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New Hadron Spectroscopy with *BABAR*[*]

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Abstract

We review hadron spectroscopy at *BABAR* with emphasis on recent results from the studies of the $X(3872)$ state, inclusive charmonia on recoil, double charmonium production, and the broad structure observed at around 4.26 GeV/c^2. These results are preliminary, unless otherwise specified.

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1 Introduction

Hadron spectroscopy plays a crucial role in validating quantum chromodynamics (QCD) and the quark substructure of matter. In recent years this field of particle physics has received a renewed interest, thanks to the discovery of many new states at the B factories. Some of these states, such as $D_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$, are by now well established and appear to be ordinary charm mesons. Others, such as $X(3872)$ and $Y(3940)$, could be new excited charmonium ($c\bar{c}$) states or new forms of matter, but require more measurements with better statistical precision for a definitive identification.

The *BABAR* experiment [1] is an e^+e^- collider experiment taking data at or just below the $\Upsilon(4S)$ resonance at the PEP-II asymmetric B factory. It was designed to study CP violation in the B system, however it has proved to have a significantly broader physics reach, especially in the spectroscopy sector. We report here recent results on new charmonium-like states studied using the *BABAR* data sample.

2 Studies of the $X(3872)$ State

The $X(3872)$ state was first observed in the decay $B^- \to X(3872)K^-, X \to J/\psi\pi^+\pi^-$ [2] by the Belle Collaboration [3]. Later it was confirmed by the CDF [4], D0 [5] and *BABAR* [6] Collaborations. The distribution of the $\pi^+\pi^-$ invariant mass in the decay $X(3872) \to J/\psi\pi^+\pi^-$ suggests that the decay may proceed through an intermediate ρ^0 resonance. If so, one can expect to find its charged isospin partner $X(3872)^-$. We have searched for this state in the decays $B^- \to J/\psi\pi^-\pi^0K^0_S$ and $B^0 \to J/\psi\pi^-\pi^0K^+$. However, no evidence for a charged $X(3872)$ has been found [7] and we set the following upper limits at 90 % confidence level (CL): $\mathcal{B}(B^- \to X(3872)^-K^0_S, X^- \to J/\psi\pi^-\pi^0) < 11 \times 10^{-6}$ and $\mathcal{B}(B^0 \to X(3872)^-K^+, X^- \to J/\psi\pi^-\pi^0) < 5.4 \times 10^{-6}$. A search for $X(3872)$ in the process $e^+e^- \to X(3872)\gamma_{ISR}$ via the decay to $J/\psi\pi^+\pi^-$, where γ_{ISR} denotes initial state radiation (ISR), has yielded a null result [8]. This strongly disfavors a $J^{PC} = 1^{--}$ assignment to X. Coupled with the fact that $X(3872)$ has a mass close to the $D^0\bar{D}^{0\star}$ threshold and has a very narrow width, this seems to tell us that X(3872) is not a simple charmonium state. Alternative proposals have been made to explain this state; for example, it could be a weakly bound $D\bar{D}^\star$ molecule-like state [10] or a diquark-antidiquark state [11]. To investigate these models, *BABAR* has updated its earlier study with increased statistics.

Using 232 million $B\bar{B}$ pairs recorded by *BABAR*, $X(3872)$ candidates are reconstructed in the decays $B^- \to J/\psi\pi^+\pi^-K^-$ and $B^0 \to J/\psi\pi^+\pi^-K^0_S$. Figure 1 shows the $J/\psi\pi^+\pi^-$ invariant mass distributions for these two B decay modes [9]. For the charged B mode, we obtain 61.2 ± 15.3 while for the B^0 mode only 8.3 ± 4.5 signal events. These yields are translated to the respective branching fractions by taking efficiency corrections into account: $\mathcal{B}^- \equiv \mathcal{B}(B^- \to X(3872)K^-, X \to J/\psi\pi^+\pi^-) = (10.1 \pm 2.5 \pm 1.0) \times 10^{-6}$ and $\mathcal{B}^0 \equiv \mathcal{B}(B^0 \to X(3872)K^0_S, X \to J/\psi\pi^+\pi^-) = (5.1 \pm 2.8 \pm 0.7) \times 10^{-6}$, where uncertainties are statistical and systematic, respectively. From these we derive a ratio of the branching fractions, $\mathcal{R} = \mathcal{B}^0/\mathcal{B}^- = 0.50 \pm 0.30 \pm 0.05$. We also measure the mass difference of the $X(3872)$ state from the charged and neutral B decay modes, Δm, to be $(2.7 \pm 1.3 \pm 0.2)\,\mathrm{MeV}/c^2$. The diquark-

