Searches for Pentaquark Baryons at Babar *

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This paper presents the results of inclusive searches for the strange pentaquark states $\Theta^+(1540)$, $\Xi^-_5(1860)$ 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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I. 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 $\Xi^-_5$, as well as the corresponding $\Xi^0_5$ 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, $\Theta_c^0$, with a mass of 3099±6 MeV/$c^2$. For these $\Theta^+$, $\Xi^-_5$ and $\Theta_c^0$ states the minimal quark content is $(uud\bar{s})$, $(d\bar{s}d\bar{s})$ and $(uud\bar{c})$, 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 $\Theta_c^0$ pentaquark should be an isospin-zero member of the $\mathbf{6}$ 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) 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 $\Theta^+$ 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 $B^+ \rightarrow p\bar{p}K^+$ final states for the isovector pentaquark candidate $\Theta^{++}$ decaying into $pK^+$ in the mass range 1.43 to 2.00 GeV/$c^2$ sets limits on $B(B^+ \rightarrow \Theta^{++}\bar{p}) \times B(\Theta^{++} \rightarrow pK^+)$ at the 10$^{-7}$ level [11]. A review of these and other Babar hadronic results can be found in these proceedings [12].

II. INCLUSIVE SEARCHES FOR STRANGE AND ANTI-CHARM PENTAKUARK 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

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on mass and spin, but not quark content (Fig. 1). If pentaquarks are produced similarly, then one might expect a pentaquark state as high as that for an ordinary baryon of the same mass and spin. The search for inclusive production of the pentaquark states $\Theta^+$, $\Xi^+_5$, $\Xi^0_5$, $\Xi^0_0$, $\Sigma^+_5$, $N^+_5$, $N^0_5$ and $\Theta^0_5$ has been performed with 123 fb$^{-1}$ of data recorded at or slightly below the $Y(4S)$ resonance \cite{14}. This paper will discuss only the $\Theta^+$, $\Xi^+_5$, $\Xi^0_5$ and $\Theta^0_5$ searches.

A search for the $\Theta^+$ is carried out in the decay mode $\Theta^+ \rightarrow pK_S^0$, where $K_S^0 \rightarrow \pi^+\pi^-$. The expected $\Theta^+$ 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 $\Lambda_c$ mass) containing $\approx$98,000 entries from $\Lambda_c \rightarrow pK_S^0$ is observed. This null result for a $\Theta^+$ 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 $\Theta^+$ has not been determined so far, width values of $\Gamma =1$ MeV (narrow) and $\Gamma =18$ 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 $e^+e^- \rightarrow$ hadrons event, and compared to the production rates of known baryons, assuming $B(\Theta^+ \rightarrow pK_S^0) = 25\%$. The measured upper limit values of 5 x 10$^{-5}$/event ($\Gamma =1$ MeV) and 11 x 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 $\Xi^0_5$ and $\Xi^0_0$ resonances was performed using the decay chain $\Xi_5 \rightarrow \Xi^-\pi^+ \rightarrow \Lambda\pi^- \rightarrow p\pi^-$. 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 $\approx$24,000 and $\approx$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 MeV/$c^2$. The fit is performed over a $\Xi^-\pi^+$ mass range from 1760 to 1960 MeV/$c^2$. As before, two different intrinsic widths of this pentaquark state are used, namely $\Gamma =1$ MeV (narrow) and $\Gamma =18$ 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 x 10$^{-5}$/event ($\Gamma =1$ MeV) and 1.1 x 10$^{-5}$/event ($\Gamma =18$ MeV), are between four and six times lower than those for conventional baryons, as shown in Fig. 1, assuming $B(\Xi^0_5 \rightarrow \Xi^-\pi^-) = 50\%$. It is not possible to determine the total production rate for the $\Xi^0_5$, as its branching fraction to $\Xi^-\pi^+$ is unknown.

We present preliminary results from a search for $\Theta^0_0$ production performed using the decay mode, $\Theta^0_0 \rightarrow pD^{*-}$, where the $D^{*-}$ is reconstructed in the $D^0\pi^-$ decay mode, and the $D^0$ in the $K^+\pi^-$ and $K^+\pi^-\pi^+$ modes; the

FIG. 1: Compilation of meson and baryon production rates in $e^+e^-$ annihilation \cite{12} from experiments at the $Z^0$ (gray) and $\sqrt{s}=10$ 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 $\Theta$ and $\Xi^0_5$ pentaquark states, assuming the branching fractions shown, and are seen to lie below the solid line.
Furthermore, since as only measurements for above background, 128,000 of which also have an identified proton in the event, but no $\Theta_{0}^{0}$.

It is interesting to note that H1 selects their mechanism, and the fact that there is no cross section measurement in Ref. [3]. It is interesting to note that H1 selects.

The invariant mass distributions for the $\Theta_{0}^{0}$ 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 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 MeV/c from 0 to 4.5 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 $\Theta_{0}^{0}$ 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 $K^{+}\pi^{-}K^{+}\pi^{-}\pi^{+}\pi^{-}$ (K^+ pi^- pi^- pi^+ pi^-) decay modes with a small dependence on p∗, the center-of-mass momentum of the $\Theta_{0}^{0}$. The quoted results assume two widths, $\Gamma = 1$ MeV, corresponding to a very narrow state, and $\Gamma = 28$ 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 $\Theta_{0}^{0}$ mass values in the vicinity of 3099 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 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 $\bar{D}^{0}$ → $K^{+}\pi^{-}$ mode, with a background of about 1,500; of these, about 550 appear in their $pD^{*-}$ mass plot, with mass below 3.6 GeV/c^2, resulting in a $\Theta_{0}^{0}$ signal yield of 51±11 events. Thus the observed $\Theta_{0}^{0}$ 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 $\Theta_{0}^{0}$ signal is observed.

It is also not possible to compare the production rate of $\Theta_{0}^{0}$ to the rates measured for ordinary charmed baryons, as only measurements for $\Lambda_{c}(2285)$ and $\Sigma_{c}(2455)$ at much lower mass than $\Theta_{0}^{0}$ are available at this point [13]. Furthermore, since $B(\Theta_{0}^{0} \rightarrow pD^{*-})$, is not known it is not possible to set an upper limit on the total production rate of the $\Theta_{0}^{0}$. 

FIG. 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 $\Theta_{0}^{0}$ has been reported.

(b) The $\Theta_{0}^{0}$ yields extracted from the fits to the (left) $pK^{+}\pi^{-}$ and (right) $pK^{+}\pi^{-}\pi^{-}\pi^{+}$ invariant mass distributions, assuming a mass of 3099 MeV/c^2 and a natural width of $\Gamma = 1$ MeV (circles) or $\Gamma = 28$ MeV (squares).
III. CONCLUSIONS

A large statistics high-resolution search for the reported pentaquark states $\Theta^+$, $\Xi^-_5$, $\Xi^0_5$ and $\Theta^0_c$ 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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