

# Evidence for the Strangeness $S=+1$ Pentaquark from LEPS and CLAS Experiments

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**Abstract.** There are now several experimental collaborations that have seen evidence for a narrow state in the mass spectrum of the  $(nK^+)$  system. Two of these experiments, from the LEPS collaboration in Japan and the CLAS collaboration in the USA, are described briefly. Both use similar photoproduction reactions with a  $K^+K^-$  pair in the final state. In addition, data from the CLAS collaboration for the  $\gamma p \rightarrow K_s K^+ n$  reaction are presented for the first time, which has no prominent peak in the  $(nK^+)$  mass spectrum when the  $K_s$  angle is limited to forward angles.

## INTRODUCTION

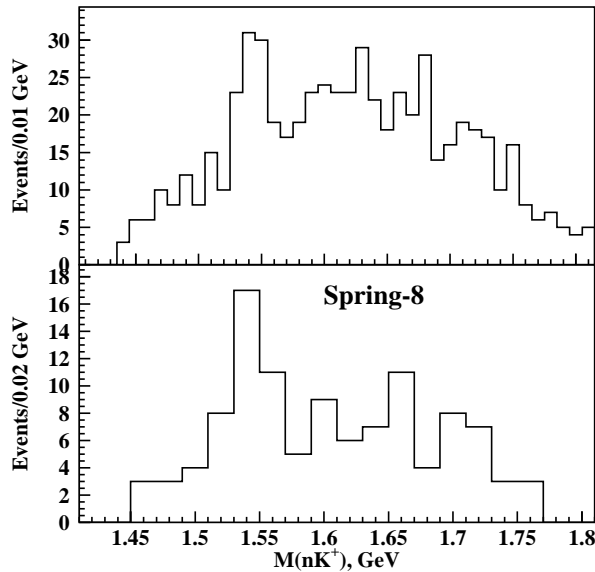
Until recently, it was thought that the pentaquark, defined as a particle resonance with four quarks and one anti-quark, did not exist. This belief was based on exhaustive searches for a strangeness  $S = +1$  resonance in the 1970's [1] yet only  $S = -1$  particles were found. This result was a bit surprising because the rules of QCD do not forbid the existence of pentaquarks.

Nonetheless, progress was made in theoretical studies of the soliton model of the nucleon [2] which predicted, in addition to the usual octet and decuplet, an anti-decuplet ( $\bar{10}$ ) of baryons that includes a  $S = +1$  particle. Real progress was made when Diakonov, Petrov and Polyakov [3] predicted the mass of this particle using symmetries of the chiral soliton model and the key identification of the  $S = 0$  baryon of the  $\bar{10}$  with the spin  $\frac{1}{2}$ ,  $P_{11}$  nucleon resonance at 1710 MeV. In this model, the mass of the pentaquark (called the  $Z^+$  in Ref. [3] but since renamed the  $\Theta^+$  by the authors) was predicted to have a specific mass of 1530 MeV and a narrow width ( $< 15$  MeV). This motivated experimenters to look again for this  $S = +1$  particle in already-existing data.

## FIRST RESULTS

The first evidence for the  $\Theta^+$  pentaquark was reported in October, 2002 [4] by the LEPS collaboration in Japan. The reaction is  $\gamma n \rightarrow K^- \Theta^+ \rightarrow K^- K^+ n$  where the neutron is bound inside a carbon nucleus, and only the  $K^+$  and  $K^-$  were detected at forward angles ( $\theta_{LAB}(K) < 30^\circ$ ). The results are now published [5] and details of the measurement can be found there. The final spectrum is shown in Fig. 1 (bottom).

After the announcement by LEPS, the CLAS collaboration started to look for the  $\Theta^+$  in existing photoproduction data on a deuterium target. The advantage of a deuterium



**FIGURE 1.** Comparison the invariant mass of the neutron- $K^+$  system,  $M(nK^+)$  for the CLAS data (top) and LEPS data (bottom).

target is that a kinematically complete reaction can be measured, in contrast to the inclusive kinematics of the carbon target. The reaction  $\gamma d \rightarrow K^- \Theta^+ p \rightarrow K^- K^+ p(n)$  was analyzed, where the neutron was deduced by the missing mass technique. Details of this result were first presented in February 2003 [6], followed by a more complete report in May [7]. Details can be found in Ref. [8]. The final spectrum is shown in Fig. 1 (top).

