September 2005

SLAC-PUB-11459

Spectroscopy and New Particles from *BABAR*

B. Aa. Petersen[a]

[a]Stanford University Physics Department,
382 Via Pueblo Mall, Stanford, CA 94305-4060, USA

Results on charmonium states and searches for pentaquark states at the *BABAR* experiment are presented.

Submitted to Nuclear Physics B - Proceedings Supplements

1. INTRODUCTION

The field of hadron spectroscopy has undergone a revival in recent years with the observation of many new states. Some of these states, such as $D_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$, are now well established and appear to be ordinary charm mesons. Others, such as $X(3872)$ and $Y(3940)$, could be new excited charmonium ($c\overline{c}$) states, but require more measurements for a definite identification. Observation of the pentaquark state $\Theta_5(1540)^+$ has been reported by about a dozen experiments, while many other experiments see no evidence for this state and in fact some are in direct contradiction of some of the observations.

The *BABAR* experiment [1] is an e^+e^- collider experiment running at or just below the $\Upsilon(4S)$ resonance. It was designed to perform precision measurements of CP violation in the B system, but has proven to have a significantly broader physics reach. Among many things, it was the first experiment to observe the $D_{sJ}(2317)^+$ state [2]. Here we report on recent results on charmonium(-like) states and the search for pentaquarks using the *BABAR* data sample.

2. STUDIES OF THE $X(3872)$ STATE

The $X(3872)$ state was first observed [3] by Belle in studies of $B^\pm \to K^\pm J/\psi\,\pi^+\pi^-$ decays. In the invariant mass spectrum of the $J/\psi\,\pi^+\pi^-$ system ($m(J/\psi\,\pi^+\pi^-)$), a narrow signal is evident at about $3872\,\mathrm{MeV}/c^2$. This could be another charmonium state, but the measured mass does not seem compatible with existing potential models. Its mass is also very close to the threshold for $D^0\overline{D}^{*0}$ production. For these reasons, other explanations have been proposed; for example, it could be a weakly bound molecule-like state of $D\overline{D}^*$ or a tetraquark state. To try to discriminate among the different models, *BABAR* has studied the $X(3872)$ state in several ways.

Using 232 million $B\overline{B}$ pairs recorded by *BABAR*, $X(3872)$ candidates are reconstructed [4] in the decay modes $B^\pm \to K^\pm J/\psi\,\pi^+\pi^-$ and $B^0 \to K^0_S J/\psi\,\pi^+\pi^-$, where J/ψ decays into di-leptons and the K^0_S into oppositely-charged pions. B decays are selected using two kinematic variables: $\Delta E = E^*_B - \sqrt{s}/2$ and the energy-substituted mass $m_{\mathrm{ES}} = \sqrt{(s/2 + \mathbf{p}_0\cdot\mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$. Here E^*_B is the energy of the B meson candidate in the center-of-mass (CM) frame, E_0 and $\sqrt{s}$ are the total energies of the e^+e^- system in laboratory and CM frames, respectively; $\mathbf{p}_0$ and $\mathbf{p}_B$ are the three-momenta of the e^+e^- system and the B candidate in the laboratory frame, respectively.

Fig. 1 shows the $m(J/\psi\,\pi^+\pi^-)$ distributions for the two B decay modes. In each case the signal yield of $B \to X(3872)K$ decays is extracted using an unbinned maximum likelihood fit to m_{ES} and $m(J/\psi\,\pi^+\pi^-)$. For the $B^\pm$ decay mode we obtain 61 ± 15 events, while for the B^0 decay mode, only 8.3 ± 4.5 events. Including systematic uncertainties, the signals are found to have a significance of 6.1σ and 2.5σ, respectively. The signal yields correspond to the branching fractions $\mathcal{B}^- = \mathcal{B}(B^- \to X(3872)K^-, X \to J/\psi\,\pi^+\pi^-) = (10.1 \pm 2.5(stat.) \pm 1.0(syst.)) \times 10^{-6}$ and $\mathcal{B}^0 = \mathcal{B}(B^0 \to X(3872)K^0, X \to J/\psi\,\pi^+\pi^-) = (5.1 \pm 2.8(stat.) \pm 0.7(syst.)) \times 10^{-6}$. From these we obtain a ratio of branching fractions, $R = \mathcal{B}^0/\mathcal{B}^- =$

