PROCEEDINGS OF SCIENCE

BABAR /Belle Heavy hadron production and decays, including the Y(4260), Y(4350) and Y(4660) states

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We present new results on charmonium-like states from the *BABAR* experiment, located at the PEP-II asymmetric energy e^+e^- collider, and from the Belle experiment, located at the KEKB asymmetric energy e^+e^- storage rings.

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1. Charmonium Spectroscopy

The charmonium spectrum consists of eight narrow states below the open charm threshold at 3.73 GeV/c^2, the $\psi(3770)$, and a significant number of states above the threshold. Below the threshold all of the states are well established, and no additional states are expected. On the other hand, our understanding is still very limited above the threshold, where there are several new "Charmonium-like" states that are very difficult to accommodate in the charmonium spectrum.

The *B*-factories are an ideal place to study charmonium states since they may be produced in four different processes:

- *B* decays, in which charmonium states with any quantum numbers can be produced.
- Two photon production where two virtual photons are emitted by the colliding e^+e^- pair ($e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-(c\bar{c})$) and charmonium states with $J^{PC} = 0^{\pm+}, 2^{\pm+}, 4^{\pm+}, ..., 3^{++}$, 5^{++}... can be produced.
- Initial State Radiation (ISR), in which a photon is emitted by the incoming electron or positron in the reaction $e^+e^- \to \gamma_{ISR}c\bar{c}$, where only states with $J^{PC} = 1^{--}$ can be formed.
- Double charmonium production, where a J/ψ or a $\psi(2S)$ is produced together with another charmonium state.

2. Study of the process $\gamma\gamma \to J/\psi\omega$

The charmonium-like state Y(3940) was first seen by Belle [1] and then confirmed by *BABAR* [2] in the same *B* meson decay mode, but with lower mass and smaller width compared to the Belle results.

In a re-analysis [3] of the *BABAR* data which used the complete $\Upsilon(4S)$ data sample, the precision of the Y(3940) measurements was improved, and evidence for the decay X(3872)$\to J/\psi\omega$ was reported. This confirmed an earlier unpublished Belle claim for the existence of this decay mode [4]. The latter was based on the behaviour of the invariant $\pi^+\pi^-\pi^0$ mass distribution near the X(3872), whereas the *BABAR* result is obtained directly from a fit the the $J/\psi\omega$ mass distribution. A subsequent paper from Belle [5] reported the observation in $\gamma\gamma \to J/\psi\omega$ of a state, the X(3915), with mass and width values similar to those obtained for the Y(3940) in the *BABAR* analysis [2].

The *BABAR* analysis of the process $\gamma\gamma \to J/\psi\omega$ has been performed [6] in order to search for the X(3915) and the X(3872) resonances via the decay to $J/\psi\omega$, using a data sample of 519 fb^{-1}. Figure 1 shows the reconstructed $J/\psi\omega$ invariant mass distribution after all the selection criteria have been applied. A large peak near 3915 MeV/c^2 is observed with a significance of 7.6 σ. An extended maximum likelihood fit to the efficiency-corrected spectrum yields the measured resonance parameter values $m[X(3915)] = (3919.4 \pm 2.2 \pm 1.6)$ MeV/c^2 and $\Gamma[X(3915)] = (13 \pm 6 \pm 3)$ MeV. The measured value of the two-photon width times the branching fraction, $\Gamma_{\gamma\gamma}[X(3915)]$ x $\mathscr{B}(X(3915) \to J/\psi\omega)$ is $(52 \pm 10 \pm 3)$ eV for the J=0 spin hypothesis, where the first error is statistical and the second is systematic. In addition, a detailed angular analysis favored the $J^P = 0^+$ quantum number assignment for the X(3915).

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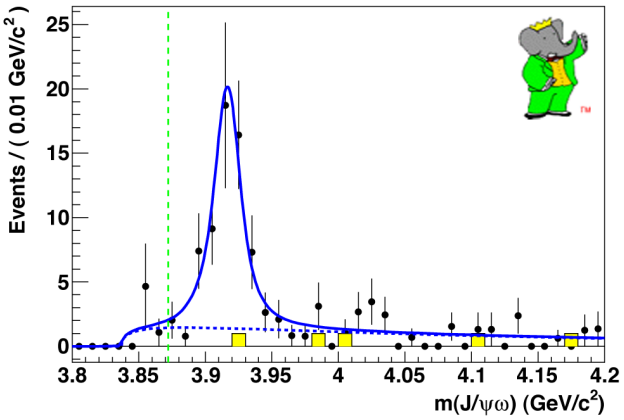

Figure 1: The efficiency-corrected invariant mass distribution for the $J/\psi\omega$ final state. The vertical dashed line is at the X(3872) mass [3].

