Search for Strange-Pentaquark Production in e^+e^- Annihilation at $\sqrt{s} = 10.58$ GeV

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(Received 1 February 2005; published 21 July 2005)

We search for strange-pentaquark states that have been previously reported by other experiments—the $\Theta(1540)^+$, $\Xi_5(1860)^{--}$, and $\Xi_5(1860)^0$—in 123 fb^{-1} of data recorded with the *BABAR* detector at the PEP-II e^+e^- storage ring. We find no evidence for these states and set 95% confidence level upper limits on the number of $\Theta(1540)^+$ and $\Xi_5(1860)^{--}$ pentaquarks produced per e^+e^- annihilation into $q\bar{q}$ and per $\Upsilon(4S)$ decay. For $q\bar{q}$ events the $\Theta(1540)^+$ [$\Xi_5(1860)^{--}$] limit is about 8 [4] times lower than the rates measured for ordinary baryons of similar mass.

DOI: 10.1103/PhysRevLett.95.042002 PACS numbers: 13.25.Hw, 12.15.Hh, 11.30.Er

Ten experimental groups have recently reported narrow enhancements near 1540 MeV/c^2 in the invariant-mass spectra for nK^+ or pK_s^0 [1]. The minimal quark content of a state that decays strongly to nK^+ is $dduu\bar{s}$; therefore, these mass peaks have been interpreted as a possible pentaquark state, called $\Theta(1540)^+$. A single experiment (NA49) has reported a narrow resonance near 1862 MeV/c^2 in the invariant-mass spectra for $\Xi^-\pi^-$ and $\Xi^-\pi^+$ [2]. The minimal quark content of the $\Xi^-\pi^-$ final state is $dssd\bar{u}$. Therefore, the latter two mass peaks have also been interpreted as possible pentaquark states, named $\Xi_5(1860)^{--}$ and $\Xi_5(1860)^0$ [also known as $\Phi(1860)$], with the latter being a mixture of $ussu\bar{u}$ and $ussd\bar{d}$. On the other hand, a number of experiments that observe large samples of strange baryons with mass similar to that of the $\Theta(1540)^+$ [e.g., $\Lambda(1520) \to pK^-$] see no evidence for the $\Theta(1540)^+$ [3]; a number of experiments that observe large samples of the nonexotic Ξ^- baryon do not observe the $\Xi_5(1860)^{--}$ or $\Xi_5(1860)^0$ states [3].

We report the results of inclusive searches for $\Theta^+ \to pK_s^0$, $\Xi_5^{--} \to \Xi^-\pi^-$, and $\Xi_5^0 \to \Xi^-\pi^+$ in e^+e^- annihilation data, where we expect equal production of the charge conjugate states; their inclusion is implied throughout this Letter. The data were recorded with the *BABAR* detector [4] at the PEP-II asymmetric-energy e^+e^- storage ring located at the Stanford Linear Accelerator Center. The data sample represents an integrated luminosity of 123 fb^{-1} collected at an e^+e^- center-of-mass (c.m.) energy at or just below the mass of the $\Upsilon(4S)$ resonance.

The *BABAR* detector is described in detail in Ref. [4]. We use charged tracks reconstructed in the five-layer silicon vertex tracker and the 40-layer drift chamber. The charged-particle momentum resolution is $[\sigma(p_T)/p_T]^2 = [0.0013p_T]^2 + 0.0045^2$, where p_T is the momentum transverse to the beam axis measured in GeV/c. Particles are identified as pions, kaons, or protons with a combination of the energy-loss measured in the two tracking detectors and the Cherenkov angles measured in the detector of internally reflected Cherenkov radiation. We use all events accepted by our trigger, which is more than 99% efficient for both $e^+e^- \to q\bar{q}$ and $e^+e^- \to \Upsilon(4S)$ events.

To evaluate the efficiency and mass resolution for reconstructing pentaquarks, we simulate pentaquark signals with the JETSET [5] Monte Carlo generator by substituting a particle with the mass, width, and decay mode of a hypothetical pentaquark for an existing baryon already simulated by JETSET. We use large control samples of known particles identified in data to correct small inaccuracies in the performance predicted by the GEANT-based [6] detector simulation. The invariant-mass resolution for the decay modes studied in this analysis ranges from less than 2 MeV/c^2 to approximately 8 MeV/c^2, depending on the final state and the momentum of the pentaquark candidate.

