 1 $^--$ | $f_{15}(980)$ | $e^+e^- \rightarrow J/\psi Y_4(2175)$ | BaBar, BESI             |
| $X(3872)$ | 3875 $\pm 4.6$ | 2.1 | 1 $^{++}$ | $\pi^+\pi^- J/\psi \gamma J/\psi$ | $B \rightarrow K X(3872)$, $\bar{p}p$ | Belle, CDF, D0, BaBar   |
| $X(3875)$ | 3875.5 $\pm 1.5$ | 3.0 $\pm 1.7$ | 2 $^{++}$ | $DD$ | $\gamma \gamma \rightarrow Z(3940)$ | BaBar                   |
| $Z(3940)$ | 3929 $\pm 5$ | 29 $\pm 10$ | 2 $^{++}$ | $e^+e^- \rightarrow J/\psi X(3940)$ | BaBar                   |
| $Y(3940)$ | 3943 $\pm 17$ | 87 $\pm 34$ | 2 $^{++}$ | $\omega J/\psi$ | $B \rightarrow K Y(3940)$ | BaBar                   |
| $Y(4008)$ | 4008 $^{+82}_{-49}$ | 226 $^{+97}_{-80}$ | 1 $^{--}$ | $\pi^+\pi^- J/\psi$ | $e^+e^- \rightarrow J/\psi$ | Belle                   |
| $X(4160)$ | 4156 $\pm 29$ | 139 $^{+133}_{-16}$ | 2 $^{++}$ | $e^+e^- \rightarrow J/\psi X(4160)$ | BaBar, CLEO, Belle     |
| $Y(4260)$ | 4264 $\pm 12$ | 83 $\pm 22$ | 1 $^{--}$ | $\pi^+\pi^- J/\psi$ | $e^+e^- \rightarrow J/\psi$ | BaBar, Belle            |
| $Y(4350)$ | 4350 $\pm 13$ | 74 $\pm 18$ | 1 $^{--}$ | $\pi^+\pi^- \psi'$ | $e^+e^- \rightarrow J/\psi$ | BaBar, Belle            |
| $Z(4430)$ | 4430 $\pm 5$ | 45 $^{+35}_{-18}$ | 1 $^{--}$ | $\pi^+\pi^- \psi'$ | $B \rightarrow K Z(4430)$ | BaBar, Belle            |
| $Y(4660)$ | 4660 $\pm 12$ | 48 $\pm 15$ | 1 $^{--}$ | $\pi^+\pi^- \psi'$ | $e^+e^- \rightarrow J/\psi$ | BaBar, Belle            |
| $Y_b$    | $\sim 10,870$ | ? | 1 $^{--}$ | $\pi^+\pi^- \Upsilon(1,2S)$ | $e^+e^- \rightarrow Y_b$ | KEK                     |

7 Acknowledgements

I thank Changchun Zhang and Ying Hua Jia for organizing this interesting and useful meeting. I was assisted in preparing this report by Sookyung Choi of Gyeongsang National University, Changzheng Yuan and Xia Wang of IHEP-Beijing, Kai-Feng Chen of National Taiwan University and Karim Trabelsi of KEK. This work is supported by the Experimental Physics Center of IHEP-Beijing and the U.S. Department of Energy.

References

1 Choi S-K et al. (Belle Collaboration). Phys. Rev. Lett. (2002) \textbf{89}:102001.
2 Uehara S et al. (Belle Collaboration). Phys. Rev. Lett.