3. Study of the $J/\psi\pi^+\pi^-$ system via Initial State Radiation (ISR)

The Y(4260) charmonium-like resonance was discovered by *BABAR* [7] in the ISR production of $J/\psi\pi^+\pi^-$. A subsequent Belle analysis [8] of the same final state suggested also the existence of an additional resonance around 4.1 GeV/c^2 that they dubbed the Y(4008). The Y(4260) parameter values extracted from the fit to the Belle data are: $m[Y(4260)] = 4263 \pm 6$ MeV/c^2 and $\Gamma[Y(4260)] = 126 \pm 18$ MeV, while the Y(4008) values are: $m[Y(4008)] = 4008 \pm 40^{+114}_{-28}$ MeV/c^2 and $\Gamma[Y(4008)] = 226 \pm 44 \pm 87$ MeV.

The *BABAR* analysis of the $J/\psi\pi^+\pi^-$ system produced in ISR has been repeated using a data sample of 454 fb^{-1} [9]. Figure 2(a) shows the fit to the $J/\psi\pi^+\pi^-$ distribution. A clear signal for the Y(4260) is observed for which the parameter values obtained are $m[Y(4260)] = 4244 \pm 5 \pm 4$ MeV/c^2, $\Gamma[Y(4260)] = 114^{+16}_{-15} \pm 7$ MeV, and Γ_{ee} x $\mathscr{B}(J/\psi\pi^+\pi^-) = 9.2 \pm 0.8$ (stat) $\pm$ 0.7 (syst) eV. No evidence was seen for the state at ~ 4 GeV/c^2 reported by Belle [8]. A study of the $\pi^+\pi^-$ system from the Y(4260) decay to $J/\psi\pi^+\pi^-$ has been performed. The dipion system is in a predominantly S-wave state. The mass distribution exhibits a dipion continuum and an $f_0(980)$ signal, for which a simple interference model indicates a branching ratio with respect to $J/\psi\pi^+\pi^-$ of 0.17 $\pm$ 0.13 (stat). The fit to the dipion invariant mass distribution is shown by the solid histogram in Figure 2(b).

The Belle collaboration has repeated this analysis with a data sample of 967 fb^{-1} collected at the $\Upsilon(nS)$ resonances (n=1,2,3,4,5) [10] . They confirm the Y(4260) with the following parameter values $m[Y(4260)] = 4258.6 \pm 8.3 \pm 12.1$ MeV/c^2 and $\Gamma[Y(4260)] = 134.1 \pm 16.4 \pm 5.5$ MeV. They confirm the Y(4008) resonance, previously reported by Belle [8] and not confirmed by *BABAR* [9]. The Y(4008) parameter values extracted from the fit are: $m[Y(4008)] = 3890.8 \pm 40.5 \pm 11.5$ MeV/c^2 and $\Gamma[Y(4008)] = 254.4 \pm 39.5 \pm 13.5$ MeV. The result of the fit to the $J/\psi\pi^+\pi^-$ invariant mass distribution is shown in Figure 3(a). The result of their fit to the $\pi J/\psi$ invariant mass distribution is shown in Figure 3(b). They report a new resonance with 5.2σ significance that can be interpreted as a new charged charmonium-like state, the $Z_c(3900)$ with mass $m[Z_c(3900)] = 3894.5 \pm 6.6 \pm 4.5$ MeV/c^2 and width $\Gamma[Z_c(3900)] = 63 \pm 24 \pm 26$ MeV. The results are consistent with those from a previous BES analysis [11].

