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Pentaquarks and new hadron spectroscopy at *BABAR*

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Abstract

Recent results on the search for pentaquarks and on charmonium spectroscopy at *BABAR* are reviewed. The latter includes the observation of the puzzling new state $X(3872) \rightarrow J/\psi\ \pi^+\ \pi^-$ in B decays, and the searches for $X(3872)$ in two-body B decays and initial state radiation events.

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1 Introduction

The *BABAR* experiment is taking data at the PEP-II e^+e^- collider at the center of mass energy of 10.58 GeV. The large data sample and the detector characteristics, which include excellent tracking and particle identification capabilities, allow a rich and diversified hadronic physics programme. I will focus here on the results on possible candidates for new forms of matter, namely the pentaquarks and the $X(3872)$, a charmonium-like resonance not fitting a pure $c\bar{c}$ assignment. Results are preliminary, unless otherwise specified.

2 Pentaquarks

Several experiments [1] have recently claimed observation of narrow baryonic resonances with exotic quantum numbers, which are regarded as 5-quark candidates. The observed states are: $\Theta_5(1540)^+$ (presumed structure $uudd\bar{s}$), $\Xi_5(1860)^{--}$ ($ddss\bar{u}$) (and its non-exotic neutral partner $\Xi_5(1860)^0$), and a charmed resonance $\Theta_{5c}(3100)^0$ ($uudd\bar{c}$). On the other hand, null results have also been published and have now outnumbered the positive claims. The controversy between experimental evidences for and against the existence is fed by the problem of comparing different production mechanisms and energy ranges. Therefore, it is of interest to perform high statistics and high resolution searches which encompass different production processes, as done by *BABAR*.

2.1 Inclusive search in e^+e^- interactions

We search for inclusive production of pentaquark states $e^+e^- \to PX$ with any final state X recoiling against the pentaquark P, using 123 fb^{-1} of data collected at the e^+e^- center of mass (CM) energy at or just below the mass of the $\Upsilon(4S)$ resonance [2]. In particular, we look for the lightest P candidates: $\Theta_5^+ \to pK_S^0$, $\Xi_5^{--} \to \Xi^-\pi^-$, and $\Xi_5^0 \to \Xi^-\pi^+$.

The invariant mass of the pK_S^0 pair is shown in the left plot in Fig. 1. There is a clear peak containing about 98,000 entries at 2285 MeV/c^2 from $\Lambda_c^+ \to pK_S^0$, which demonstrates our detection sensitivity to narrow resonances. The inset shows a magnified view of the region where the $\Theta_5(1540)^+$ has been reported. No enhancement is seen near 1540 MeV/c^2.

To form the Ξ_5^{--} and Ξ_5^0 candidates a Ξ^- is combined with a like-sign or opposite-sign pion. The Ξ^- is reconstructed in its decay $\Xi^- \to \Lambda^0\pi^-$ with $\Lambda^0 \to p\pi^-$. The invariant mass distributions are shown in Fig. 1. The peaks in the $\Xi^-\pi^+$ distribution are due to the $\Xi^0(1530)$ and $\Xi_c^0(2470)$ baryons, but no structure is visible where the $\Xi_5(1860)$ pentaquark is expected.

Null results are also obtained when the search is performed separately in ten p^* bins uniformly distributed between zero and 5 GeV/c, where p^* is the momentum of the candidate in the CM frame. A possible $\Theta_5(1540)^+$ contribution is fitted in each p^* bin using two different hypotheses on the width, Γ: $\Gamma = 8$ MeV/c^2, corresponding to the experimental upper limit and larger than our pK_S^0 resolution(≈ 2 MeV/c^2), and $\Gamma = 1$ MeV/c^2. A similar search is done for Ξ_5^{--}, assuming as widths the upper limit $\Gamma = 18$ MeV/c^2, and $\Gamma = 1$ MeV/c^2.