Work supported in part by Department of Energy contract DE-AC02-76SF00515

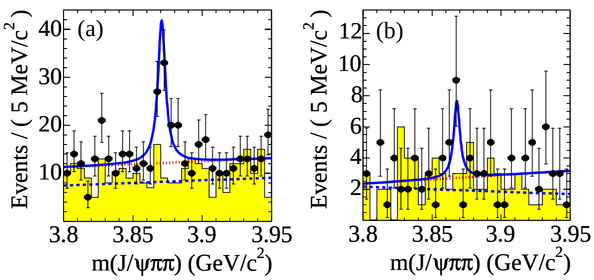

Figure 1. Signal region projections of $m(J/\psi\pi^+\pi^-)$ for (a) $B^- \to X(3872)K^-$ and (b) $B^0 \to X(3872)K^0_S$. The dashed and dotted curves show the estimated combinatorial and non-resonant background. The shaded region shows events in an $m_{\rm ES}$ sideband region.

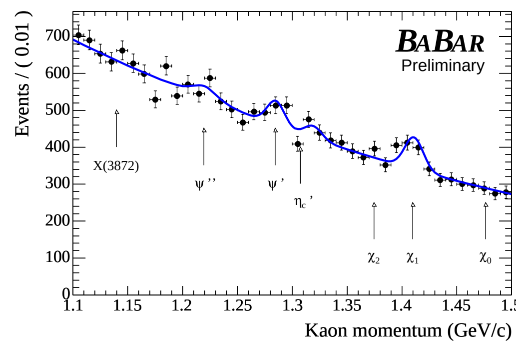

Figure 2. Kaon momentum in the B meson rest frame. The arrows show the expected positions of the charmonium states.

$0.50 \pm 0.30(stat.) \pm 0.05(syst.)$.

The invariant mass distribution of the $\pi^+\pi^-$ in $X(3872) \to J/\psi\pi^+\pi^-$ decays, suggests that the decay may proceed through a ρ^0 resonance. If so, one can expect to find charged isospin partners, $X(3872)^\pm$, of the $X(3872)$. We have searched [5] for these in the decays $B^- \to K^0_S J/\psi\pi^-\pi^0$ and $B^0 \to K^+ J/\psi\pi^-\pi^0$ using the same technique as for the neutral $X(3872)$. No evidence of a charged $X(3872)$ is found and we set the following limits at 90% confidence level (CL): $\mathcal{B}(B^- \to X^- K^0_S, X^- \to J/\psi\pi^-\pi^0) < 11 \times 10^{-6}$ and $\mathcal{B}(B^0 \to X^- K^+, X^- \to J/\psi\pi^-\pi^0) < 5.4 \times 10^{-6}$.

3. INCLUSIVE $B^\pm \to X_{c\bar{c}}K^\pm$ RECONSTRUCTION

An alternative method of observing charmonium states in B decays involves reconstructing everything except the charmonium state itself. Charged B mesons are fully reconstructed [6] in many different decay modes, $D^{(*)}nH$, where H is a combination of $\pi^\pm, \pi^0, K^\pm$ and K^0_S hadrons. In $210\,\mathrm{fb}^{-1}$ of data, about 380,000 $B^\pm$ mesons are fully reconstructed. The fully-reconstructed $B^\pm$ meson defines the rest frame of the second B meson. A neural network is used to select a kaon from the decay of the second B meson. The kaon momentum in the B rest frame is related to the mass (m_X) of the system recoiling against it by $m_X = \sqrt{m_B^2 + m_K^2 - 2E_K m_B}$. Any two-body decay $B^\pm \to X_{c\bar{c}}K^\pm$ should yield a signal in the kaon momentum spectrum at the momentum corresponding to the $X_{c\bar{c}}$ value.

The kaon momentum spectrum shows clear signals for J/ψ and η_c mesons, and, as shown in Fig. 2, several excited charmonium signals are also present. An unbinned maximum likelihood fit is used to extract the yields for nine known charmonium states. Together with the number of reconstructed $B^\pm$ mesons and estimated efficiencies, this allows us to measure or set limits on the absolute branching fractions of all nine modes. The results are listed in Table 1.

Table 1
Absolute branching fractions for $B^\pm \to X_{c\bar{c}}K^\pm$. Upper limits are given at 90% CL.

