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Searches for Pentaquark Baryons at *BABAR* [1]

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Abstract. This paper presents the results of inclusive searches for the strange pentaquark states $\Theta^+(1540)$, $\Xi_5^{--}(1860)$ and $\Xi_5(1860)^0$ as well as the anti-charm pentaquark state $\Theta_c(3099)^0$ in a dataset of 123.4 fb^{-1} collected on and 40 MeV below the $\Upsilon(4S)$ resonance by the *BABAR* detector at the e^+e^- PEP-II storage rings. No evidence for the pentaquark states is found and upper limits on the rate of $\Theta^+(1540)$ and $\Xi_5^{--}(1860)$ production in e^+e^- annihilation are obtained.

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INTRODUCTION

In the past two years several experimental groups have reported observations of a new, manifestly exotic (B=1, S=1) baryon resonance, the $\Theta^+(1540)$ [1], with an unusually narrow width ($\Gamma < 8$ MeV). Also, the NA49 experiment reported evidence for an additional narrow exotic (B=1, S= -2) state, the Ξ_5^{--}, as well as the corresponding Ξ_5^0 state, with mass about 1862 MeV/c^2 [2]. More recently the H1 collaboration reported [3] a narrow ($\Gamma < 30$ MeV) exotic anti-charmed (B=1, C= -1) resonance, Θ_c^0, with a mass of 3099 ± 6 MeV/c^2. For these Θ^+, Ξ_5^{--} and Θ_c^0 states the minimal quark content is $(udud\bar{s})$, $(dsds\bar{u})$ and $(udud\bar{c})$, respectively. These results have prompted a surge of pentaquark searches in experimental data of many kinds, mostly with negative results [4]. Several theoretical models [5, 6, 7] have been proposed to describe possible pentaquark structure. They predict that the lowest-mass states containing u, d and s quarks should occupy a spin-1/2 anti-decuplet and octet. The Θ_c^0 pentaquark should be an isospin-zero member of the $\overline{6}$ representation of the 60-plet of SU(4) [8].

The *BABAR* experiment [9] at the SLAC PEP-II e^+e^- collider takes data at center-of-mass energy of $\approx$10.58 GeV. *BABAR* is well suited to search for these states, since it provides excellent pion, kaon and proton identification and good tracking, with the result that excellent mass resolution can be achieved. Charged particle tracks are measured by a five-layer silicon vertex tracker (SVT) and a 40-layer drift-chamber (DCH)

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located in a 1.5-T solenoidal magnetic field. Charged particles are identified by means of specific ionization (dE/dx) measurements in the SVT and DCH, and from the pattern of Cherenkov photons in the Cherenkov radiation detector (DIRC).

In addition to the inclusive searches for the strange and anti-charm pentaquark states in e^+e^- annihilations presented in this paper, there is also an inclusive search for the Θ^+ in electro- and hadro-production in the material of the *BABAR* detector which shows no evidence for this state [10]. Furthermore an exclusive search in B^+ decay to $p\bar{p}K^+$ final states for the isovector pentaquark candidate Θ^{*++} decaying into pK^+ in the mass range 1.43 to 2.00 GeV/c^2 sets limits on $\mathscr{B}(B^+ \to \Theta^{*++}\bar{p}) \times \mathscr{B}(\Theta^{*++} \to pK^+)$ at the 10^{-7} level [11]. A review of these and other *BABAR* hadronic results can be found in these proceedings [12].

INCLUSIVE SEARCHES FOR STRANGE AND ANTI-CHARM PENTAQUARK BARYONS

Although experiments with a baryon in the beam or the target might seem to have some advantage in pentaquark production, e^+e^- interactions are also known for democratic production of hadrons. Mesons and baryons with non-zero charm and strangeness (up to three units) have been observed with production rates that appear to depend on mass and spin, but not quark content (Fig. 1). If pentaquarks are produced similarly, then one might expect a pentaquark rate as high as that for an ordinary baryon of the same mass and spin. The search for inclusive production of the pentaquark states [13] Θ^+, Ξ_5^+, Ξ_5^0, Ξ_5^-, Ξ_5^{--}, Σ_5^+, N_5^0, N_5^+ and Θ_c^0 has been performed with 123 fb^{-1} of data recorded at or slightly below the $\Upsilon(4S)$ resonance [14]. This paper will discuss only the Θ^+, Ξ_5^{--}, Ξ_5^0 and Θ_c^0 searches.

