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Studies of Charmonium Production at BABAR

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We present recent results on charmonium and charmonium-like states from the BABAR B-factory located at the PEP-II asymmetric-energy e^+e^- collider at the SLAC National Accelerator Laboratory.

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1 Introduction

The charmonium spectrum consists of eight narrow states below the open charm threshold (3.73 GeV) and several tens of states above that. Below the threshold almost all states are well-established. In contrast very little is known at higher masses where there have been discoveries [1] of several new charmonium-like states for which the interpretation is still not clear. In the following sections we will review recent *BABAR* results in this area.

2 Study of $J/\psi\omega$ production in two-photon interactions

The Y(3940) was observed by Belle [2] in B decays and confirmed by *BABAR* [3]. In a re-analysis [4] of the *BABAR* data sample the precision of the Y(3940) parameters was improved and evidence was found also for the decay $X(3872) \to J/\psi\omega$. This confirmed an earlier unpublished Belle claim [5] for the existence of this decay mode. A subsequent Belle paper [6] reported evidence of a structure in the process $\gamma\gamma \to J/\psi\omega$ that they named the X(3915), with mass and width values similar to those obtained for the Y(3940) by *BABAR* [3]. In this context *BABAR* has performed a study of the process $\gamma\gamma \to J/\psi\omega$ [7] to search for the X(3915) and the X(3872) using a data sample corresponding to an integrated luminosity of 519 fb^{-1}. We searched for the X(3872) since, until recently [8], its quantum numbers were ambiguous between $J^{PC} = 1^{++}$ and $J^{PC} = 2^{-+}$. For the former the state cannot be produced in two-photon collisions. Figure 1 shows the reconstructed $J/\psi\omega$ mass distribution after all selection criteria have been applied. A large peak near 3915 MeV/c^2 is observed with a significance of 7.6 σ. The measured parameters for the resonance, obtained from a maximum likelihood fit, are $m_{X(3915)} = (3919.4 \pm 2.2 \pm 1.6)$MeV/c^2 and $\Gamma_{X(3915)} = (13 \pm 6 \pm 3)$MeV. The value of the two-photon width times the branching fraction is found to be $\Gamma_{\gamma\gamma}(X(3915)) \times \mathcal{B}(X(3915) \to J/\psi\omega) = 52 \pm 10 \pm 3$ eV for the spin 0 hypothesis, and $10.5 \pm 1.9 \pm 0.6$ eV for spin 2, where the first error is statistical and the second is systematic.

We performed an angular analysis based on the predictions of Rosner [9] in an attempt to establish the quantum numbers of the X(3915). We first discriminate between $J^P = 0^\pm$ and $J^P = 2^+$ using the relevant final state angular distributions. In all cases the $J^P = 0^\pm$ hypothesis describes the data better than the $J^P = 2^+$ hypothesis [7]. We then discriminate between $J^P = 0^-$ and $J^P = 0^+$. In all cases the $J^P = 0^+$ hypothesis gives a smaller χ^2. In summary we find that assignment of $J^P = 0^+$ is preferred. This assignment favors the interpretation of the X(3915) as the $\chi_{c0}(2P)$ charmonium state.

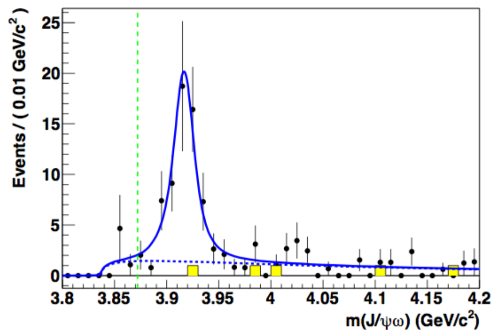

Figure 1: The efficiency-corrected invariant mass distribution for the $J/\psi\omega$ final state. The solid curve represents the total fit function. The dashed curve is the background contribution. The shaded histogram is the non $J/\psi\omega$ background estimated from sidebands. The vertical dashed line is placed at the nominal X(3872) mass.