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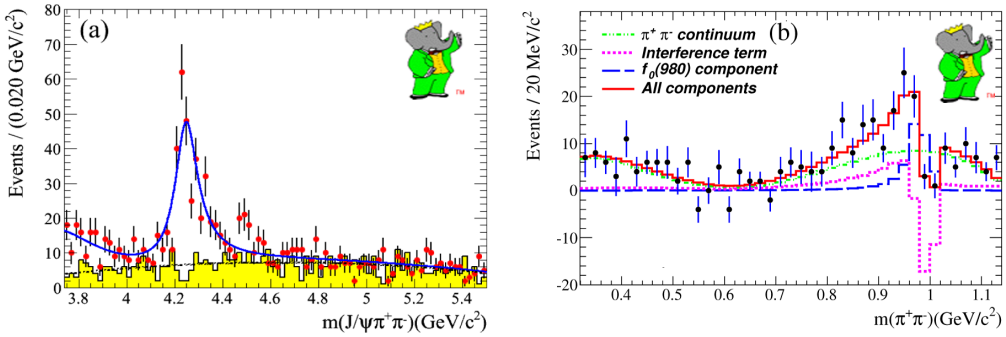

Figure 2: (a) The fit to the $J/\psi\pi^+\pi^-$ invariant mass distribution. (b) The fit to the dipion invariant mass distribution from the Y(4260) signal region [9].

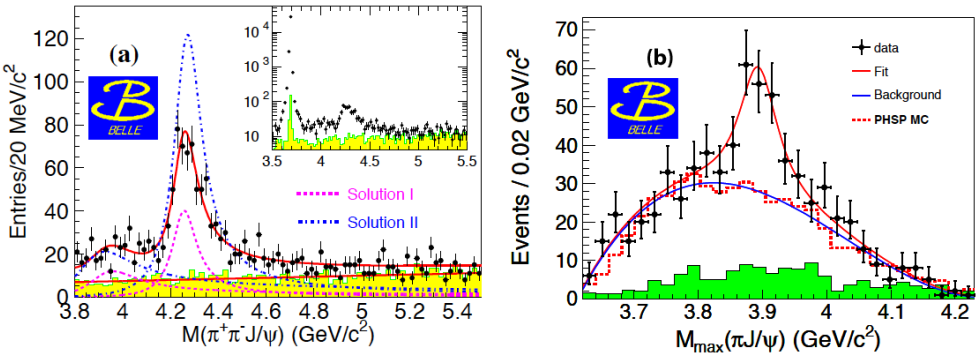

Figure 3: (a) The fit to the $J/\psi\pi^+\pi^-$ invariant mass distribution. (b) The fit to the distribution of the larger $J/\psi\pi$ invariant mass [10].

4. Study of the $\psi(2S)\pi^+\pi^-$ system via ISR

The Y(4350) charmonium-like resonance was discovered by *BABAR* [12] in ISR production of $\psi(2S)\pi^+\pi^-$. Belle reported also the existence of an additional resonance around 4.660 GeV/c^2 [13]. The Y(4350) parameter values extracted from their fit are: $m[Y(4350)] = 4361 \pm 9 \pm 9$ MeV/c^2 and $\Gamma[Y(4350)] = 74 \pm 15 \pm 10$ MeV, while the Y(4660) parameter values are: $m[Y(4660)] = 4664 \pm 11 \pm 5$ MeV/c^2 and $\Gamma[Y(4660)] = 48 \pm 15 \pm 3$ MeV.

The *BABAR* analysis studies the $\psi(2S)\pi^+\pi^-$ system produced via ISR using the full datasets collected at the $\Upsilon(nS)$, n=2,3,4; this corresponds to an integrated luminosity of 520 fb^{-1} [14]. An unbinned extended-maximum-likelihood fit is performed to the $\psi(2S)\pi^+\pi^-$ invariant mass distribution and simultaneously to the background distribution. The result of the fit is shown in Figure 4. The Y(4350) parameter values extracted from the fit are: $m[Y(4350)] = 4340 \pm 16 \pm 9$ MeV/c^2 and $\Gamma[Y(4350)] = 94 \pm 32 \pm 13$ MeV, while the Y(4660) parameters are: $m[Y(4660)] = 4669 \pm 21 \pm 3$ MeV/c^2 and $\Gamma[Y(4660)] = 104 \pm 48 \pm 10$ MeV.

5. Evidence for $\psi_2(1D)$

The D-wave charmonium levels are expected to be situated between the $D\bar{D}$ and $D\bar{D}^*$ thresholds [15]. Among them, the η_{c2} with $J^{PC} = 2^{-+}$ and ψ_2 with $J^{PC} = 2^{--}$ have unnatural spin

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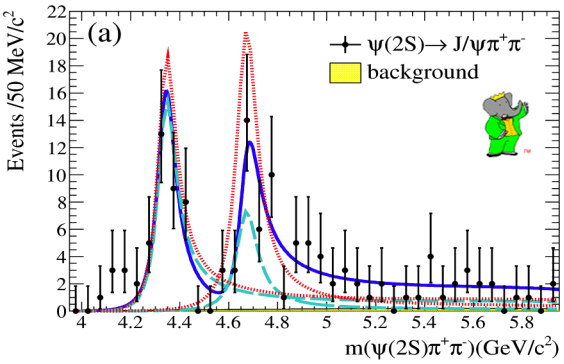

Figure 4: Fit to the invariant mass distribution of the $\psi(2S)\pi^+\pi^-$ system [14].

parities and cannot decay to $D\bar{D}$. Thus they remain the only undiscovered narrow charmonia.