A search for the Θ^+ is carried out in the decay mode $\Theta^+ \to pK_S^0$, where $K_S^0 \to \pi^+\pi^-$. The expected Θ^+ mass resolution is about 2 MeV/c^2. However no peak is seen at the expected mass but a large signal at 2285 MeV/c^2 (with a mass resolution of 6 MeV/c^2 at the Λ_c mass) containing ≈98,000 entries from $\Lambda_c \to pK_S^0$ is observed. This null result for a Θ^+ mass of 1540 MeV/c^2 is quantified by fitting the convolution of a Gaussian and a P-wave Breit-Wigner for the signal line-shape, and a seventh-order-polynomial times a threshold function for the background shape, to the pK_S^0 invariant-mass distribution in the interval from threshold to 1800 MeV/c^2. Since the intrinsic width of the Θ^+ has not been determined so far, width values of $\Gamma = 1$ MeV (for a narrow Θ^+) and $\Gamma = 8$ MeV (best upper limit) are used, and the results quoted for each assumed width. The upper limit, at 95% confidence level, is determined for the number of produced pentaquarks per $e^+e^- \to$ *hadrons* event, and compared to the production rates of known baryons, assuming $\mathscr{B}(\Theta^+ \to pK_S^0) = 25\%$. The measured upper limit values of 5×10^{-5}/event ($\Gamma = 1$ MeV) and 11×10^{-5}/event ($\Gamma = 8$ MeV) are between eight and 15 times lower than expected for conventional baryons, as shown in Fig. 1.

A search for the Ξ_5^0 and Ξ_5^{--} resonances was performed using the decay chain $\Xi_5 \to \Xi^-\pi$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$. In each case, no peak is seen at the expected mass. In the $\Xi^-\pi^+$ spectrum, prominent peaks for the $\Xi(1530)^0$ and $\Xi_c(2470)^0$ with ≈24,000

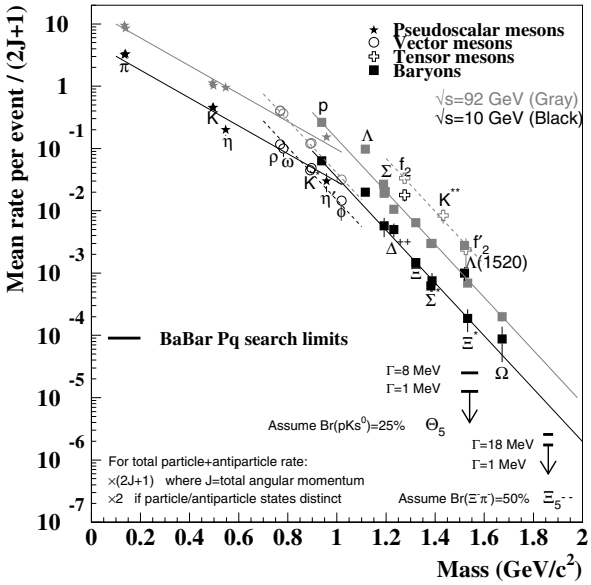

FIGURE 1. Compilation of meson and baryon production rates in e^+e^- annihilation [15] from experiments at the Z^0 (gray) and $\sqrt{s} \approx 10\,\text{GeV}$ (black) as a function of baryon mass. The vertical scale accounts for the number of spin and particle+antiparticle states, and the lines are chosen to guide the eye. The arrows indicate our upper limits on spin-1/2 Θ^+ and Ξ_5^{--} pentaquark states, assuming the branching fractions shown, and are seen to lie below the solid line.

