Evidence for a narrow baryon state at $1528 \pm 2.6\text{(stat)} \pm 2.1\text{(syst)}$ MeV is presented in quasi-real photoproduction on a deuterium target through the decay channel $pK_S^0 \rightarrow p\pi^+\pi^-$. The statistical significance of the peak in the $pK_S^0$ invariant mass spectrum is 4 standard deviations and its extracted intrinsic width $\Gamma = 17 \pm 9\text{(stat)} \pm 3\text{(syst)}$ MeV. This state may be interpreted as the predicted $S=+1$ exotic $\Theta^+$ $(uudd\bar{s})$ pentaquark baryon.

1. Introduction

One of the central mysteries of hadronic physics has been the failure to observe baryon states beyond those whose quantum numbers can be explained in terms of three quark configurations. Exotic hadrons with manifestly more complex quark structures, in particular exotics consisting of five quarks, were proposed on the basis of quark and bag models in the early days of QCD. More recently, an exotic baryon of spin 1/2, isospin 0, and strangeness $S=+1$ was discussed as a feature of the Chiral Quark Soliton model. In this approach the baryons are rotational states of the soliton nucleon in spin and isospin space, and the lightest exotic baryon lies at the apex of an anti-decuplet with spin 1/2, which corresponds to the third rotational excitation in a three flavor system. Treating the known $N(1710)$ resonance as a member of the anti-decuplet, Diakanov, Petrov, and Polyakov derived a mass of 1530 MeV and a width of less than 15 MeV for this exotic baryon, since named the $\Theta^+$. It corresponds to a $uudd\bar{s}$ configuration, and decays through the channels $\Theta^+ \rightarrow pK^0$ or $nK^+$. However, measurements of $K^+$ scattering on proton and deuteron targets showed no evidence for strange

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baryon resonances, and appear to limit the width to remarkably small values of order an MeV.

Experimental evidence for the Θ⁺ first came from the observation of a narrow resonance⁶ at 1540±10(syst) MeV in the $K^-$ missing mass spectrum for the $\gamma n \rightarrow K^+ K^- n$ reaction on $^{12}$C. This result was confirmed since then by a series of experiments, with the observation of sharp peaks⁷–¹⁷ in the $nK^+$ and $pK^0_S$ invariant mass spectra near 1530 MeV, in most cases with a width limited by the experimental resolution. There are also many unpublished reports of failures to observe this signal.

2. Experiment

Presented here are the results of a search for the Θ⁺ in quasi-real photoproduction on deuterium.¹² The data were obtained by the HERMES experiment with the 27.6 GeV positron beam of the HERA storage ring at DESY. The HERMES spectrometer is described in detail in Ref. 18. The analysis searched for inclusive photoproduction of the Θ⁺ followed by the decay $\Theta^+ \rightarrow pK^0_S \rightarrow p\pi^+\pi^-$. Events selected contained at least three tracks: two oppositely charged pions in coincidence with one proton. Identification of charged pions and protons was accomplished with a Ring-Imaging Čerenkov (RICH) detector,¹⁹ which provides separation of pions, kaons and protons over most of the kinematic acceptance of the spectrometer. In order to keep the contaminations for pions and protons at negligible levels, protons were restricted to a momentum range of 4–9 GeV/c and pions to a range of 1–15 GeV/c.

The event selection included constraints on the event topology to maximize the yield of the $K^0_S$ peak in the $M_{\pi^+\pi^-}$ spectrum while minimizing its background. Based on the intrinsic tracking resolution, the required event topology included a minimum distance of approach between the two pion tracks less than 1 cm, a minimum distance of approach between the proton and reconstructed $K^0_S$ tracks less than 6 mm, a radial distance of the production vertex from the positron beam axis less than 4 mm, a $z$ coordinate of the production vertex within the ±20 cm long target cell of $-18 \text{ cm} < z < +18 \text{ cm}$ along the beam direction, and a $K^0_S$ decay length greater than 7 cm. To suppress contamination from the Λ(1116) hyperon, events were rejected where the invariant mass $M_{\pi^+\pi^-}$ fell within $2 \sigma$ of the nominal Λ mass, where $\sigma = 2.6 \text{ MeV}$ is the apparent width of the Λ peak observed in this experiment.
3. Results

