Pentaquark searches at HERMES

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Abstract. An experimental search for exotic baryons was performed with the HERMES experiment at DESY in quasi-real photoproduction. Positive evidence is presented for a Θ^+ at a mass of $1528 \pm 2.6(stat) \pm 2.1(sys)$ MeV. No evidence for possible Θ^{++}, $\Xi^{--}(1860)$ and $\Xi^0(1860)$ resonances was found, instead, upper limits for their production cross section are given. In addition, photoproduction crosssections for the $\Lambda(1520)$ and $\Xi^0(1530)$ resonances are presented, because they have similar decay modes as the Θ^{++} and $\Xi^{--}(1860)$, respectively.

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INTRODUCTION

A recent prediction of the existence of narrow exotic baryon resonances [1], based on the Chiral Soliton Model, has triggered an intensive search for the exotic members of an anti-decuplet. In this anti-decuplet all three vertices are manifestly exotic. The lightest exotic member, lying at its apex, was predicted to have a mass of 1530 MeV and a narrow width. It corresponds to a $uudd\bar{s}$ configuration, and decays through the channels $\Theta^+ \to pK^0$ or $\Theta^+ \to nK^+$. Other approaches, based on the constituent quark model [2], or on the Chiral Soliton model [3], predict that rather than an isosinglet Θ^+, an isotriplet or an isovector Θ particle should exist.

The first experimental evidence for the Θ^+ came from the LEPS experiment [4] in Japan, which reported the observation of a narrow resonance at $1540 \pm 10(\mathrm{sys})$ MeV by analyzing the K^- missing mass spectrum in the reaction $\gamma n \to K^- K^+ n$ on ^{12}C. The decay mode corresponds to an S=+1 resonance, containing an $\bar{s}$ quark with baryon number +1, signaling a manifestly exotic pentaquark state with minimum quark content ($uudd\bar{s}$). Confirmation came quickly from a series of experiments [5, 6], with the observation of narrow peaks in pK^0 or nK^+ mass spectra near 1530 MeV, in each case with a width consistent with the experimental resolution. Doubts concerning the validity of these observations have been raised recently, because of the failure to observe a signal in many other experiments [7].

Experimental evidence for a second exotic member of the anti-decuplet came from the reported observation of a S=−2, Q=−2 baryon resonance in proton-proton collisions

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at $\sqrt{s} = 17.2$ GeV at the CERN SPS [8]. A narrow peak at a mass of about 1862 MeV in the $\Xi^-\pi^-$ invariant mass spectrum was proposed as a candidate for the predicted exotic $\Xi^{--}_{3/2}$ baryon with S=−2, I=$\frac{3}{2}$ and a quark content of ($ddss\bar{u}$). At the same mass, a peak was observed that is a candidate for the $\Xi^0_{3/2}$ member of this isospin quartet. This state has not been confirmed by other experimental searches [9, 10, 11].

EXPERIMENT

The HERMES collaboration has performed an experimental search for the Θ^+, Θ^{++}, Ξ^{--} and Ξ^0 particles in quasi-real photoproduction on a deuterium target. The data were obtained using the 27.6 GeV positron beam of the HERA storage ring at DESY. The analysis searched for inclusive photo-production of the Θ^+, either off a proton or a neuteron, followed by the decay $\Theta^+ \to pK^0_S \to p\pi^+\pi^-$. The search for the Θ^{++} was pursued via the possible decay mode $\Theta^{++} \to pK^+$. The search for inclusive photo-production of $\Xi(1860)$ pentaquarks was performed assuming the decay modes: $\Xi^{--} \to \Xi^-\pi^- \to \Lambda\pi^-\pi^- \to p\pi^-\pi^-\pi^-$ or $\Xi^0 \to \Xi^-\pi^+ \to \Lambda\pi^-\pi^+ \to p\pi^-\pi^-\pi^+$.