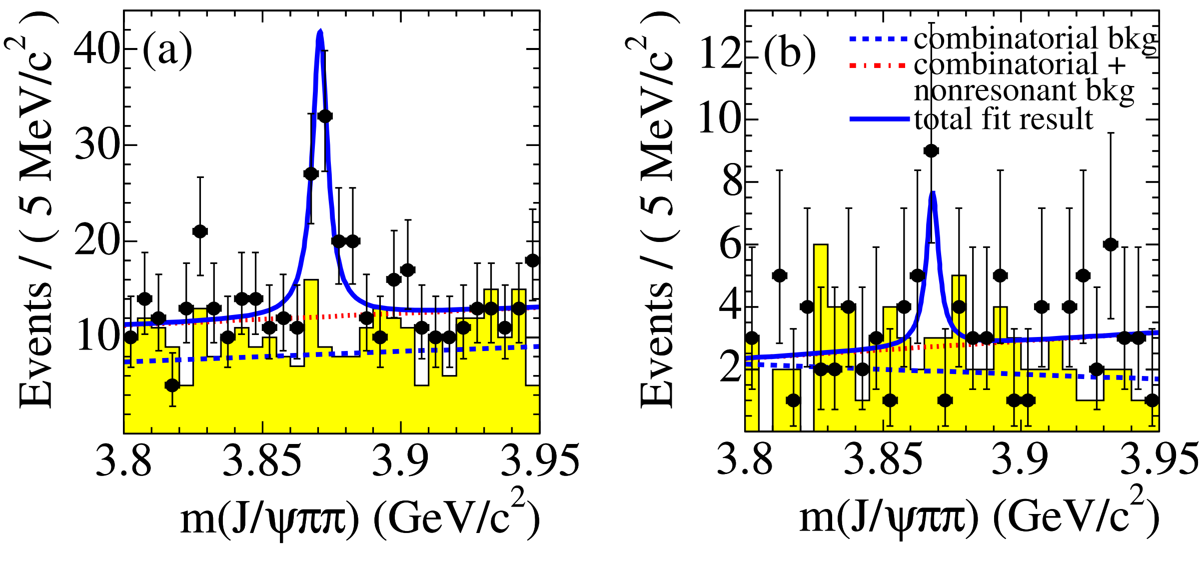

Figure 1: $J/\psi\pi^+\pi^-$ invariant mass distribution in the signal region for (a) $B^- \to X(3872)K^-$ and (b) $B^0 \to X(3872)K^0_S$.

antidiquark model predicts $\mathcal{R} = 1$ and Δm to be $(7 \pm 2)\,\mathrm{MeV}/c^2$. The expected ratio of branching fractions is consistent with our measurement, $0.13 < \mathcal{R} < 1.10$ at 90 % CL and the observed Δm is both consistent with zero and the model prediction within two standard deviations (σ). This result seems to slightly disfavor the molecule model that predicts $\mathcal{R}$ to be at most 10 %. However, we need more data to convincingly discriminate between these models.

3 Inclusive Charmonia on recoil

A novel recoil technique is devised to measure various charmonium states $X_{c\bar{c}}$ in inclusive B decays to the two-body final state $B^- \to K^- X_{c\bar{c}}$. Two body decays are identified by their characteristic monochromatic line without any necessity of reconstructing the decay products of $X_{c\bar{c}}$. Therefore, this method allows us to determine the absolute branching fractions (or set upper limits) for the production of any known or unknown charmonium resonances. The analysis is performed using 210 fb^{-1} of data where a charged B meson is fully reconstructed, so that the momentum of the recoiling B candidate can be calculated from the measured B and the beam parameters. The kaon energy ($E^\star_K$) in the second B rest frame is related to the mass (m_{X}) of the system recoiling against it by $m_{\mathrm{X}} = \sqrt{m_B^2 + m_K^2 - 2E^\star_K m_B}$, where m_B is the charged B meson mass. Therefore, the signature of any charmonium states will be visible as a peak in the kaon momentum (or energy) spectrum as shown in Figure 2. The J/ψ, η_c and χ_{c1} signals are clearly seen in the figure. We also have $3.2\,\sigma$, $1.8\,\sigma$ and $1.4\,\sigma$ indications for $\psi(2S)$, $\eta_c(2S)$ and $\psi(3770)$, respectively. No evidence for $X(3872)$ is found and we derive $\mathcal{B}(B^- \to X(3872)K^-) < 3.2 \times 10^{-4}$, which, in conjunction with the world-average value of