3 Search for the $Z_1(4050)^+$ and $Z_2(4250)^+$

In 2008 the Belle Collaboration reported the observation of a resonance-like structure called the $Z(4430)^+$ decaying to $\psi(2S)\pi^+$ in the process $B \to \psi(2S)K\pi$ [10]. This claim generated a great deal of interest [11] since such a state must have a minimum quark content $c\bar{c}\bar{d}u$, and thus would represent an unequivocal manifestation of a four-quark meson state. The *BABAR* collaboration searched for the $Z(4430)^+$ in an analysis of the process $B \to \psi(2S)K\pi$, and also in $B \to J/\psi K\pi$ [12], but without finding significant structure in $\psi(2S)\pi$ nor in $J/\psi\pi$ invariant mass. In 2009 the Belle Collaboration reported the observation of two additional resonance-like structures similar to the $Z(4430)^+$ in the study of $\overline{B}^0 \to \chi_{c1}K^-\pi^+$ [13]. These new structures were labeled as the $Z_1(4050)^+$ and the $Z_2(4250)^+$, both decaying to $\chi_{c1}\pi^+$.

Using a data sample from an integrated luminosity of 429 fb^{-1}, *BABAR* has searched for the $Z_1(4050)^+$ and $Z_2(4250)^+$in the processes $\overline{B}^0 \to \chi_{c1}K^-\pi^+$ and $B^+ \to K^0_s\chi_{c1}\pi^+$ [14], where the $\chi_{c1} \to J/\psi\gamma$. In the *BABAR* analysis the $\chi_{c1}\pi^+$ mass distribution, after background subtraction and efficiency-correction, has been modeled using the angular information from the $K\pi$ mass distribution as represented using only low-order Legendre polynomial moments. The excellent description of the $\chi_{c1}\pi^+$ mass distribution obtained in this approach shows no need for any additional resonance structure in order to describe the distribution. Figure 2 shows the result of the fit to the $\chi_{c1}\pi^+$ mass spectrum using two or one scalar Breit-Wigners with parameters fixed to the Belle measured values. In all the fit cases there are no significant resonant structures, since the statistical significance obtained is less than 2σ. The upper limits (ULs) at the 90 % CL on the branching fractions are, for the one resonance fit

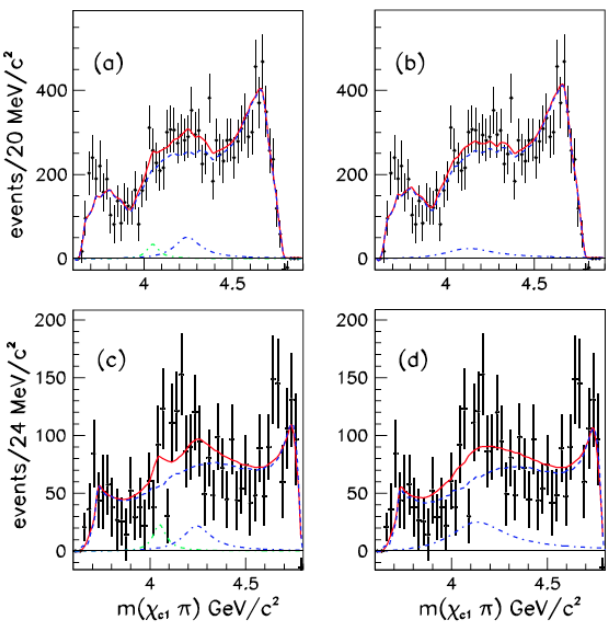

Figure 2: (a),(b) Background-subtracted and efficiency-corrected $\chi_{c1}\pi$ mass distribution for $B \to \chi_{c1}K\pi$. (a) Fit with the $Z_1(4050)^+$ and $Z_2(4250)^+$ resonances. (b) Fit with only the $Z_1(4050)^+$ resonance. (c),(d) Efficiency-corrected and background-subtracted $\chi_{c1}\pi$ mass distribution in the $K\pi$ mass region for which Belle found the maximum resonance activity: $1.0 < m^2(K\pi) < 1.75$ GeV^2/c^4. (c) Fit with $Z_1(4050)^+$ and $Z_2(4250)^+$ resonances. (d) Fit with only the $Z(4150)^+$ resonance. The dot-dashed curves indicate the fitted resonant contributions.