and ≈8,000 entries respectively, are seen. No structure is observed in the exotic $\Xi^-\pi^-$ spectrum. A linear function is used for the background, while the signal is modeled as described above. The resolution function is derived from the $\Xi(1530)^0$ and $\Xi_c(2470)^0$ signals in data and simulation, and is described by a Gaussian function with an RMS of $8\,\text{MeV}/c^2$. The fit is performed over a $\Xi^-\pi^-$ mass range from 1760 to $1960\,\text{MeV}/c^2$. As before, two different intrinsic widths of this pentaquark state are used, namely $\Gamma = 1\,\text{MeV}$ (narrow) and $\Gamma = 18\,\text{MeV}$ (best experimental upper limit) in order to determine 95% confidence level upper limit values for the production rate in e^+e^- interactions. The values obtained, 0.74×10^{-5}/event ($\Gamma = 1\,\text{MeV}$) and 1.1×10^{-5}/event ($\Gamma = 18\,\text{MeV}$), are between four and six times lower than those for conventional baryons, as shown in Fig. 1, assuming $\mathscr{B}(\Xi_5^{--} \to \Xi^-\pi^-) = 50\%$. It is not possible to determine the total production rate for the Ξ_5^0, as its branching fraction to $\Xi^-\pi^+$ is unknown.

We present preliminary results from a search for Θ_c^0 production performed using the decay mode, $\Theta_c^0 \to pD^{*-}$, where the D^{*-} is reconstructed in the $\bar{D}^0\pi^-$ decay mode, and the $\bar{D}^0$ in the $K^+\pi^-$ and $K^+\pi^-\pi^-\pi^+$ modes; the selection criteria are designed for high efficiency and low bias against production mechanism. The selected candidates satisfy the following criteria: the $\bar{D}^0$ and D^{*-} candidates both have mass values within $20\,\text{MeV}/c^2$ of the respective average peak values, and their mass difference is within $2\,\text{MeV}/c^2$ of the average peak value. These values are chosen to minimize the upper limit on the total cross section after a momentum-dependent correction for efficiency.

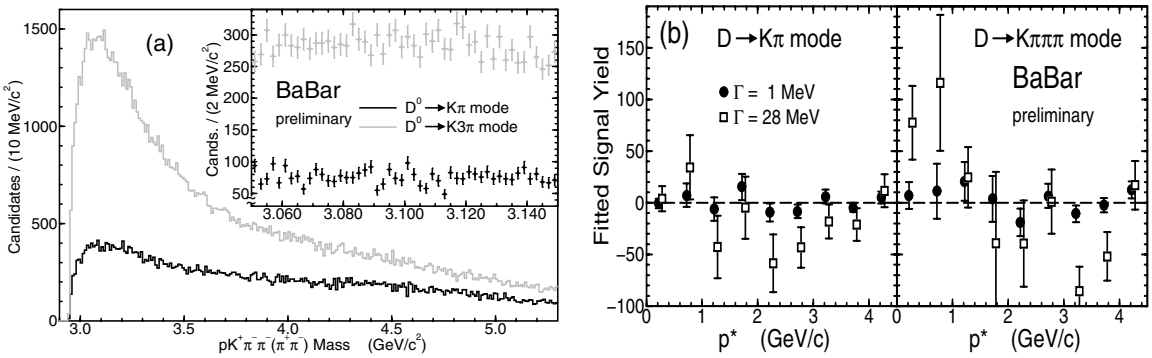

FIGURE 2. (a) Invariant mass distributions of $D^{*-}p$ with $\bar{D}^0$ in the $K^+\pi^-$(black) and $K^+\pi^-\pi^-\pi^+$(gray) modes for combinations satisfying the criteria described in the text. The data are plotted for the full kinematically allowed $D^{*-}p$ range and, in the inset, with statistical uncertainties and a suppressed zero on the vertical axis, for the mass range in which the Θ_c^0 has been reported. (b) The Θ_c^0 yields extracted from the fits to the (left) $pK^+\pi^-\pi^-$ and (right) $pK^+\pi^-\pi^-\pi^+\pi^-$ invariant mass distributions, assuming a mass of $3099\,\mathrm{MeV}/c^2$ and a natural width of $\Gamma = 1\,\mathrm{MeV}$ (circles) or $\Gamma = 28\,\mathrm{MeV}$ (squares).