Belle reported preliminary results on the resonant structure of the $B^+ \to K^+\chi_{c1}\gamma$ decays, with $\chi_{c1} \to J/\psi\gamma$. In the channel $\chi_{c1}\gamma$ Belle finds the first evidence for the $\psi_2(1D)$ charmonium state (see Figure 5), with mass $M = (3823.5 \pm 2.8)$ MeV/c^2 and significance of 4.2σ, including systematic uncertainty. The measured width is consistent with zero, $\Gamma = (4 \pm 6)$ MeV; it is likely that the width is very small, since the state is observed in radiative decay and typical charmonium radiative decay widths are at the $O(100)$ keV level. The odd C-parity (fixed by decay products) allows discrimination between the η_{c2} and ψ_2 hypotheses. No signal is found in the $\chi_{c2}\gamma$ channel, in agreement with expectations for the ψ_2 [15]. Belle measures $\mathscr{B}(B^+ \to K^+\psi_2) \times \mathscr{B}(\psi_2 \to \chi_{c1}\gamma) = (9.7^{+2.8}_{-2.5} \pm 1.1) \times 10^{-6}$. Using the expected value $\mathscr{B}(\psi_2 \to \chi_{c1}\gamma) \sim \frac{2}{3}$ [15], it follows that $\mathscr{B}(B^+ \to K^+\psi_2)$ is a factor 50 smaller than the corresponding branching fractions to the J/ψ, $\psi(2S)$ and χ_{c1}. This is attributed to factorization suppression [16].

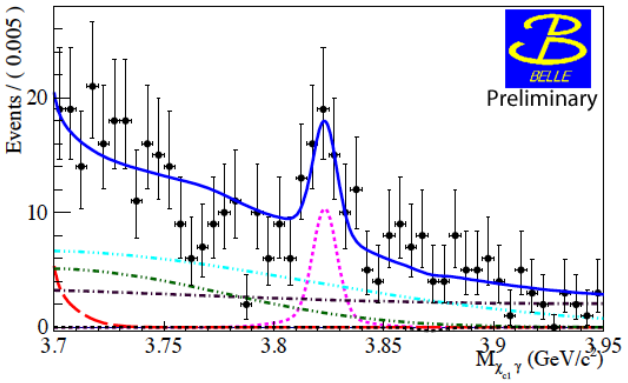

Figure 5: The $M(\chi_{c1}\gamma)$ spectrum for the $B^+ \to K^+\chi_{c1}\gamma$ candidates

6. Observation of $\psi(4040)$ and $\psi(4160)$ transitions to $J/\psi\eta$

The Belle collaboration has observed transitions from the $\psi(4040)$ and the $\psi(4160)$ to $J/\psi\eta$ (see Figure 6) using the ISR scan of the $e^+e^- \to J/\psi\eta$ cross section with a data sample of 980 fb^{-1}

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[17]. The partial widths of these transitions are $\Gamma \sim 1$ MeV, which are anomalously large. For the first time ψ states that are considered to be "conventional charmonia" show anomalous properties.

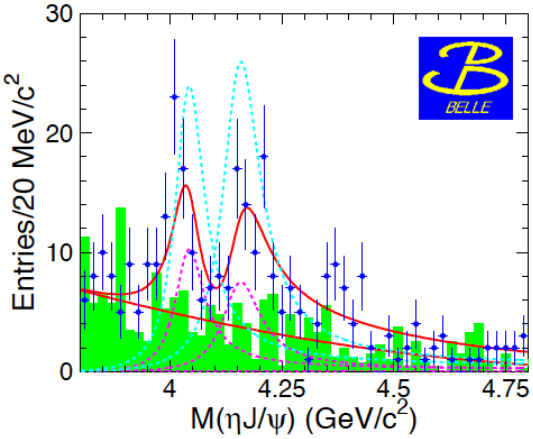

Figure 6: The $\eta J/\psi$ invariant mass distribution [17].

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