We reconstruct Θ^+ candidates in the pK_S^0 decay mode, where $K_S^0 \to \pi^+\pi^-$. A sample of K_S^0 candidates is obtained from all pairs of oppositely charged tracks we identify loosely as pions [with more than 99% efficiency and (70–90)% rejection of K and p depending on momentum] that pass within 6 mm of each other. We require each candidate to have (i) a reconstructed trajectory passing within 6 mm of the interaction point (IP) in the plane transverse to the beam direction and within 32 mm of the IP along the beam direction; (ii) a positive flight distance, defined as the projection on its momentum direction of a vector from its point of closest approach to the beam axis to its decay point; (iii) a helicity angle θ_H, defined as the angle between the π^+ and the $\pi^+\pi^-$ flight directions in the $\pi^+\pi^-$ rest frame, satisfying $|\cos\theta_H| < 0.8$, which removes 20% of the signal and most background from Λ^0 decays and photon conversions; and (iv) an invariant mass within 10 MeV/c^2 of the nominal K_S^0 mass. This selection yields a signal of 2.7×10^6 K_S^0 over a background of 2.2×10^6 in the $\pi^+\pi^-$ mass window.

We combine these K_S^0 candidates with tracks we identify as p or $\bar{p}$ [with (55–99)% efficiency and (95–99)% rejection of π and K] that extrapolate within 15 mm (10 cm) of the IP in the plane transverse to (along) the beam direction. The invariant-mass distribution of pK_S^0 pairs in data is shown in Fig. 1. No enhancement is seen near the mass of the reported $\Theta(1540)^+$ (inset of Fig. 1). There is a clear peak containing 98 000 entries at 2285 MeV/c^2 from $\Lambda_c^+ \to pK_S^0$, with a mass resolution below 6 MeV/c^2.

We consider several additional criteria that might reduce background to a pentaquark signal. Increasing the required flight distance of the K_S^0 candidates increases the Λ_c^+ signal-to-background ratio, but does not reveal any additional structure. We also tried requiring at least one K^- and/or $\bar{p}$ candidate in the event. The Λ_c^+ signal is still visible and there is no sign of a pentaquark peak.

To enhance our sensitivity to any production mechanism that gives a pK_S^0 momentum spectrum in the c.m. frame (p^*) different from that of the background, we split the data into ten subsamples according to the value of p^* for the pK_S^0 candidate. The ten p^* ranges are 500 MeV/c wide

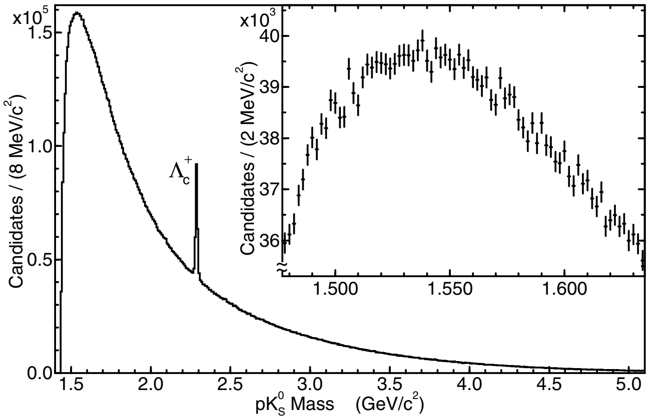

FIG. 1. Distribution of the pK_S^0 invariant mass for combinations satisfying the criteria described in the text. The same data are plotted for the full kinematically allowed pK_S^0 mass range and, in the inset, with statistical uncertainties and a suppressed zero on the vertical scale, for the mass range in which the $\Theta(1540)^+$ has been reported.

and cover values from 0 to 5 GeV/c, the kinematic limit for a particle of mass 1700 MeV/c^2. The background is lower at high p^*, so we are more sensitive to mechanisms that produce harder spectra. There is no evidence of a pentaquark signal in any p^* range.