Particle	$\mathcal{B}(10^{-4})$	Particle	$\mathcal{B}(10^{-4})$
η_c	8.9 ± 1.5	η_c'	3.1 ± 1.5
J/ψ	8.1 ± 1.6	ψ'	4.2 ± 1.4
χ_{c0}	< 1.8	ψ''	3.2 ± 2.3
χ_{c1}/h_c	7.0 ± 1.6	$X(3872)$	< 3.2
χ_{c2}	< 2.0		

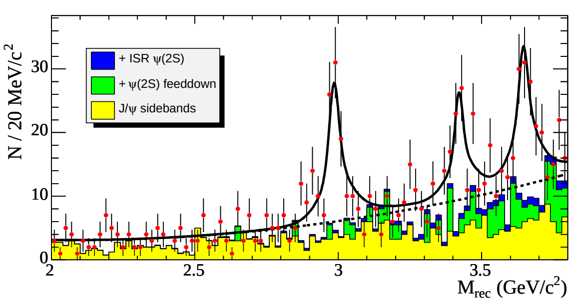

Figure 3. Inclusive mass recoiling against a J/ψ. The dashed curve represents the background component from the fit. The histograms indicate different sources of background.

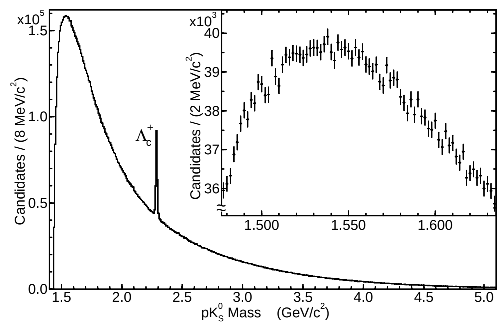

Figure 4. Distribution of the pK^0_S invariant mass. The inset shows the region where a $\Theta_5(1540)^+$ state should manifest itself.

From the upper limit on $\mathcal{B}(B^{\pm} \to X(3872)K^{\pm})$ and the measurement of $\mathcal{B}(B^- \to X(3872)K^-, X \to J/\psi\pi^+\pi^-)$, we estimate $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) > 4.3\%$ at 90% CL.

4. DOUBLE CHARMONIUM PRODUCTION

In *BABAR* charmonium states are produced not only in B decays. We have measured [7] the cross sections for double charmonium production in the process $e^+e^- \to \gamma^* \to J/\psi\, c\overline{c}$ using $124\,\mathrm{fb}^{-1}$ of data. Only $c\overline{c}$ states with even C-parity are expected, although if there is a contribution from $e^+e^- \to \gamma^*\gamma^* \to J/\psi\, c\overline{c}$, odd C-parity states can also be produced.

The J/ψ mesons are reconstructed in their dilepton decay modes and used to calculate the mass of the recoil system. The main background is from J/ψ mesons produced in ISR and other QED processes. This is suppressed by requiring at least five charged tracks in each event and limiting the corresponding missing momentum.

The recoil mass spectrum is shown in Fig. 3. Three even C-parity charmonium states, η_c, χ_{c0} and η_c', are observed, while there is no evidence for odd C-parity states. 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 least five tracks in the event, we report the product of the branching fraction to states with more than two charged tracks and the production cross section, $\mathcal{B}(c\overline{c} \to> 2\ \text{charged})\sigma(e^+e^- \to J/\psi\, c\overline{c})$. The results are $17.6 \pm 2.8^{+1.5}_{-2.1}\,\mathrm{fb}$, $10.3 \pm 2.5^{+1.4}_{-1.8}\,\mathrm{fb}$ and $16.4 \pm 3.7^{+2.4}_{-3.0}\,\mathrm{fb}$ for $J/\psi\,\eta_c$, $J/\psi\,\chi_{c0}$ and $J/\psi\,\eta_c'$, respectively. These cross sections are much larger than those predicted by NRQCD calculations [8].

5. PENTAQUARK SEARCHES

After the first report [9] of the pentaquark $\Theta_5(1540)^+$, many other experiments have reported evidence of the same state, while one experiment [10] has reported evidence for the $\Xi_5(1860)^{--}$ pentaquark state. *BABAR* has searched for both of these states in several different production scenarios.