Identification of charged pions and protons was accomplished with a Ring-Imaging Čerenkov (RICH) detector [12]. The data from the simulation indicated that cross contaminations in the search of the Θ^+ and Θ^{++} resonances is negligible if protons are restricted to a momentum range of 4–9 GeV/c, kaons to 2–15 GeV/c and pions to 1–15 GeV/c. In the search of the $\Xi(1860)$ baryons, the requirements on the proton and pion momenta were relaxed to a momentum range of 2–15 GeV/c and 0.25–15 GeV/c respectively, because the intermediate Λ and $\Xi^-(1321)$ particles were clearly identified in the particle reconstruction.

The event selection included constraints on the event topology to maximize the yield of the K^0_S, Λ or $\Xi^-(1321)$ peaks in the $M_{\pi^+\pi^-}$, $M_{p\pi^-}$ and $M_{\Lambda\pi^-}$ spectra, respectively, while minimizing their background.

RESULTS

To search for $\Xi^{--}_{3/2}$ ($\Xi^0_{3/2}$) candidates, first events were selected with an invariant mass $M_{p\pi^-}$ within $\pm 3\sigma$ of the centroid of the Λ peak. These events were combined with a π^- to form the Ξ^-. In the next step, events were selected with a $M_{\Lambda\pi^-}$ invariant mass within $\pm 3\sigma$ of the centroid of the Ξ^- peak. The resulting spectrum of the invariant mass of the $p\pi^-\pi^-\pi^-$ and $p\pi^-\pi^-\pi^+$ system is displayed in Fig. 1. While no peak structure is observed near 1862 MeV, one appears at the mass of the known $\Xi^0(1530)$ resonance.

To search for the Θ^+ candidates, events were selected with a $M_{\pi^+\pi^-}$ invariant mass within $\pm 2\sigma$ of the centroid of the K^0_S peak. The resulting $p\pi^+\pi^-$ invariant mass spectrum is shown in Fig. 2 (left panel). A narrow peak is observed at $1528.0 \pm 2.6 \pm 2.1$ MeV with a Gaussian width of $\sigma = 8 \pm 2$ MeV and a statistical significance of $N_s/\delta N_s = 3.7\sigma$. The state observed here may be interpreted as the predicted exotic Θ^+ pentaquark S=+1 baryon.

In view of the speculation that the observed resonance is isotensor [2, 3], the possibility that the Θ^{++} partner is present in the M_{pK^+} spectrum was explored. Although Fig. 2 (right panel) shows a clear peak for the $\Lambda(1520)$ in the M_{pK^-} spectrum, there is no peak

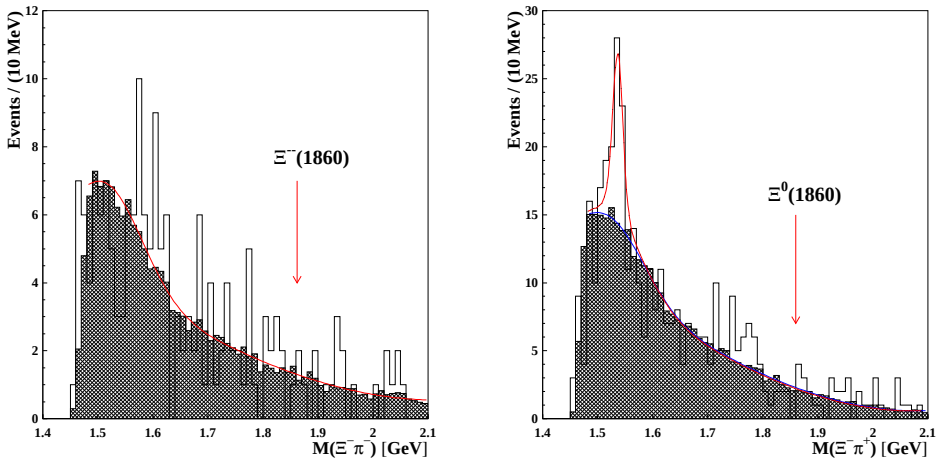

FIGURE 1. Invariant mass distribution of the $p\pi^-\pi^-\pi^-$(plus c.c.) system (left panel) and $p\pi^-\pi^-\pi^+$(plus c.c.) (right panel). The mixed-event background is represented by the gray shaded histogram, which is normalized to the background component of the fitted curve. The arrow shows the hypothetical $\Xi^{--}_{3/2}$ mass. The excess near $1770\,MeV$(right panel) has a statistical significance of only $1.8\,\sigma$. The peak near $1530 MeV$ represents the $\Xi^0(1530)$ resonance.