We quantify these null results by fitting a signal-plus-background function to the pK_S^0 invariant-mass distribution in each p^* range, for each set of selection criteria. We use a p-wave Breit-Wigner line shape convolved with a resolution function derived from the Λ_c^+ data and simulation. The latter is a sum of two Gaussian functions with a common center and an overall root-mean-squared (rms) deviation ranging from 2.5 MeV/c^2 at low p^* to 1.8 MeV/c^2 at high p^*; this is narrower than at the Λ_c^+ mass due to the proximity to the pK_S^0 threshold. The best upper limit of 8 MeV/c^2 [1] on the natural width Γ of the Θ^+ is larger than our pK_S^0 mass resolution, and Γ could be very small. Therefore, we use $\Gamma = 1$ MeV/c^2 and $\Gamma = 8$ MeV/c^2 in the fit and quote results for each assumed width. We account for broad structures (known and unknown resonances and reflections) in the mass distribution by using a wide range, from threshold to 1800 MeV/c^2, and a seventh-order polynomial times a threshold function for the background shape; seventh is the lowest order giving an acceptable χ^2.

We perform fits at several fixed Θ^+ mass values in the range allowed by other experiments, 1520–1550 MeV/c^2. In every case we find good fit quality and a signal consistent with zero. We consider systematic effects in the fitting procedure by varying the signal and background functions and fit range; changes in the signal yield are negligible compared with the statistical uncertainties. Results using different subsamples and mass values are consistent within expected statistical variations. Since the nominal selection results in the smallest absolute uncertainties after efficiency corrections, we use it to set upper limits on the production cross section. Since there is no hint of a signal anywhere in this mass range, we present results for a representative fixed mass value; we choose 1540 MeV/c^2, as our background is highest at this point and we obtain limits near, but above, the median of those tested.

We convert the signal yield in each range of p^* into a cross section by dividing by the reconstruction and selection efficiency, the $K_S^0 \to \pi^+\pi^-$ branching fraction, the integrated luminosity, and the p^* range. If the Θ^+ decays strongly, we expect only two possible decay modes, nK^+ and pK^0, with very similar Q values, so we assume $\mathcal{B}(\Theta^+ \to pK_S^0) = 1/4$. The efficiency for the simulated pentaquark signal varies from 13% at low p^* to 22% at high p^*. The efficiency calculation is verified by measuring the differential cross section for Λ_c^+ production in the combination of $q\bar{q}$ ($q = d, u, s, c$) and $\Upsilon(4S)$ events represented in our data.

The resulting differential cross sections are shown for $\Gamma = 1$ MeV/c^2 and for $\Gamma = 8$ MeV/c^2 in Fig. 2. The error bars include the relative systematic uncertainties on the luminosity (1%) and efficiency (4.9% dominated by the uncertainties on track and displaced-vertex reconstruction efficiencies). We derive an upper limit on the Θ^+ production cross section for each p^* range under the assumption that it cannot be negative: a Gaussian function centered at the measured value with rms equal to the total uncertainty is integrated from zero to infinity, and the point at which the integral reaches 95% of this total is taken as the limit. These 95% confidence level (CL) upper limits are also shown in Fig. 2.

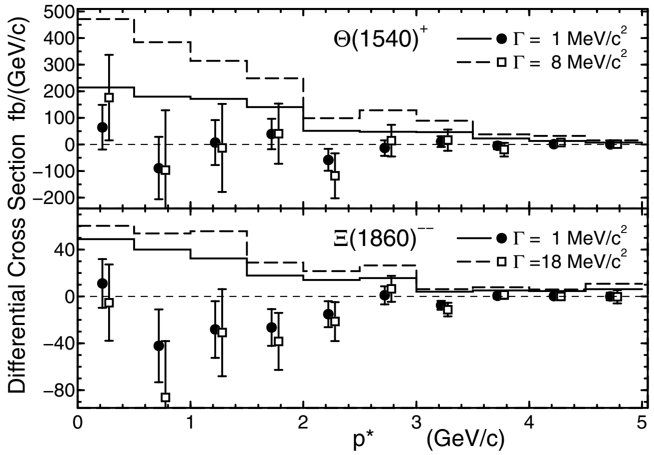

FIG. 2. The measured differential production cross sections (symbols) and corresponding 95% CL upper limits (lines) for Θ^+ (top panel) and Ξ_5^{--} (bottom panel), assuming natural widths of $\Gamma = 1$ MeV/c^2 (solid lines) and at the current experimental upper limit on Γ (open symbols and dashed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

TABLE I. The measured total production cross section and 95% CL upper limits (UL) on the cross section and yield per event for $\Theta(1540)^+$ and $\Xi_5(1860)^{--}$ pentaquark candidates. The natural widths $\Gamma = 8[18]$ MeV/c^2 refer to the upper limits on the widths of the $\Theta(1540)^+$ [$\Xi_5(1860)^{--}$], used in the fits.

