Results on Charmonium-like States from Belle

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Abstract. We present results from the Belle experiment on various charmonium-like states: \(X(3872), Y(3940), X(3940), Z(3930),\) and \(Y(4260).\) Several of these are difficult to interpret within the conventional quark model and may represent new types of hadronic structure.

1. Introduction
The Belle experiment has reconstructed large samples of \(B\) decays to multi-hadron final states. These samples can be used to search for structure in the invariant mass spectra of the final-state particles, and in this manner identify new hadronic states. This method has been exploited to identify several new and unexpected states. Here we discuss five: \(X(3872), Y(3940), X(3940), Z(3930),\) and \(Y(4260).\) Several of these do not follow the conventional quark-model paradigm.

2. The \(X(3872)\)
The \(X(3872)\) was first observed at Belle using 140 fb\(^{-1}\) of data \cite{1} by plotting the \(J/\psi \pi^+\pi^-\) mass spectrum resulting from \(B^+ \rightarrow J/\psi \pi^+\pi^- K^+\) decays \((J/\psi \rightarrow \ell^+\ell^-)\). A small but unambiguous peak was observed 186 MeV/\(c^2\) above the large 0 peak. Fitting the small peak to a Breit-Wigner function yielded \(M = (3872 \pm 0.7)\) MeV (90% CL); the event yield corresponds to \(B(B^+ \rightarrow J/\psi \pi^+\pi^- K^+) = (14 \pm 5)\)%.

With a larger 256 fb\(^{-1}\) data sample \cite{3} Belle observed a significant signal for \(X(3872) \rightarrow J/\psi \gamma\) (Fig. 1). This decay establishes the C-parity to be +1. The ratio \(\Gamma(X \rightarrow J/\psi \gamma)/\Gamma(X \rightarrow J/\psi \pi^+\pi^-) = (14 \pm 5)\)%.

The \(J^P\) assignment of the \(X(3872)\) was investigated by plotting various angular distributions in \(X \rightarrow J/\psi \pi^+\pi^-\) decays \cite{4}. To increase statistics, the neutral mode \(B^0 \rightarrow J/\psi \pi^+\pi^- K^0_S\) is included. From the distribution of the angle \(\psi \) in the \(\pi^+\pi^-\) rest frame between the \(\pi^+\pi^-\) decay axis and the \(J/\psi\) direction, \(0^+\) is found to be disfavored. From the distribution of the angle \(\theta_{\ell\pi}\) between the \(\pi^+\pi^-\) and \(\ell^+\ell^-\) directions, \(0^+\) is found to be disfavored.
of angles $\theta_k$ and $\chi$ in the $X(3872)$ rest frame agree well with those expected for a 1+ state (Fig. 3). The angle $\theta_k$ is that between the $\ell^+$ and the z-axis, which is defined as normal to the $\pi^+K$ decay plane, and $\chi$ is the angle between the $\pi^+$ and $K$ directions. A $^-$ state cannot be excluded, but this would imply that the $(\pi\pi)\cdot J/\psi$ system has $L=1$, which is disfavored by the $\pi^+\pi^-$ mass spectrum. This spectrum peaks near the upper endpoint, which is not expected for $L=1$ as high masses are nominally suppressed by a “centrifugal barrier” term $q_\psi^{2L+1}$, where $q_\psi$ is the $J/\psi$ momentum in the $X(3872)$ rest frame [5].

Finally, Belle tentatively identifies $X(3872) \rightarrow D^0\overline{D}^0\pi^0$ decays with 414 fb$^{-1}$ of data [6] by selecting $B \rightarrow D^{0}\overline{D}^{0}\pi^0\{K^+, K^0_S\}$ candidates using $M_{bc}$ and performing a two-dimensional fit to the variables $\Delta E$ and $Q \equiv M(D^{0}\overline{D}^{0}\pi^0) - 2M(D^0) - M(\pi^0)$. Both $\Delta E$ and $Q$ exhibit sharp signal peaks (Fig. 4). The fit gives $24.1 \pm 6.1$ events, which has a statistical significance of 6.4$\sigma$, and $M(D^{0}\overline{D}^{0}\pi^0) = (3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8)$ MeV/c$^2$, where the last error is due to uncertainty in $M_{D^0}$ [7]. This mass value is 2.0$\sigma$ higher than that measured with $X \rightarrow J/\psi \pi^+\pi^-$ decays; more data is needed to understand this difference. The observed rate for $X(3872) \rightarrow D^0\overline{D}^0\pi^0$ is large: assuming $\Gamma(B^+ \rightarrow XK^+) = \Gamma(B^0 \rightarrow XK^0)$, $\Gamma(X \rightarrow D^{0}\overline{D}^{0}\pi^0)/\Gamma(X \rightarrow J/\psi \pi^+\pi^-) = 8.8^{+3.1}_{-3.0}$. This decay disfavors $J^P = 2^-$, as such a state formed from three pseudoscalars would have one meson pair with $L=2$, and thus $D^0\overline{D}^0\pi^0$ production near threshold would be suppressed by an $L=2$ centrifugal barrier.