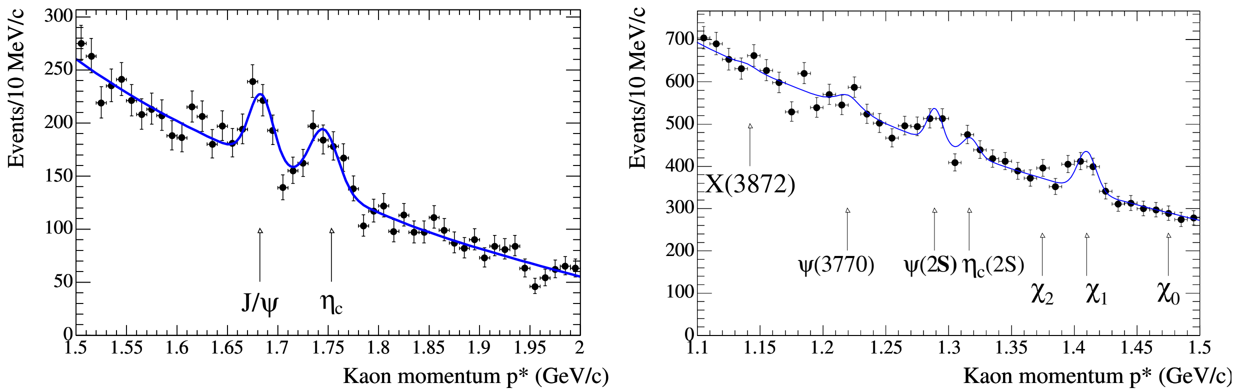

Figure 2: Kaon momentum in the recoiling (second) B meson rest frame.

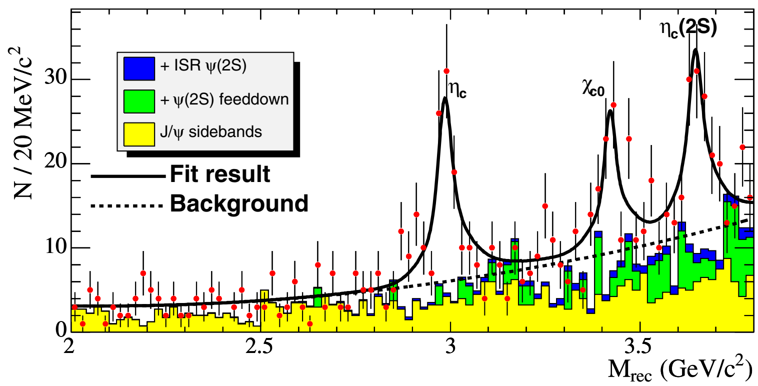

Figure 3: Mass of the system recoiling against the reconstructed J/ψ.

the branching fraction product,allows us to set the lower limit $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) > 4.2\,\%$ at $90\,\%$ CL.

4 Double Charmonium Production

In *BABAR*, exclusive B decays are not the only source of charmonium states. We have also studied double charmonium production in the process $e^+e^- \to \gamma^\star \to J/\psi\, c\bar{c}$ using 124 fb^{-1} of data [12]. Only $c\bar{c}$ states with even C-parity are expected in this reaction, although if there is a contribution from $e^+e^- \to \gamma^\star\gamma^\star \to J/\psi\, c\bar{c}$, odd C-parity states could also be produced. In this study, we first reconstruct a J/ψ candidate via its leptonic decay mode and then calculate the mass of the system recoiling against it (see Figure 3). Three even C-parity charmonium states, η_c, χ_{c0} and $\eta_c(2S)$, are observed, while there is no evidence for any odd C-parity states such as J/ψ. The distribution is fit to obtain the yield for each state, from which the production cross section is calculated. Due to the requirement of at