Particle	Total production cross section (fb) $\Gamma = 1$	Total production cross section (fb) $\Gamma = 8[18]$	UL on total cross section (fb) $\Gamma = 1$	UL on total cross section (fb) $\Gamma = 8[18]$	UL on yield per $q\bar{q}$ event (10^{-5}/event) $\Gamma = 1$	UL on yield per $q\bar{q}$ event (10^{-5}/event) $\Gamma = 8[18]$	UL on yield per $\Upsilon(4S)$ decay (10^{-5}/event) $\Gamma = 1$	UL on yield per $\Upsilon(4S)$ decay (10^{-5}/event) $\Gamma = 8[18]$ MeV/c^2
$\Theta^+ + \bar{\Theta}^-$	-19 ± 93	7 ± 183	171	363	5.0	11	18	37
$\Xi_5^{--} + \bar{\Xi}_5^{++}$	-53 ± 25	-93 ± 38	25	36	0.74	1.1	2.4	3.4

We derive model-independent upper limits on the total number of pentaquarks produced per $q\bar{q}$ event and per $\Upsilon(4S)$ decay by summing the differential cross section over the kinematically allowed p^* range for $q\bar{q}$ events (the entire p^* range) and for B meson decays ($p^* < 2.5$ GeV/c), respectively, taking into account the correlation in the systematic uncertainty. The central value and the 95% CL upper limit on the total Θ^+ (plus $\bar{\Theta}^-$) production cross section for the p^* range from 0 to 5 GeV/c are shown in Table I. Dividing this limit and the corresponding limit for the p^* range from 0 to 2.5 GeV/c by the cross section for $e^+e^- \rightarrow q\bar{q}$ and for $e^+e^- \rightarrow \Upsilon(4S)$, respectively, we calculate limits on the number of pentaquarks per event, given in Table I. For the maximum width ($\Gamma = 8$ MeV/c^2), we obtain a limit roughly a factor of 8 below the typical values measured for ordinary octet and decuplet baryons of the same mass [7].

We search, as well, for the reported $\Xi_5(1860)^{--}$ and $\Xi_5(1860)^0$ states decaying into a Ξ^- and a charged pion, where $\Xi^- \rightarrow \Lambda^0\pi^-$ and $\Lambda^0 \rightarrow p\pi^-$. We reconstruct $\Lambda^0 \rightarrow p\pi^-$ candidates from all pairs of charged tracks that satisfy loose proton and pion identification requirements and pass within 6 mm of each other. The Λ^0 candidate must have a positive flight distance from the IP and an invariant mass within 10 MeV/c^2 of the nominal Λ^0 mass. Each is combined with an additional negatively charged track passing loose pion identification requirements to form Ξ^- candidates, which are required to form a good vertex, to have a positive flight distance from the IP, and to have an invariant mass within 20 MeV/c^2 of the nominal Ξ^- mass. The flight distance of the Λ^0 candidate from the $\Lambda^0\pi^-$ vertex is required to be positive. This selection yields a signal of 250 000 Ξ^- over a background of 92 000 in the $\Lambda^0\pi^-$ mass window. Finally, we combine the Ξ^- candidates with an additional charged track consistent with coming from the IP and passing loose pion identification requirements. The cosine of the angle between the reconstructed Ξ^- trajectory, extrapolated back to the IP, and the additional track is required to be less than 0.998. This last requirement is especially important, since the Ξ^- is charged and has a long lifetime; if it has a long flight distance, it can produce a reconstructed track that, if combined with itself, forms a false peak in the invariant-mass distribution. The reconstruction efficiency for the simulated pentaquark signal varies from 6.5% at low p^* to 12% at high p^*.

The invariant-mass distributions for $\Xi^-\pi^-$ and for $\Xi^-\pi^+$ combinations are shown in Fig. 3. In the $\Xi^-\pi^+$ mass spectrum, we see peaks for the $\Xi(1530)^0$ (24 000 in the peak) and $\Xi_c(2470)^0$ (8000) baryons, but no other structure is visible. There are no visible narrow structures in the $\Xi^-\pi^-$ mass spectrum.