3. The Y(3940)

The $Y(3940)$ is observed as an enhancement near threshold in the $J/\psi \omega$ mass spectrum in $B \rightarrow J/\psi \omega\{K^+, K^0_S\}$ decays [8]. In this analysis, which uses 253 fb$^{-1}$ of data, $\omega$ mesons are reconstructed via $\omega \rightarrow \pi^+\pi^-\pi^0$, where the $J/\psi \pi^+\pi^-$ mass is required to be well above the $\psi'$ mass. The requirement $m(K\omega) > 1.6$ GeV/c$^2$ is also imposed to reject feed-down background from $K^+_1(1400) \rightarrow K\omega$. The final event sample is divided into bins of $m(J/\psi\omega)$, and, for each bin, the signal yield is obtained by fitting the $M_{bc}$ and $\Delta E$ distributions. Plotting the resulting yields gives the $J/\psi \omega$ mass spectrum shown in Fig. 5. This spectrum is inconsistent with a threshold function but is well-described by a Breit-Wigner function; the result of a fit is $M = (3943 \pm 11 \pm 13)$ MeV/c$^2$ and $\Gamma = (87 \pm 22 \pm 26)$ MeV. The event yield corresponds to $B(B \rightarrow YK) \times B(Y \rightarrow J/\psi\omega) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5}$. This branching fraction is large for a conventional $c\bar{c}$ charmonium state; however, the fit mass is lighter than expected for a $c\bar{c}$-glue hybrid state.

4. The X(3940)

Complicating the interpretation of the $Y(3940)$ is the observation by Belle of an apparently distinct state at the same mass. This state is observed [9] using 357 fb$^{-1}$ of data in inclusive $e^+e^- \rightarrow J/\psi X$ production by reconstructing $J/\psi \rightarrow \ell^+\ell^-$ decays and calculating the “recoil mass” $M_{\text{rec}}(\psi) = \sqrt{(E_{\text{CM}} - E_\psi)^2 - p_\psi^2}$, where $p_\psi$ is evaluated in the CM frame and $E_\psi = \sqrt{p_\psi^2 + m_\psi^2}$. Assuming momentum conservation, $M_{\text{rec}}(\psi)$ is the invariant mass of the state produced in association with the $J/\psi$. The resulting distribution is shown in Fig. 6(top) and shows several peaks: the $\eta_c$ at 2970 MeV/c$^2$, the $\chi_{c0}$ at 3406 MeV/c$^2$, the $\eta'_c$ at 3626 MeV/c$^2$, and an unexpected but prominent peak near 3940 MeV/c$^2$. Fitting this peak to a Breit-Wigner plus a smooth background function gives $M = 3936 \pm 14$ MeV/c$^2$; the statistical significance of the signal yield is 5.0$\sigma$. This state is referred to as the $X(3940)$.

Since $M(X(3940))$ is above $DD$ threshold, one can search for $X(3940) \rightarrow D^{(*)}D^{(*)}$ decays. To overcome the small reconstruction efficiency for $D^0$ or $D^+$ (i.e., due to small reconstructible branching fractions), only one $D$ is reconstructed and the other is identified via the recoil mass.
Figure 1. $B \rightarrow J/\psi \gamma \{K^+, K_S^0\}$ candidates. The top plot shows $M_{bc}$ distributions in bins of $M(J/\psi \gamma)$; the bottom plot shows the signal yields obtained from fitting these distributions.