Comparing both figures, the prominent feature is a peak at the same mass, 1.54 GeV, with a width of  $< 25$  MeV. The width of the peak is consistent with the known resolution of each experiment. This suggests that the intrinsic resolution of the resonance is smaller than the measured widths, although the small statistics prevents a definite conclusion. The shape of the background under the peaks is described in the respective references ([5, 8]). As long as the conservation laws of baryon number and strangeness hold, the resonance peak is a pentaquark made up of  $(uudd\bar{s})$  construction. This is consistent with the  $\Theta^+$  prediction of Diakonov *et al.*, but until the spin and parity of this resonance is measured, we can not be sure that it is, indeed, the  $\Theta^+$  particle as predicted.

The CLAS data are shown again in Fig. 2 along with a fit to the peak. The background has been modeled by s-wave (non-resonant) photoproduction of  $K^+K^-$  pairs. The production cross section is just the phase space of 3-body ( $K^+K^-$  from a nucleon) and 4-body ( $K^+K^-$  from both nucleons in deuterium). Using this background shape, the fit gives a statistical significance of  $4.7 \sigma$ , calculated as a fluctuation of the excess above the background shape ( $1 \sigma = \sqrt{N_{Bg}}$ , where  $N_{Bg}$  is the number of counts in the background within  $\pm 20$  MeV of the peak's central mass). The uncertainty in the statistical significance depends on the shape of the background, and different choices of background give values ranging from 4.6 to  $5.8 \sigma$ .

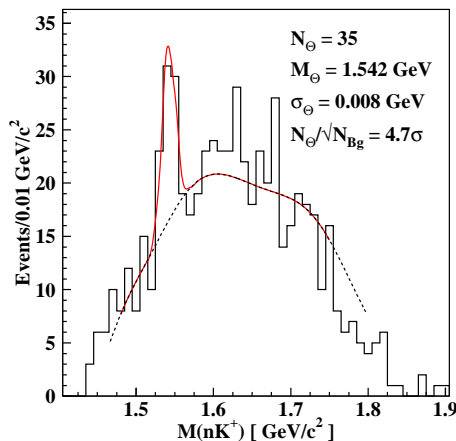


FIGURE 2. Peak fit using a MC background shape for the  $M(nK^+)$  spectrum.

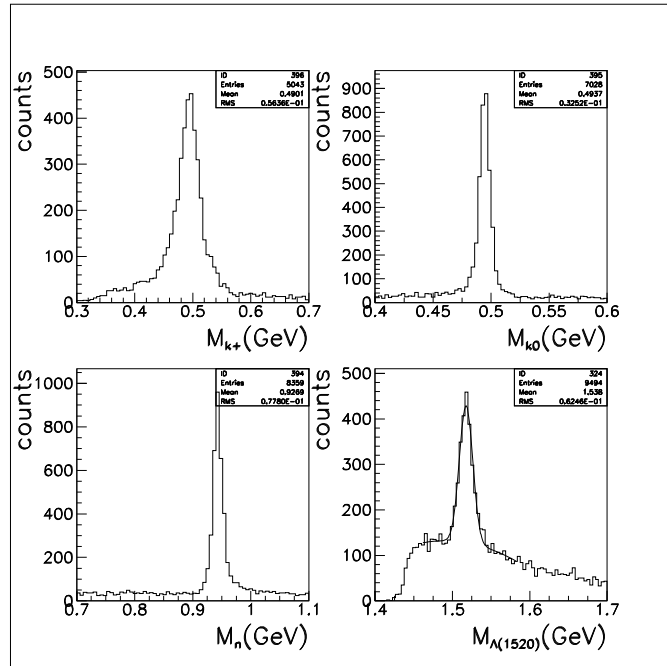
If the  $\Theta^+$  exists, then it should be produced in a variety of reactions. In addition to photoproduction from the neutron, which must be bound in a nucleus, it is natural to look for photoproduction from the proton. Preliminary results on the reaction  $\gamma p \rightarrow K^- \pi^+ \Theta^+$  have already been presented [7]. Another reaction is  $\gamma p \rightarrow \bar{K}^0 \Theta^+$  which was published by the SAPHIR collaboration [9] (which are also reported in these proceedings).