$\mathcal{B}(\overline{B}^0 \to Z^+K^-) \times \mathcal{B}(Z^+ \to \chi_{c1}\pi^+) < 4.7 \times 10^{-5}$, while for the two-resonance fit $\mathcal{B}(\overline{B}^0 \to Z_1^+K^-) \times \mathcal{B}(Z_1^+ \to \chi_{c1}\pi^+) < 1.8 \times 10^{-5}$ and $\mathcal{B}(\overline{B}^0 \to Z_2^+K^-) \times \mathcal{B}(Z_2^+ \to \chi_{c1}\pi^+) < 4.0 \times 10^{-5}$.

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

In 2005 *BABAR* discovered the Y(4260) in the process $e^+e^- \to \gamma_{ISR}Y(4260)$, with the $Y(4260) \to J/\psi\pi^+\pi^-$ [15]. Since this resonance is produced directly in e^+e^- annihilation it has $J^{PC} = 1^{--}$. The observation of the decay mode $J/\psi\pi^0\pi^0$ [16] established that it has zero isospin. However it is not observed to decay to $D^*\overline{D^*}$ [17], nor to $D_s^*\overline{D_s^*}$ [18], so that its properties do not lend themselves to a simple charmonium interpretation, and its nature remains unclear. A subsequent Belle analysis [19] of the same final state suggested also the existence of an additional resonance around 4.1

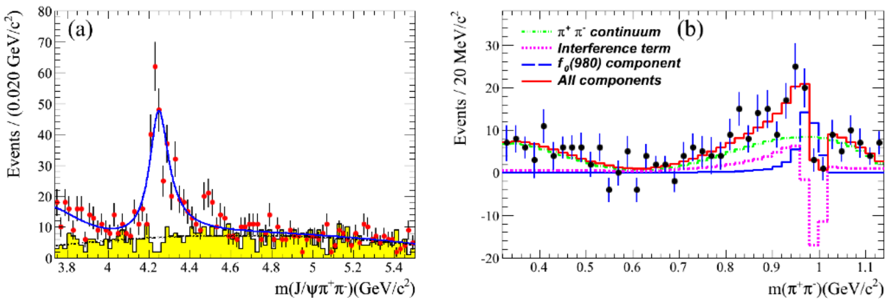

Figure 3: (a): The $J/\psi\pi^+\pi^-$ mass spectrum from 3.74 GeV/c^2 to 5.5 GeV/c^2; the points represent the data and the shaded histogram is the background from the J/ψ sidebands; the solid curve represents the fit result. (b) The $\pi^+\pi^-$ mass distribution from Y(4260) decay to $J/\psi\pi^+\pi^-$. The solid histogram represents the result of the fit using the model described in the text.