Figure 2. $X(3872) \rightarrow J/\psi \pi^+\pi^-$: background-subtracted $M(\pi^+\pi^-\pi^0)$ spectrum.

Figure 3. $X(3872) \rightarrow J/\psi \pi^+\pi^-$ candidates: background-subtracted spectra for $|\cos \theta_L|$ and $|\cos \chi|$ (see text). The unshaded and shaded histograms show the MC and $M(J/\psi \pi^+\pi^-)$ sideband distributions, respectively.

Figure 4. $B \rightarrow D^0\bar{D}^0\pi^0 K$ candidates: $M(D^0\bar{D}^0\pi^0) - 2M(D^0) - M(\pi^0)$ and $\Delta E$ distributions for $5.273 < M_{bc} < 5.286$ GeV/c$^2$. The peaks indicate $X(3872) \rightarrow D^0\bar{D}^0\pi^0$.

Figure 5. $B \rightarrow J/\psi \omega K$ candidates: background-subtracted $m(J/\psi \omega)$ spectrum. Left: fit to a threshold function. Right: fit to a Breit-Wigner plus smooth background function.
$\chi^c \eta^c (2S) X(3940)$

$\text{Figure 6. } e^+e^- \rightarrow J/\psi X \text{ inclusive events: } M_{\text{recoil}}(J/\psi) \text{ recoil mass distribution (top) and } M_{\text{recoil}}(J/\psi D) \text{ distribution (bottom).}$

$\text{Table 1. } X(3940) \text{ measurements from Ref. [9].}$

| Fit                          | Measurement | Value          |
|------------------------------|-------------|----------------|
| Inclusive sample (Fig. 6, top) | $M$         | 3936 ± 14 MeV/c$^2$ |
|                              | $\Gamma$   | 39 ± 26 MeV    |
| Exclusive sample (Fig. 7)    | $M$         | 3943 ± 6 MeV/c$^2$ |
|                              | $\Gamma$   | 15.4 ± 10.1 MeV |
|                              | $B(X \rightarrow DD^*)|_{(# \text{trks} > 2)}$ | (96$^{+45}_{-32}$ ± 22)% |
|                              | $B(X \rightarrow DD)$ | < 41% (90% C.L.) |
|                              | $B(X \rightarrow J/\psi \omega)$ | < 26% (90% C.L.) |

$M_{\text{recoil}}(J/\psi D)$. This recoil mass distribution is shown in Fig. 6(bottom) and exhibits three peaks; these correspond to the processes $e^+e^- \rightarrow J/\psi DD, J/\psi DD^*, \text{ and } J/\psi D^* D^*$. To search for $X(3940) \rightarrow D^{(*)} D^{(*)}$, events with $M_{\text{recoil}}(J/\psi D) \approx M_{D^{(*)}}$ are selected (i.e., $e^+e^- \rightarrow J/\psi DD^{(*)}$) and the recoil mass $M_{\text{recoil}}(J/\psi)$ plotted. These distributions are shown in Fig. 7. While the $J/\psi DD$ events show no structure, the $J/\psi DD^*$ events show a peak near 3940 MeV/c$^2$. The statistical significance of the excess of events is 5.0$\sigma$. Fitting the peak to a Breit-Wigner gives $M = (3943 \pm 6)$ MeV/c$^2$ and $\Gamma = (15.4 \pm 10.1)$ MeV, which are consistent with the values obtained from fitting Fig. 6(top). Fig. 7 implies $X(3940) \rightarrow DD^*$ but $X(3940) \not\rightarrow DD$.

To determine whether $X(3940) = Y(3940)$, Belle reconstructs $\omega \rightarrow \pi^+ \pi^- \pi^0$ decays, selects events in which the recoil mass $M_{\text{recoil}}(J/\psi \omega) \approx M_{J/\psi}^\omega$ (i.e., $e^+e^- \rightarrow J/\psi J/\psi \omega$), and plots the $J/\psi \omega$ invariant mass. A peak would indicate $X(3940) \rightarrow J/\psi \omega$. No peak is seen, and one concludes that $X(3940)$ and $Y(3940)$ are unrelated. All $X(3940)$ measurements are listed in Table 1.