## NEW EXPERIMENTAL RESULTS

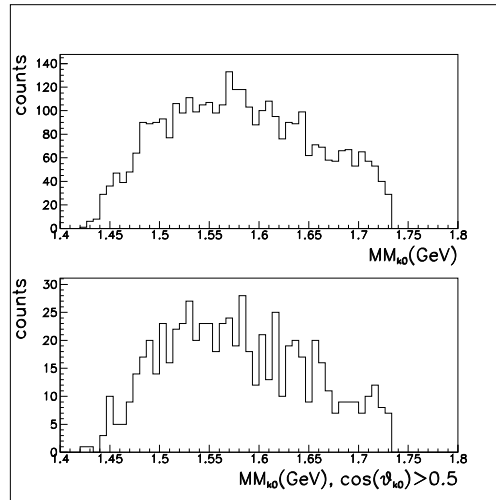
We present here *preliminary* results of the CLAS collaboration [10] for analysis of the reaction  $\gamma p \rightarrow \bar{K}^0 K^+ n$  where the neutron is measured by the missing mass technique. Fig. 3 shows the the mass calculated from the momentum and velocity of detected particles. The  $K^+$  (top left) is detected directly. The  $K^0$  mass (top right) is from  $K_s$  decay, made from the invariant mass of a detected  $\pi^+ \pi^-$  pair. The  $n$  mass (bottom left) is from the missing momentum and energy. The  $\Lambda(1520)$  mass (bottom right) is from the invariant mass of the deduced 4-vectors of the  $n$  and the  $K_s$ . All mass spectra show clear peaks with very little background, showing that particle identification is quite good. Several thousand good ( $K_s K^+$ ) events are identified for further analysis.

One must be careful in the analysis of the proton data because the  $K_s$  is a linear combination of  $K^0$  and anti- $K^0$ . Hence, the strangeness of the reaction is not uniquely identified by the  $K_s$  particle, and other reactions can produce the same final state. As shown above, the  $\gamma p \rightarrow K^+ \Lambda^*$  reaction, where  $\Lambda^* \rightarrow K^0 n$ , has the same final state as  $\gamma p \rightarrow \bar{K}^0 \Theta^+$  where the  $\Theta^+$  can decay to  $K^+ n$ . Also, since the  $K_s$  is determined from a  $\pi^+ \pi^-$  pair, the reaction  $\gamma p \rightarrow K^+ \Lambda^*$  followed by  $\Lambda^* \rightarrow \Sigma \pi \rightarrow \pi^+ \pi^- n$  has the same particles in the final state.

After rejecting events where a  $\pi n$  invariant mass equals the  $\Sigma$  mass, and also events in the  $\Lambda(1520)$  peak (see Fig. 3), the missing mass of the  $K_s^0$  spectrum is shown in Fig. 4. This spectrum should show a peak at the mass of the  $\Theta^+$  if this state is produced with a



**FIGURE 3.** The masses calculated from coincident  $K^+$ ,  $\pi^+$  and  $\pi^-$  particles in photoproduction from a proton target at CLAS.



**FIGURE 4.** The missing mass spectrum for  $K_S^0$  production from the reaction  $\gamma p \rightarrow \bar{K}^0 n$  and event selection as described in the text[10].

cross section sufficiently larger than the non-resonant background. If the  $\Theta^+$  is produced in a  $t$ -channel process, then selecting events with forward angles of the  $K_S$  ( $\cos \theta_{K_S} > 0.5$  where the angle is in the photon-proton center of mass system) could enhance the signal over the background. The bottom plot in Fig. 4 shows the spectrum after this event cut. In both cases, no prominent peak is observed.

## SUMMARY AND CONCLUSIONS

The lack of a strong signal in the *preliminary* analysis of the  $\gamma p \rightarrow K_s^0 K^+ n$  reaction at CLAS is surprising, considering that there are several measurements that have shown strong evidence for the  $\Theta^+$ . One possible explanation is that the coupling constant at the  $K^* p \Theta^+$  vertex is small, giving a small cross section in the  $t$ -channel. (The  $K^*$  vector meson is necessary as a virtual particle at forward angles since the neutral kaon couples to the photon primarily through a magnetic M1 transition). Of course, another possibility is that the  $\Theta^+$  does not exist, and that the other experiments are just unfortunate statistical fluctuations. (At the time of writing this paper, the latter possibility seems less likely, as more reports supporting the  $\Theta^+$  have been announced.)

A full understanding of the experimental situation for evidence of the  $\Theta^+$  must await future measurements. It is difficult to be patient at a time where excitement surrounds the announcement of a new particle, which could be the beginning of a new class of particles (pentaquarks). However, we must be cautious, and let the facts emerge. If the  $\Theta^+$  exists, then experiments with better statistics and more understanding of the background will find clear evidence for this particle. Until then, there are positive signs but no definite conclusions regarding the existence of pentaquarks.

## ACKNOWLEDGMENTS

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