The resulting invariant $M_{\pi^+\pi^-}$ spectrum yields a $K_S^0$ peak at $496.8 \pm 0.2$ MeV, which is within 1 MeV of the expected value of $497.7 \pm 0.03$ MeV. To search for the $\Theta^+$, events were selected with a $M_{\pi^+\pi^-}$ invariant mass within $\pm 2\sigma$ about the centroid of the $K_S^0$ peak. The resulting spectrum of the invariant mass of the $p\pi^+\pi^-$ system is displayed in Fig. 1 (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 $N_s/\delta N_s = 3.7$. Here, $N_s$ is the full area of the peak from a fit to the data of a Gaussian plus a third-order polynomial, and $\delta N_s$ is its fully correlated uncertainty. All correlated uncertainties from the fit, including those of the background parameters, are accounted for in $\delta N_s$. There is no known positively charged strangeness-containing baryon in this mass region (other than the $\Theta^+$) that could account for the observed peak.

In an attempt to better understand the signal and its background, two additional models for the background were explored. For the first model, a version of the PYTHIA6 code tuned for HERMES kinematics is taken to

![Figure 1. Distribution in invariant mass of the $p\pi^+\pi^-$ system subject to various constraints described in the text.](image-url)
represent the non-resonant background, and the remaining strength in the spectrum is attributed to a combination of known broad resonances and a new structure near 1.53 GeV. For the second model, the non-resonant background is simulated by combining from different events a kaon and proton that satisfy the same kinematical requirements as the tracks taken from single events in the main analysis. This procedure yields a shape that is very similar to that from the PYTHIA6 simulation, as shown in Fig. 1 (right panel). By fitting a polynomial to the mixed-event background normalized to the PYTHIA6 simulation, a peak is obtained at 1527.0 ± 2.3 ± 2.1 MeV with a Gaussian width of $\sigma = 9.2 \pm 2$ MeV and a statistical significance of $N_s/\delta N_s = 4.3$. The resulting values from the two fits for the centroid are found to be consistent, while the width and significance depend on the method chosen to describe the remaining strength of the spectrum.

Using a $\Theta^+$ “toy Monte Carlo” with $\Gamma_{\Theta^+} = 2$ MeV, an instrumental width of 10–14.6 MeV (FWHM) was derived. This is somewhat smaller than the observed 19–24 MeV (FWHM) width of the peak. Therefore, the peak of interest was re-fit with a Breit-Wigner form convoluted with a Gaussian whose width was fixed at the simulated resolution. The resulting value for the intrinsic width is $\Gamma = 17 \pm 9$(stat)±3(syst) MeV.

In order to study the isospin of the observed resonance, the possibility that the $\Theta^{++}$ partner is present in the $M_{pK^+}$ spectrum was explored. Although Fig. 2 shows a clear peak for the $\Lambda(1520)$ in the $M_{pK^-}$ invariant mass spectrum, there is no peak structure observed in the $M_{pK^+}$ invariant mass distribution. The upper limit of zero counts is at the 91% confidence level. The failure to observe a $\Theta^{++}$ suggests that the observed $\Theta$ is not isotensor and is probably isoscalar.

Estimates of the spectrometer acceptance times efficiency from the toy Monte Carlo simulation mentioned above were used to estimate some cross sections. Taking the branching fraction of the $\Theta^+$ to $pK^0_S$ to be 1/4, the cross section for its photoproduction is found to range from about 100 to 220 nb ±25%(stat), depending on the model for the background and the functional form fitted to the peak. The cross section for photoproduction of the $\Lambda(1520)$ is found to be 62±11(stat) nb. All of these estimates are subject to an additional factor of two uncertainty, to account for the assumptions about the kinematic distribution of the parents used in the simulation.