5.1. Inclusive e^+e^- production

Using a data sample of $123\,\mathrm{fb}^{-1}$ we have performed a search [11] for inclusive production in e^+e^- annihilation of the two pentaquark states. The states are sought in the decay modes $\Theta_5^+ \to pK^0_S$ and $\Xi_5^{--} \to \Xi^-\pi^-$ and the corresponding decay vertices are required to come from e^+e^- collision region. The secondary decays are reconstructed in the modes $K^0_S \to \pi^+\pi^-$ and $\Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-$.

Fig. 4 shows the invariant mass spectrum of all selected pK^0_S candidates. A clear signal for

$\Lambda_c^+ \to pK_S^0$ is seen, but there is no evidence of any Θ_5^+ state. The mass resolution in the Θ_5^+ region is about 2 MeV/c^2. Similarly the invariant mass spectrum for the $\Xi^-\pi^-$ candidates shows no evidence of a Ξ_5^{--} state. We set upper limits at 95% CL on the total production cross section for these two states in e^+e^- annihilations of 171 fb and 25 fb for Θ_5^+ and Ξ_5^{--}, respectively. These limits assume widths of 1 MeV/c^2, $\mathcal{B}(\Theta_5^+ \to pK_S^0) = 0.25$ and $\mathcal{B}(\Xi_5^{--} \to \Xi^-\pi^-) = 0.5$. The limits are about eight and four times lower than the rates measured in e^+e^- collisions for ordinary baryons of similar mass.

5.2. Electro- and hadro-production

A second search for $\Theta_5^+ \to pK_S^0$ has been performed by studying pK_S^0 candidates inconsistent with coming from the e^+e^- collision region. These particles are produced in interactions with detector material. The incoming particles are hadrons from a primary interaction (hadro-production), off-momentum beam particles (electro-production) or other background particles. The distribution of the pK_S^0 vertices is consistent with the material distribution in *BABAR*. The invariant mass distribution of the pK_S^0 candidates, shown in Fig. 5, shows no evidence of a Θ_5^+ pentaquark. Restricting the data sample to candidates in which a third non-baryon particle is coming from the same vertex also shows no evidence for Θ_5^+. About 25% of the candidates in Fig. 5 come from beam particles interacting in a small region of the detector made primarily of Beryllium. Selecting just events from that particular region allows us to study events from electro-production in Beryllium, but again no signal for Θ_5^+ is seen.

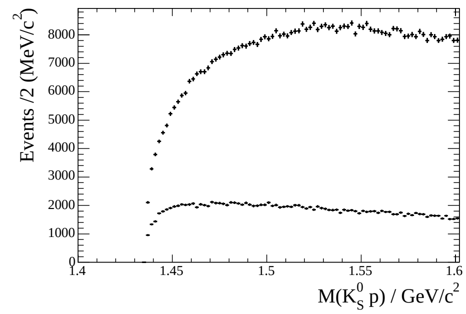

Figure 5. Invariant mass distribution of pK_S^0 candidates produced in material interaction. The upper points are from the K_S^0 signal region, while the lower points are from K_S^0 mass sidebands.

6. SUMMARY

The *BABAR* experiment is in an excellent position to study charmonium states. This paper summarizes several of the techniques used at *BABAR* to measure production cross sections and branching fractions for a variety of such states and to search for new states.

We have also searched for $\Theta_5(1540)^+$ and $\Xi_5(1860)^{--}$ in inclusive e^+e^- production and for $\Theta_5(1540)^+$ production in particle interactions with detector material. No evidence of pentaquark production has been found at *BABAR*.

REFERENCES

1. B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instr. Methods Phys. Res., Sect. A **479**, 1 (2002).
2. B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **90**, 242001 (2003).
3. S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).
4. B. Aubert *et al.* (*BABAR* Collaboration), Submitted to Phys. Rev. Lett., hep-ex/0507090.
5. B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **71**, 031501 (2005).
6. B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **92**, 071802 (2004).
7. B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **72**, 031101 (2005).
8. E. Braaten and V. L. Chernyak, Phys. Lett. B **612**, 215 (2005).
9. T. Nakano *et al.* (LEPS Collaboration), Phys. Rev. Lett. **91**, 012002 (2003).
10. C. Alt *et al.* (NA49 Collaboration), Phys. Rev. Lett. **92**, 042003 (2004).
11. B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **95**, 042002 (2005).