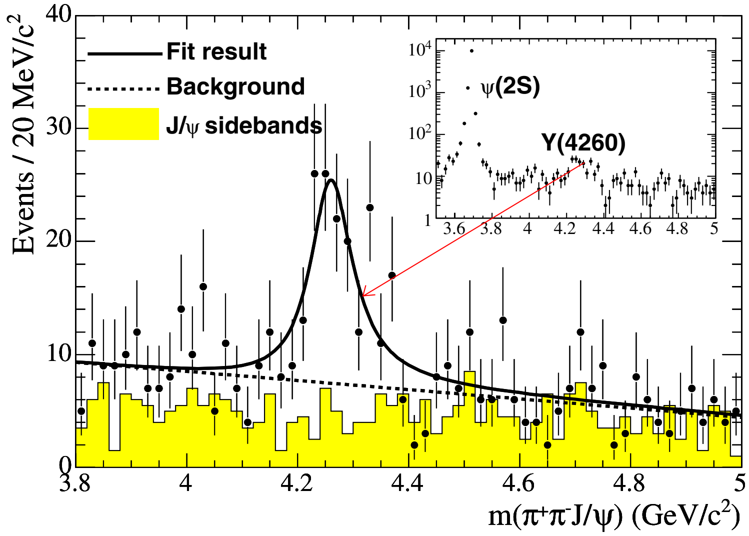

Figure 4: $J/\psi\pi^+\pi^-$ invariant mass spectrum in the range 3.8−5.0 GeV/c^2 and (inset) over a wider range that includes the $\psi(2S)$ state.

least five charged tracks in the event for background suppression, we report the product of the branching fraction to states with more than two tracks and the production cross section. The results are $17.6 \pm 2.8^{+1.5}_{-2.1}$ fb, $10.3 \pm 2.5^{+1.4}_{-1.8}$ fb and $16.4 \pm 3.7^{+2.4}_{-3.0}$ fb for η_c, χ_{c0} and $\eta_c(2S)$, respectively. These values are an order of magnitude higher than those predicted by non-relativistic QCD [13]. However, recent works incorporating charm quark dynamics [14] seem to narrow down the discrepancy.

5 Observation of $Y(4260)$

ISR events produced in the $\Upsilon(4S)$ energy region at the B factories act as a probe of interesting physics occurring at a lower center-of-mass energy. Motivated by this, *BABAR* has investigated the $e^+e^- \to J/\psi\pi^+\pi^-\gamma_{ISR}$ process across the charmonium mass range, using a data sample of 233 fb^{-1} integrated luminosity [15]. These events are characterized by two pions, two leptons (electron or muon) making a J/ψ candidate and a very small recoil mass against the $J/\psi\pi^+\pi^-$ system. Figure 4 shows the $J/\psi\pi^+\pi^-$ invariant mass spectrum for the selected candidates. An enhancement of events near 4.26 GeV/c^2 is clearly observed in addition to the expected $\psi(2S)$ peak. No other structures are evident in the spectrum including the $X(3872)$. Using a maximum likelihood fit, we obtain a signal yield of 125 ± 23 with a statistical significance of $8\,\sigma$ (the signal is referred to as $Y(4260)$). The mass and width of the particle are found to be $4259 \pm 8^{+2}_{-6}$ MeV/c^2 and $88 \pm 23^{+6}_{-4}$ MeV, respectively. We also calculate a value of $\Gamma(Y(4260) \to e^+e^-) \cdot \mathcal{B}(Y \to J/\psi\pi^+\pi^-) = 5.5 \pm 1.0^{+0.8}_{-0.7}$ eV. Although all these results are from a single resonance fit, we cannot exclude or establish a multi-resonance hypothesis at the current level of statistics. More data are needed to reveal its exact nature.

6 Conclusions

The last few years have been very exciting for hadron spectroscopy studies at the B factories. Specifically, *BABAR* is pioneering several sensitive searches for new charmonium states, some of which are summarized in this paper, including the first measurement of the $X(3872)$ state in neutral and charged B decays and the observation of a new broad resonance $Y(4260)$.

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