These null results are used to set limits on the differential production cross section of $\Theta_5(1540)^+$ and Ξ_5^{--} in e^+e^- interactions, shown in Fig. 2, assuming $\mathcal{B}(\Theta_5(1540)^+ \to pK_S^0) = 1/4$ and $\mathcal{B}(\Xi_5^{--} \to \Xi^-\pi^-) = 1/2$. The corresponding upper limits at 95% CL on the total production rates per $q\bar{q}$ event are 11×10^{-5} and 1.1×10^{-5}, respectively, for the maximum widths. These values are about a factor eight and four below the typical values measured for ordinary baryons of the same mass.

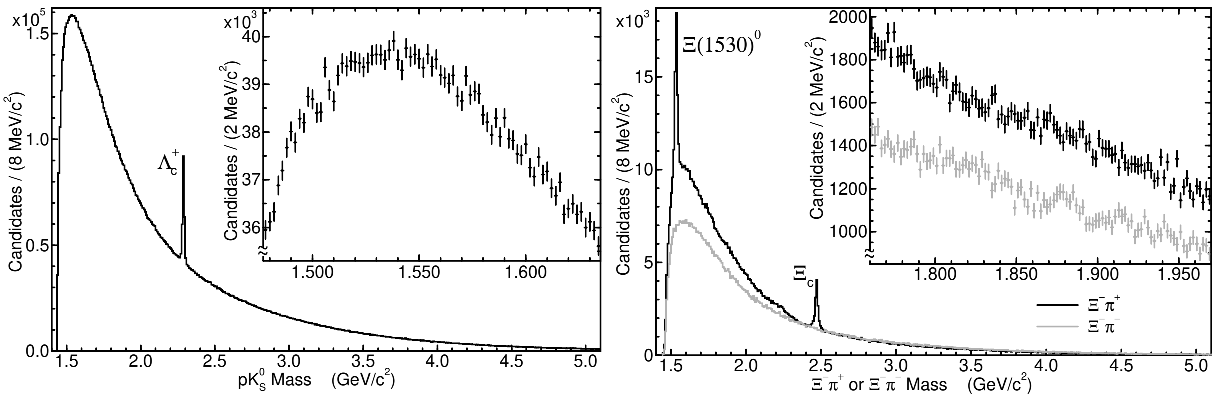

Figure 1: Invariant mass distributions found in the inclusive search for pentaquarks in e^+e^- collisions: pK_S^0 invariant mass (left) and of $\Xi^-\pi$ (right). In the plot on the right distributions are shown for $\Xi^-\pi^+$ (black) and $\Xi^-\pi^-$ (grey). The insets are magnification of the mass regions in which pentaquark states have been reported.

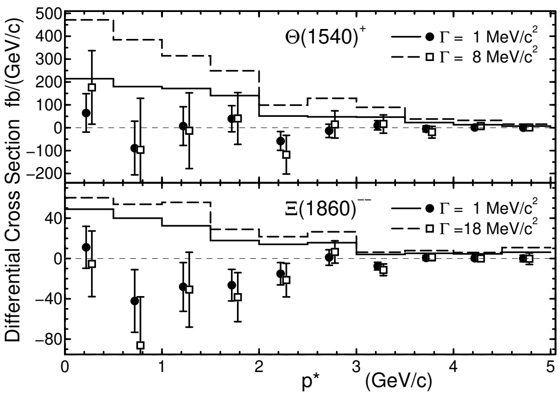

Figure 2: The measured differential production cross sections (symbols) and corresponding 95% CL upper limits (lines) for Θ_5^+ (top) and Ξ_5^{--} (bottom), assuming natural widths of $\Gamma = 1$ MeV/c^2 (solid) and at the current experimental upper limit (open/dashed), as function of CM momentum.