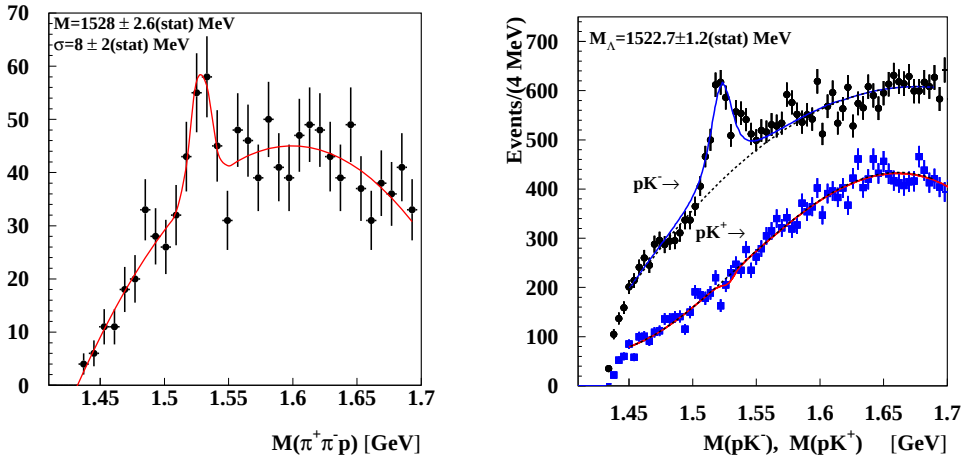

FIGURE 2. Distribution in invariant mass of the $p\pi^+\pi^-$ system (left panel). The smooth curve results from a fit to the data of a Gaussian plus a third-order polynomial. Spectra of invariant mass (right panel) M_{pK^-}(top) and M_{pK^+}(bottom).

structure observed in the M_{pK^+} mass distribution at that mass. This suggests that if the observed peak is the Θ^+, it is likely to be isoscalar.

A Breit-Wigner form convoluted with a Gaussian representing the simulated instrumental resolution was used to estimate the intrinsic width of the observed resonance ($\Gamma = 17 \pm 9(\text{stat}) \pm 3(\text{sys})$ MeV[6]). Estimates of the total spectrometer acceptance from detector simulations have been used to extract the inclusive cross section in the reaction $\gamma^* D \to \Theta^+ X$. The result varies between 100 and 220 nb $\pm 25\%(\text{stat})$ depending on the model for the background and the functional form fitted to the peak. An additional factor

of two uncertainty is due to the unknown initial kinematic distributions. The cross section for photo-production of the $\Lambda(1520)$ is found to be $62 \pm 11(\text{stat})$ nb. If the branching ratio(BR) for the $\Xi^0(1530) \to \Xi^-\pi^+$ decay is taken to be $2/3$ [13], its photoproduction cross section is found to be between 8.8 and 24 nb[14]. The results for the upper limits for the $\Xi^{--}(\Xi^0)(1860)$ photo production cross section times BR is found to be 1.0 to 2.1 nb (1.2 to 2.5 nb) at the 90% C.L.

In summary it is important to note that the existence of pentaquark baryons is still unsettled. The experiments reporting evidence for the Θ^+ are confronted with a growing number of experiments that fail to see a signal. Given the present ambiguous experimental situation, opposing views can be found in the recent literature on this subject [15, 16], in efforts to resolve the apparent experimental inconsistencies. All this brings us to the conclusion that only dedicated, high-statistics and high-resolution measurements can settle the question whether or not exotic baryons such as the hypothetical Θ^+ pentaquark state do exist.

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