GeV/c^2 that they named the Y(4008). *BABAR* has performed an analysis [20] of this process using a data sample corresponding to an integrated luminosity of 454 fb^{-1}. Figure 3(a) shows the invariant mass distribution for $J/\psi\pi^+\pi^-$ after all selection criteria have been applied . A clear signal for the Y(4260) is seen. We performed an unbinned-maximum-likelihood fit, and obtained $m_{Y(4260)} = 4244 \pm 5 \pm 4$ MeV/c^2, $\Gamma_{Y(4260)} = 114^{+16}_{-15} \pm 7$ MeV and $\Gamma_{ee} \times \mathcal{B}(J/\psi\pi^+\pi^-) = 9.2 \pm 0.8 \pm 0.7$ eV. There is no evidence for the Y(4008) found by Belle [19]. In this *BABAR* analysis a detailed study of the $\pi^+\pi^-$ system from the Y(4260) decay to $J/\psi\pi^+\pi^-$ has been performed. The $\pi^+\pi^-$ mass distribution shown in Figure 3(b) peaks near the $f_0(980)$ mass, but is displaced from the nominal $f_0(980)$ position, and occurs at $\sim$ 940 MeV/c^2. The fact that the peak is displaced, together with the particular shape of $m(\pi^+\pi^-)$ distribution, suggests the possibility interference between the $f_0(980)$ and an $m(\pi^+\pi^-)$ continuum. To test this possibility the $f_0(980)$ amplitude and phase have been taken from the *BABAR* analysis [21] of $D_s^+ \to \pi^+\pi^-\pi^+$ and this complex amplitude has been used in a simple model to describe the $\pi^+\pi^-$ mass distribution of the form $|\sqrt{pol} + e^{i\phi}F_{f_0(980)}|^2$ where "*pol*" is a polynomial function used to describe the $m(\pi^+\pi^-)$ continuum, and $F_{f_0(980)}$ is the amplitude from $D_s^+ \to \pi^+\pi^-\pi^+$ [21] analysis; ϕ allows for a phase difference between these amplitudes. The result of this fit is shown in Figure 3(b) and it indicates that if there is a real $f_0(980)$ contribution to the decay of the Y(4260) to $J/\psi\pi^+\pi^-$ its contribution is small, since we obtain $\frac{\mathcal{B}(Y_{4260}\to J/\psi f_0(980),\ f_0(980)\to\pi^+\pi^-)}{\mathcal{B}(Y_{4260}\to J/\psi\pi^+\pi^-)} = (17 \pm 13)\%$.

5 Conclusion

We have presented studies of charmonium-like states at BABAR . We have confirmed the existence of the X(3915), and determined its preferred quantum numbers to be $J^P = 0^+$. We also presented the search for the $Z_1(4050)^+$ and $Z_2(4250)^+$, and the update of the BABAR analysis of the decay $Y(4260) \to J/\psi\pi^+\pi^-$. All these measurements may help our understanding of the charmonium-like states discovered at the B-factories.

References

[1] Eur. Phys. J. C **71**, 1534 (2011).

[2] K. Abe *et al.*, Phys. Rev. Lett. **94**, 182002 (2005).

[3] J. P.Lees *et al.*, Phys. Rev. Lett. **101**, 082001 (2008).

[4] P. del Amo Sanchez *et al.*, Phys. Rev. D **82**, 011101 (2010).

[5] K. Abe *et al.*, arXiv:hep-ex/0505037.

[6] S. Uehara *et al.*, Phys. Rev. Lett. **104**, 092001 (2010).

[7] J. P.Lees *et al.*, Phys. Rev. D **86**, 072002(R) (2012).

[8] R. Aaij *et al.*, Phys. Rev. Lett. **110**, 222001 (2013).

[9] J. L. Rosner, Phys. Rev. D **70**, 094023 (2004).

[10] S.K. Choi *et al.*, Phys.Rev.Lett. **100**, 142001 (2008); R. Mizuk *et al.*, Phys. Rev. D **80**, 031104 (2009).

[11] M. Karliner and H. J. Lipkin, arXiv:hep-ph/0802.0649.

[12] B. Aubert et *et al.*, Phys. Rev. D **79**, 112001 (2009).

[13] R. Mizuk *et al.*, Phys.Rev. D **78**, 072004 (2008).

[14] J. P. Lees *et al.*, Phys. Rev. D **85**, 052003 (2012).

[15] B. Aubert *et al.*, Phys. Rev. Lett. **95**, 142001 (2005).

[16] T. E. Coan *et al.*, Phys. Rev. Lett. **96**, 162003 (2006).

[17] B. Aubert et *et al.*, Phys. Rev. D **79**, 092001 (2009); G. Pakhlova *et al.*, Phys. Rev. D **77**, 011103 (2008).

[18] P. del Amo Sanchez *et al.*, Phys. Rev. D **82**, 052004 (2010).

[19] C. Z. Yuan *et al.*, Phys. Rev. Lett. **99**, 182004 (2007).

[20] J. P. Lees *et al.*, Phys. Rev. D **86**, 051102 (2012).

[21] B. Aubert *et al.*, Phys.Rev. D**79**, 032003 (2009).