$\text{Figure 7. } M_{\text{recoil}}(J/\psi)$ distribution for events having $M_{\text{recoil}}(J/\psi D) \approx M_D$ (top) and $M_{\text{recoil}}(J/\psi D) \approx M_D^*$ (bottom).
5. The $Z(3930)$

The $Z(3930)$ was observed using 395 fb$^{-1}$ of data in $e^+e^- \rightarrow e^+e^-\gamma\gamma$ (“two-photon”) events in which the two photons emerge as a $D^0\bar{D}^0$ or $D^+D^-$ pair [10]. To reject background from $e^+e^- \rightarrow \gamma\text{ISR} D^{(*)}\bar{D}^{(*)}$ events ($\bar{c}\bar{c}$ production with initial-state-radiation (ISR)), the longitudinal momentum of the $D\bar{D}$ system is required to be greater than \[ M(D\bar{D})^2 - \alpha^2/\beta + \gamma, \] where $\alpha = 7 \text{ GeV}/c^2$, $\beta = 14 \text{ GeV}/c^3$, and $\gamma = 0.6 \text{ GeV}/c$.

The $D^0\bar{D}^0$ and $D^+D^-$ invariant mass distributions after all selection criteria are applied both exhibit small peaks near 3.9 GeV/c$^2$. Fitting these peaks to a common Breit-Wigner gives $M = (3929 \pm 5 \pm 2) \text{ MeV}/c^2$, $\Gamma = (29 \pm 10 \pm 2) \text{ MeV}$, and a signal yield of 64 $\pm$ 18 events. This yield corresponds to 5.3$\sigma$ statistical significance and is sufficient to construct the helicity angle distribution, which is sensitive to the angular momentum $J$. Figure 8 shows the $\cos \theta^*$ spectrum, where the helicity angle $\theta^*$ is defined as the angle between the $D^0$ momentum and the beam axis in the $\gamma\gamma$ rest frame. The spectrum is obtained by binning events in $\cos \theta^*$ and, for each bin, fitting the $M_{\text{rec}}$ and $\Delta E$ distributions to obtain the signal yield. Fitting this spectrum to a constant, which corresponds to $J=0$, gives a poor fit ($\chi^2$/d.o.f. = 23/9); but fitting to a $\sin^4 \theta^*$ function, which corresponds to $J=2$, gives a good fit ($\chi^2$/d.o.f. = 1.9/9). Thus $J=2$ is preferred. The $Z(3930)$ mass, width, and spin $J$ are consistent with the values expected for the $\chi_{c2}^+$ state (the first radial excitation of the $\chi_{c2}$), and thus the $Z(3930)$ is usually identified as $\chi_{c2}^+$. 

6. The $Y(4260)$

The $Y(4260)$, discovered by the BaBar experiment [11], is observed in the ISR process $e^+e^- \rightarrow \gamma\text{ISR} J/\psi \pi^+\pi^-\pi^-$ using 553 fb$^{-1}$ of data [12]. For these events the $M_{\text{rec}}(J/\psi \pi^+\pi^-)$ recoil mass distribution exhibits a sharp peak near zero, which confirms that the $J/\psi \pi\pi$ system is recoiling against a single photon. Selecting events in this peak and plotting the $J/\psi \pi^+\pi^-\pi^-$ invariant (non-recoil) mass shows a sharp peak at $M_{\psi'}$. Fitting this peak to a Breit-Wigner gives $M_{\psi'} = (3686.0 \pm 0.1) \text{ MeV}/c^2$, in good agreement with the PDG value (3686.09 $\pm$ 0.03) MeV/c$^2$ [7]. The invariant mass distribution in a higher mass range is shown in Fig. 9: here a prominent peak is seen near 4 GeV/c$^2$. Fitting this to a Breit-Wigner plus a smooth background function gives $M = (4295 \pm 10^{+10}_{-3}) \text{ MeV}/c^2$, $\Gamma = (133 \pm 26^{+13}_{-6}) \text{ MeV}$, and a signal yield of $165 \pm 24^{+2}_{-23}$ events. The mass value is similar to, but somewhat higher than, that measured by BaBar: $(4259 \pm 8^{+2}_{-6}) \text{ MeV}/c^2$ [11]. If we also reconstruct the initial state $\gamma\text{ISR}$, the efficiency drops substantially; however, the $J\psi \pi^+\pi^-\pi^-$ mass spectrum still exhibits a peak at 4290 MeV/c$^2$ (Fig. 10).