2.2 Search of $\Theta_5(1540)^+$ in electro- and hadro-production

In addition to e^+e^- collisions, we have analysed events due to the interactions with the detector material of beam-halo electrons and positrons (electro-production), and of hadrons from the primary collision (hadro-production). The target material is mainly due to the Be beam-pipe and to the inner detector (a five layers silicon-vertex tracker). We search for $\Theta_5(1540)^+ \rightarrow pK^0_S$ using simple cuts on the position of the vertex, on the invariant mass of the K^0_S, and dE/dx information to identify protons and charged pions. The spatial distribution of the pK^0_S vertices reproduces to high accuracy the known geometry of the beam-pipe and of the inner detector, giving confidence that these events are due to interactions in the detector material. The momentum distribution of the K^0_S and proton are almost entirely confined to the region below 1.5 GeV/c, thus very similar to those measured by many experiments which have observed $\Theta_5(1540)^+$. However, our pK^0_S invariant mass distribution shows no evidence of a structure near 1.54 GeV/c^2 in a sample corresponding to 230 fb^{-1} of data.

3 Results on the $X(3872)$

The discovery of the $X(3872) \rightarrow J/\psi\ \pi^+\ \pi^-$ by the Belle Collaboration [3] has been confirmed by CDF [4], D0 [5] and *BABAR* [6]. While the existence of this high mass narrow resonance is not questioned, its nature is still very much debated. The most likely charmonium candidate is the $J^{PC} = 2^{--}$, $^3D_2\ \psi_2$ state, which, however, should have a large radiative transition into χ_c, which was not observed [3]. Inspired by its mass, right at the $D^0\overline{D}^{*0}$threshold, a number of non-Standard Model interpretations have recently been proposed including a $D^0\overline{D}^{*0}$molecule model and diquark-antidiquark model. In the molecule model [7] the $X(3872)$ is a loosely bound S-wave $D^0\overline{D}^{*0}$, with quantum numbers $J^{PC} = 1^{++}$, that is produced in weak decays of B mesons into $D^0\overline{D}^{*0}K$. Using factorization, heavy-quark symmetry and isospin symmetry, the branching fraction for $B^0 \rightarrow X(3872)K^0$ is predicted to be suppressed by more than an order of magnitude compared to that for $B^+ \rightarrow X(3872)K^+$. The diquark-antidiquark model [8] predicts two neutral states in the mass range of the $X(3872)$, with different quark composition, $X_u = [\bar{c}\bar{u}]$[cu] and $X_d = [\bar{c}\bar{d}]$[cd], which can mix. If one amplitude (from X_d or X_u) is dominant in the charged mode and the other in the neutral mode, the model predicts the rates to be equal and the mass difference to be (7 ± 2) MeV/c^2. This model also predicts the existence of charged partners of the $X(3872)$, at a level which is not excluded by a previous *BABAR* analysis [9].

We reconstruct the exclusive decay $B^- \rightarrow X(3872)K^-$ and $B^0 \rightarrow X(3872)K^0_S$, $X(3872) \rightarrow J/\psi\pi^+\pi^-$, in a data sample corresponding to the integrated luminosity of 211 fb^{-1}. The distributions of the invariant mass m_X of the $J/\psi\pi^+\pi^-$ system are shown in Fig. 3. We find a 5.7σ significance for the B^- mode and 2.5σ for the B^0 mode, including systematic uncertainties. The mass difference of the $X(3872)$ produced in B^0 and B^- decays is $\Delta m = (2.7 \pm 1.3 \pm 0.2)$ MeV/c^2 and is both consistent with zero and with the diquark-antidiquark model prediction. From the number of signal events, the efficiencies, the secondary branching fractions and the number of $B\overline{B}$ events, we obtain the branching fraction products $\mathcal{B}(B^- \rightarrow X(3872)K^-, X(3872) \rightarrow J/\psi\pi^+\pi^-) = (8.5 \pm 2.4 \pm 0.8) \times 10^{-6}$ and $\mathcal{B}(B^0 \rightarrow X(3872)K^0_S, X(3872) \rightarrow J/\psi\pi^+\pi^-) = (5.1 \pm 2.8 \pm 0.7) \times 10^{-6}$. The ratio of neutral to charged branching fractions $R = 0.61 \pm 0.36 \pm 0.06$ is more consistent with isospin conserving decays ($R = 1$), than the molecule model ($R < 0.1$).