A total of about 55,000 (73,000) true $D^{*-} \to K^+\pi^-(K^+\pi^-\pi^-\pi^+)\pi^-$ are present in the selected data over a background of 4,000 (62,000).

The invariant mass distributions for the Θ_c^0 candidates in the data are shown in Fig. 2(a) for the two $\bar{D}^0$ decay modes separately. The distributions show no narrow structure, and in particular they are all quite smooth in the region near $3099\,\mathrm{MeV}/c^2$, as shown in the inset. To avoid sensitivity to the details of the production mechanism, the p^* distribution is divided into nine intervals of width $500\,\mathrm{MeV}/c$ from 0 to $4.5\,\mathrm{GeV}/c$, and then a fit to the invariant mass distribution is carried out for each p^* interval.

As for the previous searches a P-wave Breit-Wigner line-shape convolved with the resolution function is used for the signal modeling. The Θ_c^0 invariant mass resolution is obtained from simulation [16], and is represented by a sum of two Gaussian functions with a common center. The overall resolution, defined as the FWHM of the resolution function divided by 2.355, averages 2.8 (3.0) MeV/c^2 for the $K^+\pi^-$ ($K^+\pi^-\pi^-\pi^+$) decay modes with a small dependence on p^*, the center-of-mass momentum of the Θ_c^0. The quoted results assume two widths, $\Gamma = 1\,\mathrm{MeV}$, corresponding to a very narrow state, and $\Gamma = 28\,\mathrm{MeV}$, corresponding to the width observed by H1. The background is described in each p^* bin by a threshold function. Maximum likelihood fits are performed at several fixed Θ_c^0 mass values in the vicinity of $3099\,\mathrm{MeV}/c^2$. In every case the fit quality is good and the signal obtained is consistent with zero. Results using different mass values are consistent within expected statistical variations. Fixing the mass to the reported value of $3099\,\mathrm{MeV}/c^2$ results in the event yields shown in Fig. 2(b). There is no evidence of a pentaquark signal in any p^* range, and the roughly symmetric scatter of the points about zero indicates low momentum-dependent bias in the background function.

It is not possible to compare the sensitivity of our search with that of H1, due to the presumably different production mechanism, and the fact that there is no cross section measurement in Ref. [3]. It is interesting to note that H1 selects about 3,500 D^{*-} using only the $\bar{D}^0 \to K^+\pi^-$ mode, with a background of about 1,500; of these,

about 550 appear in their pD^{*-} mass plot, with mass below $3.6\,\mathrm{GeV}/c^2$, resulting in a Θ_c^0 signal yield of 51 ± 11 events. Thus the observed Θ_c^0 account for roughly 1/70 of their D^{*-} production. In contrast, the *BABAR* search reconstructs about 750,000 D^{*-} above background, 128,000 of which also have an identified proton in the event, but no Θ_c^0 signal is observed.

It is also not possible to compare the production rate of Θ_c^0 to the rates measured for ordinary charmed baryons, as only measurements for $\Lambda_c(2285)$ and $\Sigma_c(2455)$ at much lower mass than Θ_c^0 are available at this point [15]. Furthermore, since $\mathscr{B}(\Theta_c^0 \to pD^{*-})$, is not known it is not possible to set an upper limit on the total production rate of the Θ_c^0.

CONCLUSIONS

A large statistics high-resolution search for the reported pentaquark states Θ^+, Ξ_5^{--}, Ξ_5^0 and Θ_c^0 in e^+e^- annihilations has been performed at *BABAR*. Large signals for known baryon states have been found, but no excess is seen at the reported mass values for the pentaquark states.

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