To search for sub-structure, the data is binned in $M(\pi^+\pi^-)$ and, for each bin, the signal yield obtained by fitting the $M(J/\psi \pi^+\pi^-)$ distribution. The resulting yields are corrected for efficiency and plotted in Fig. 11 along with the corresponding MC spectrum. The two spectra appear qualitatively different. The analogous spectra for $\psi' \rightarrow J/\psi \pi^+\pi^-\pi^-$ events show excellent agreement between data and MC.

7. Summary

In summary, we have discussed five new states or enhancements: $X(3872)$, $Y(3940)$, $Z(3930)$, and $Y(4260)$. These states have rekindled broad interest in $c\bar{c}$ spectroscopy. The $X(3872)$ is now well-established; the decay to $J/\psi \gamma$ implies $C=+1$, and an angular analysis favors $J^P = 1^+$. However, its mass is low for a conventional $c\bar{c}$ state; it has a large rate to $D^0\bar{D}^0\pi^0$; and it decays to both $J/\psi \pi^+\pi^-$ and $J/\psi \omega$, which is isospin-violating. Thus the $X(3872)$ is not easy to classify as charmonium and is often described as a $D^0\bar{D}^0$ “molecule” [13].
Figure 8. $e^+e^- \rightarrow e^+e^- \gamma \gamma \rightarrow e^+e^- D^0 \bar{D}^0$ events. Left: $D^0 \bar{D}^0$ mass distribution for two ranges of $\cos \theta^*$ (see text). Right: background-subtracted $|\cos \theta^*|$ spectrum.

Figure 9. $M(J/\psi \pi^+\pi^-)$ distribution for $e^+e^- \rightarrow \gamma_{ISR} J/\psi \pi^+\pi^-$ events having recoil mass $M_{rec}(J/\psi \pi^+\pi^-)$ near zero. The solid curve is the result of a fit to a Breit-Wigner.

Figure 10. $M(J/\psi \pi^+\pi^-)$ distribution for $e^+e^- \rightarrow \gamma_{ISR} J/\psi \pi^+\pi^-$ events having recoil mass $M_{rec}(J/\psi \pi^+\pi^-)$ near zero. The $\gamma_{ISR}$ is reconstructed.

Figure 11. Background-subtracted, efficiency-corrected $M(\pi^+\pi^-)$ spectrum for $e^+e^- \rightarrow \gamma_{ISR} J/\psi \pi^+\pi^-$ events in which $M(J/\psi \pi^+\pi^-) \approx 4260$ MeV/$c^2$. The histogram shows the MC spectrum.

This description is consistent with its mass being just below $D^0 \bar{D}^0$ threshold, i.e., the binding energy would be small.

The $Y(3940)$ enhancement near threshold has a large rate to $J/\psi \omega$ for a $c\bar{c}$ state. However, its mass is relatively light for it to be a $c\bar{c}$-glue hybrid state. This state has not yet been confirmed by other experiments and remains a puzzle.

The $X(3940)$ peak observed in inclusive $J/\psi$ production has a large rate to $DD^*$ but no observed rate to $DD$ or $J/\psi \omega$. The absence of the latter mode implies that $X(3940)$ and $Y(3940)$ are distinct. The mass and width of the $X(3940)$ are consistent with those expected for the $\eta_c(3S)$ [14], but other $c\bar{c}$ assignments are possible.

The $Z(3930)$ is found in two-photon events. Its mass, width, and spin $J$ (determined from an angular analysis of ~50 events) are consistent with expectations for the $\chi_{c2}$ state, and it is
usually considered as such.

The $Y(4260)$ is found in ISR events decaying to $J/\psi \pi^+\pi^-$. The observed rate is higher than that expected for a $c\bar{c}$ state, which would preferentially decay to $D(\pi^+)\bar{D}(\pi^-)$. The latter mode is not seen. Also, the $\pi^+\pi^-$ mass distribution looks notably different than that from MC simulation. Thus the $Y(4260)$ is considered unlikely to be a simple radial excitation, and it is often considered a quark-gluon hybrid [15]. Hopefully, further measurements of this state (and the other $X, Y, Z$ states) will advance our understanding of hadronic structure and QCD in the non-perturbative regime.

8. References

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