As in the Θ^+ search, we examine ten ranges of p^* for the $\Xi^-\pi^-$ candidates, and fit a signal-plus-background function to the $\Xi^-\pi^-$ invariant-mass distribution in each range. Here no broad resonances or reflections are evident, and we perform simpler fits over a $\Xi^-\pi^-$ mass range from 1760 to 1960 MeV/c^2 using a linear background function. 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 a rms of 8 MeV/c^2. For the Breit-Wigner width, we consider 1 MeV/c^2, corresponding to a very narrow state, and 18 MeV/c^2, taken conservatively as the expected width due to resolution in [2]. We fix the Ξ_5^{--} mass to 1862 MeV/c^2. In all ranges of p^*, the signal is consistent with zero. Systematic uncertainties on the fitting procedure are again found to be negligible compared with the statistical uncertainties, and variations of the Ξ_5^{--} mass and selection criteria give consistent results.

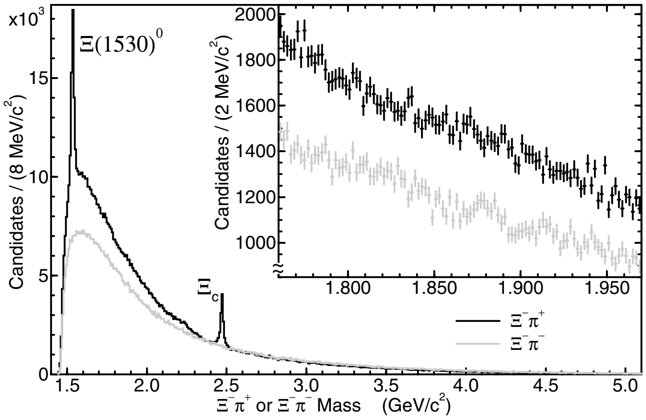

FIG. 3. $\Xi^-\pi^+$ (black) and $\Xi^-\pi^-$ (gray) invariant-mass distributions. The same data are plotted for the full kinematically allowed $\Xi^-\pi^\pm$ mass range and, in the inset, with statistical uncertainties and a suppressed zero on the vertical scale, for the mass range in which the $\Xi_5(1860)^{--}$ and $\Xi_5(1860)^0$ have been reported.

We convert the measured yields for the $\Xi_5^{--} \to \Xi^- \pi^-$ decays into cross sections as for the Θ^+. The efficiency determined from simulation is verified by measuring the differential cross section for the observed $\Xi(1530)^0$ signal. The average relative systematic uncertainty on the efficiency is 6.2% with a slight p^* dependence, and is larger than that for the pK_S^0 mode because there are two displaced vertices and more particles in the final state. We have used a $\Xi^- \pi^-$ branching fraction of one-half for purposes of calculating cross sections and limits, under the assumption that the two-body modes $\Xi^- \pi^-$ and $\Sigma^- K^-$ dominate and have similar branching fractions.

The measured cross section and 95% CL upper limits for Ξ_5^{--} (plus $\bar{\Xi}_5^{++}$) production are shown in Fig. 2 and Table I. For $\Gamma = 18\ \mathrm{MeV}/c^2$, the limit on the total production rate per $q\bar{q}$ event is roughly a factor of 4 below the typical values measured for ordinary octet and decuplet baryons of the same mass [7].

We perform a similar search for $\Xi_5^0 \to \Xi^- \pi^+$, finding no signal in any p^* bin. Since many decay modes are kinematically accessible to such a state with a mass of $\sim 1862\ \mathrm{MeV}/c^2$ and the branching fraction is unknown *a priori*, we omit this state from Table I and express our upper limit on the total production of Ξ_5^0 and $\bar{\Xi}_5^0$ per $q\bar{q}$ event as $0.8 \times 10^{-5}/\mathcal{B}(\Xi_5^0 \to \Xi^- \pi^+)$, at the 95% CL, assuming a mass of $1862\ \mathrm{MeV}/c^2$ and width of $18\ \mathrm{MeV}/c^2$.

In summary, we have performed a search for the reported pentaquark states $\Theta(1540)^+$, $\Xi_5(1860)^{--}$, and $\Xi_5(1860)^0$ in e^+e^- annihilations. We observe large signals for known baryon states but no excess at the measured mass values for the pentaquark states.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACyT (Mexico), A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

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