In addition, we have used a complementary approach, based on the measurement of the kaon momentum spectrum in the B rest frame, to measure the inclusive B decays to two-body final

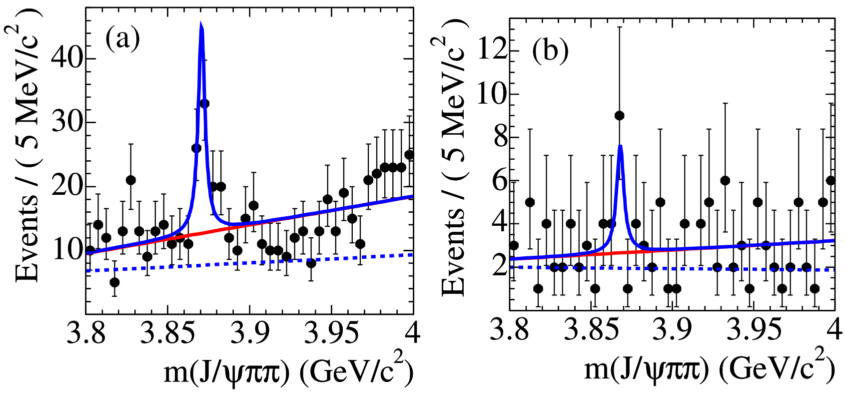

Figure 3: Invariant mass distributions m_X for (a) $B^- \to X(3872)K^-$ and (b) $B^0 \to X(3872)K^0_S$. The lines represent the result of the projection on m_X of the fit used to extract the yields and the resonance parameters. A clear signal peak is visible over the linear background components.

state $B \to KX$, where X can be any state, including the $X(3872)$. Two body decays can be identified by their characteristic monochromatic line, and no reconstruction of the X decay is necessary. Therefore, this method allows to determine the absolute branching fraction (or set upper limits) for production of all known charmonium resonances and the $X(3872)$. The analysis is performed on a sample of $\Upsilon(4S)$ events where a candidate B meson is fully reconstructed, so that the momentum of the recoiling B can be calculated from the measured B and the beam parameters. We find a significant signal for J/ψ, η_c, χ_{c1}, $\psi(2S)$, but no evidence of $X(3872)$. We derive $\mathcal{B}(B^- \to X(3872)K^-) < 3.2 \times 10^{-4}$, which, in conjunction with the branching fraction product, allows to set the lower limit $\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-) > 4.2\%$ at 90% C.L.

In order to narrow down the quantum numbers of the $X(3872)$, we have also looked for $X(3872) \to J/\psi\ \pi^+\ \pi^-$ in e^+e^- initial state radiation events, allowed for $J^{PC} = 1^{--}$. We find no evidence of a signal and set an upper limit on the product $\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-) \times \Gamma^X_{ee} < 6.2$ eV [10] at 90% C.L.

4 Conclusions

In summary, *BABAR* is carrying out several sensitive searches for pentaquarks and new hadrons. Pentaquark production has given null results in both e^+e^- interactions and fixed-target electro- and hadro-production. The upper limits on the production rates in e^+e^- are well below the rates for ordinary baryons of similar masses. The energy range probed in the fixed-target experiment is similar to that of previous electro-production experiments that have observed $\Theta_5(1540)^+$, suggesting that prior claims are less than convincing.

The narrow state $X(3872)$ has been confirmed by *BABAR* in the decay of B mesons. Measurements of the mass and branching fractions have been presented for the first time separately for charged and neutral B decays. As the statistical precision will increase they will allow to distinguish among different hypotheses on the $X(3872)$ nature.

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