\footnote{The indicated range in width depends on the background model and on the mass reconstruction method used.\textsuperscript{12}}
A comparison of the mass values reported to date for the $\Theta^+$ state by other experiments to the present results indicates that there are large variations in mass. However, this is not uncommon for new decaying particles. Nevertheless, there is clearly a need for better estimates of experimental uncertainties. By fitting the available mass values with a constant, the weighted average is $1532.5 \pm 2.4$ MeV. The uncertainty of the average was scaled by the usual factor of square root of the reduced $\chi^2$.

It is important to note though, that the experimental status of pentaquark baryons is still controversial. The signal of the $\Theta^+$ claimed by Refs. 6–17 fails to appear in the data from a large number of other experiments, as shown in Table 1. Unfortunately, none of these eleven results have been published at the time of this workshop, and only three have appeared on the e-Print archive server.

### 3.1. Systematic Studies

The general experimental situation is quite unsettled at this point. There are many open questions that need to be answered: how real are the positive results, and equally, how real are the null results; what is the actual mass, intrinsic width, the spin and parity, etc., of this new particle. In particular, the positive results need to be checked whether they were produced from fake peaks that can arise from kinematic reflections or from detector acceptance and kinematic constraints on the data. While the former
Table 1. Summary of null results for three possible pentaquark states. Evidence for the $\Xi^{-\pi^+}(1862)$ and the $\Theta_c(3100)$ has been reported by Refs. 25 and 26, respectively. Only the null results from the experiments with a $^*$-symbol have appeared on the e-print archive server at the time of this workshop.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Theta^+(1540)$</th>
<th>$\Xi^{-\pi^+}(1862)$</th>
<th>$\Theta_c(3100)$</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA-B*</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$pA \rightarrow \Theta^+ X, \Xi^{-\pi^-} X$</td>
</tr>
<tr>
<td>E690</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$pp \rightarrow \Theta^+ X, \Xi^{-\pi^-} X$</td>
</tr>
<tr>
<td>CDF</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$p\overline{p} \rightarrow \Theta^+ X, \Xi^{-\pi^-} X, \Theta^\circ X$</td>
</tr>
<tr>
<td>HyperCP</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$\pi, K, p \rightarrow \Theta^+ X$</td>
</tr>
<tr>
<td>BaBar</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$e^+e^- \rightarrow \Theta^+ X, \Xi^{-\pi^-} X$</td>
</tr>
<tr>
<td>ZEUS</td>
<td>No</td>
<td>NO</td>
<td>NO</td>
<td>$ep \rightarrow \Theta^+ X, \Xi^{-\pi^-} X, \Theta^\circ X$</td>
</tr>
<tr>
<td>ALEPH</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$e^+e^- \rightarrow \Theta^+ X$</td>
</tr>
<tr>
<td>DELPHI</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$e^+e^- \rightarrow \Sigma^- K^0 p$</td>
</tr>
<tr>
<td>PHENIX</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$AuAu \rightarrow \Theta^+ X$</td>
</tr>
<tr>
<td>FOCUS</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$\gamma A \rightarrow \Theta^\circ X$</td>
</tr>
<tr>
<td>BES*</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>$e^+e^- \rightarrow J/\Psi - \Theta^+ \overline{\Theta}^-$</td>
</tr>
</tbody>
</table>

check has not been entirely done for the present result, the PYTHIA 6 and $\Theta^+$ Monte Carlos have not produced any fake peaks due to acceptance or kinematic constraints.

Because the present experiment does not precisely determine the strangeness of the observed peak, the question has arisen whether it is a true pentaquark (with strangeness $S=+1$) state or a previously unobserved $\Sigma^{++}$ resonance. Under the assumption that the peak is a $\Sigma^{++}$ resonance, there should also appear a peak in the $M_{\Lambda\pi^+}$ spectrum. However, as can be seen in Fig. 3, no peak appears in the $M_{\Lambda\pi^+}$ spectrum near 1.53 GeV, even though the well established $\Sigma(1385)^+$ baryon resonance is clearly seen. Furthermore, the $M_{\Lambda\pi^-}$ spectrum clearly shows the well known $\Sigma(1385)^-$ and $\Xi^-$ states, demonstrating the ability of the current experiment to identify narrow resonances in $\Lambda\pi$ invariant mass spectra near 1530 MeV. This indicates that the observed peak in the $M_{\rho\pi^+\pi^-}$ invariant mass spectrum cannot be a previously unobserved $\Sigma^{++}$ resonance.

Although the present experiment has excellent particle identification for protons and kaons, the $M_{\rho\pi^+\pi^-}$ invariant mass spectrum exhibits a relatively large background under the peak of interest. Most of this background is from $K_S$ mesons that originate from processes other than $\Theta^+$ decay. A large fraction of such $K_S$ mesons from exclusive processes can be removed if an additional hadron is required in the event. Due to the limited acceptance of the HERMES spectrometer, however, this additional requirement reduces the number of events that passed all the kinematic constraints from
Figure 3. Distribution in invariant mass of the $(p\pi^-)\pi^-$ (left panel) and $(p\pi^-)\pi^+$ (right panel) system. There is no peak in the $(p\pi^-)\pi^+$ invariant mass spectrum near 1.53 GeV. The shaded histogram represents the mixed-event background.

1203 to 395, in 86% of which the extra hadron was a pion. Requiring the additional hadron to be a pion, here termed $\pi^+_{4th}$, removes $K_S$ mesons from the process $\gamma p \rightarrow \phi p \rightarrow K_L^0 K_S^0 p$, because it is rather unlikely to detect a pion from $K_L$ decay in our detector. The additional pion further helps to remove $K_S$ from $p(K^+)\rightarrow pK_0^0 \pi^+_{4th}$ by introducing a new veto constraint on the $M_{K_S^0\pi^0}$ invariant mass. Since the proton and the additional pion can come from a $\Lambda \rightarrow p\pi^-_{4th}$ decay, an additional veto constraint is placed on the $M_{p\pi^-_{4th}}$ invariant mass. Figure 4 shows the $\Theta^+$ mass spectrum with an additional pion in the event after applying these two new constraints (on the $K^+$ and $\Lambda$) in addition to all the standard kinematic constraints. The mass and the width of the peak are in good agreement with the published results, however, the ratio of signal to background improves from 1:3 (see Fig. 1) to 2:1.

It was further investigated whether the fourth hadron could come from the following exclusive processes: $\gamma p \rightarrow K^0\Theta^+ \rightarrow (\pi^+\pi^-)(K^0_S p \rightarrow \pi^+\pi^- p)$, or $\gamma n \rightarrow K^-\Theta^+ \rightarrow K^- (K^0_S p \rightarrow \pi^+\pi^- p)$. Results from a Monte Carlo study revealed that the associated $K^-$ or $K_S$ from these exclusive processes go to backward angles, and that even the pions from $K_S$ decay are inaccessible with the HERMES detector. This is due to the PID threshold on the proton, which requires that the momentum of the $\Theta^+$ must be larger than 7 GeV. Therefore, the tagged pion events cannot originate from these exclu-
Figure 4. Invariant mass distribution of $M_{p\pi^+\pi^-}$ with an additional pion, subject to the constraints in event topology discussed in the text.

sive processes, which implies that the production cross section has to be at least partially inclusive. This is an interesting observation because it does not support a possible explanation for the discrepancy between the positive results from low energy experiments, which are mainly from exclusive reactions, and the null results at high energy experiments, which are primarily inclusive measurements. The idea was that the $\Theta^+$ would be produced in exclusive processes, and the cross sections for such processes typically decrease with increasing energy (with the exception of elastic scattering). Even though the cross sections for inclusive processes tend to increase with energy, it was hypothesized that the $\Theta^+$ would not be produced in inclusive processes, thus failing to appear in high energy experiments. However, the present new data (as well as the observation of the $\Theta^+$ by ZEUS\textsuperscript{13}) appear to contradict this idea.

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