Status of Pentaquark Search at Jlab

Valery Kubarovsky and Paul Stoler
For the Jefferson Lab CLAS Collaboration

aRensselaer Polytechnic Institute, Troy, NY 12180

We review the current experimental situation of pentaquark searches, and second generation experiments, with emphasis on the Jefferson Lab program.

1. INTRODUCTION

The possibility of the existence of pentaquarks has been theoretically discussed for many years. However, the subject has been thrust to the forefront during the past two years by the report of the possible observation of a such a state at Spring-8 [1] and ITEP [2]. This was immediately followed up by several positive signals from groups analyzing previously obtained data [3,4,5,6], so that at this writing there are more than a dozen observations of a state having mass $M = 1522 - 1555$ MeV, strangeness $S = +1$, (the negative of that for normal strange baryons), and very narrow width $\Gamma < 10$ MeV [12,3,11,7,9,10,11]. This new state, dubbed $\Theta^+$ [12], was identified as a candidate for the $\bar{u}u\bar{d}\bar{s}$ lowest lying member of a predicted pentaquark baryon anti-decuplet [13], illustrated in Fig. 1.

Figure 1. Anti-decuplet of baryons. The corners of this diagram are manifestly exotic.

In addition to the exotic $\Theta^+$, the anti-decuplet predicts the existence of two other exotic states which have $S=-2$ and charge $Q=-2$ and $Q=+1$, denoted $\Xi_{-5}^-$ and $\Xi_{5}^+$ respectively. The subscript “5” indicates the five-quark (pentaquark) nature of the states and is used to distinguish them from ordinary cascade states. These exotic cascade states have isospin $3/2$. Two additional partners, denoted $\Xi_{5}^-$ and $\Xi_{0}^0$, are also 5-quark states but are not explicitly exotic. The CERN NA49 collaboration has recently reported evidence for $\Xi_{5}^-$ [14].

The HERA H1 collaboration reported the observation of a narrow resonance in $D^{*+}\bar{p}$ and $D^{*+}\bar{p}$ invariant mass combinations in inelastic electron-proton collisions [15]. The resonance has a mass of $3099\pm 5$ MeV and a measured Gaussian width of $12\pm 3$ MeV, compatible with the experimental resolution. The resonance was interpreted as a possible anti-charmed pentaquark baryon with a minimal constituent quark composition of $uudd\bar{c}$, together with the charge conjugate.

Still, there are important difficulties which need to be resolved before any claims can be made about the existence of pentaquarks. Perhaps most importantly, several high-energy accelerator laboratories have been unable to observe any corroborating signal, even in cases with high statistical precision [16].
In the following section we review the current experimental situation, and planned second generation experiments, with emphasis on the Jlab program.

2. CURRENT EXPERIMENTAL SITUATION

The properties of the observed candidate pentaquark signals involving a variety of probes and targets are presented in Table 1. The initial reported observation was at LEPS \[1\] in the reaction $\gamma + n \rightarrow K^+K^-n$ utilizing a CH$_2$ target. The statistical significance of the signal was estimated as $4.6\sigma$. The DIANA \[2\] collaboration then reported a possible $\Theta^+$ signal in the charge-exchange reaction $K^+Xe \rightarrow K^0pXe'$. This very narrow peak was observed in the $K^0p$ effective mass spectrum with $4.4\sigma$ statistical significance. Soon thereafter the Jefferson Lab (JLab) CLAS collaboration \[17\] reported a positive result \[3,4\] on a deuterium target.

All of the above sightings were on nuclear targets. The first positive observations reported on a proton target were in photoproduction from the JLab CLAS \[3,5\] and the SAPHIR \[6\] collaborations. Since then there have been observations with quasi-real photoproduction on deuterium \[7\]. Positive observations were also made with neutrino interactions \[8\], and hadron-hadron collisions \[9,11\] on various targets. Fig. 2 summarizes the published mass values of various experiments.

There are several noteworthy difficulties which have led to reservations about accepting the existence of pentaquarks as being established. The statistical significance in every measurement is relatively small. The positions of the observed peaks vary somewhat from case to case, with the masses of the $K^+n$ \[18\] (see Fig. 3).

A major problem, frequently mentioned, is that the high statistics searches at a number of high energy facilities have not seen evidence of this state \[16\]. Clearly the observation of pentaquark states in all high energy experiments would have been powerful corroborations. However the very different kinematical and experimental conditions between these high energy semi-inclusive experiments and the low energy exclusive experiments do not allow a direct comparison. These null re-

Table 1
The $\Theta^+$ positive observations

| Exp. | Mass (MeV) | Width (MeV) | Stat. sign. | Ref. |
|------|------------|-------------|-------------|-----|
| LEPS | 1540±10 | <25 | 4.6$\sigma$ | \[1\] |
| DIANA | 1539±2 | <9 | 4.4$\sigma$ | \[2\] |
| CLAS(d) | 1542±4 | <21 | 5.2$\sigma$ | \[3\] |
| CLAS(p) | 1555±10 | <26 | 7.8$\sigma$ | \[4\] |
| SAPHIR | 1540±2 | <25 | 4.8$\sigma$ | \[5\] |
| HERMES | 1528±3 | 17±9 | 4-6$\sigma$ | \[7\] |
| ITEP | 1533±5 | <20 | 6.7$\sigma$ | \[8\] |
| SVD-2 | 1526±3 | <24 | 5.6$\sigma$ | \[9\] |
| COSY | 1530±5 | <18 | 4-6$\sigma$ | \[10\] |
| ZEUS | 1522±3 | 8±4 | 4.6$\sigma$ | \[11\] |

![Figure 2](image-url)
preliminary result [21] for the reaction $\gamma n \to K^-K^+n$ using new data on a deuteron target. The spectra shown in Fig. 4 appear to confirm their initial observation. This is considered one of the most compelling positive results since it involves minimal kinematic cuts. Followup experiments in COSY to increase the statistics of their $pp \to \Sigma^+K^0\pi^-$ are scheduled for 2005. An extensive experimental program has begun at JLab. In the following we focus on the JLab initial published results followed by a brief description of the ongoing and planned next generation experiments.

3. THE JEFFERSON LAB PROGRAM

3.1. Published Jefferson Lab Results

The initial JLab results for deuteron and proton targets were obtained in the exclusive analysis of CLAS data that were recorded in experiments performed several years earlier.

Photoproduction on a Deuteron Target.

The experiment was carried out with tagged pho-
tons having maximum energy 3.1 GeV, incident on a 10 cm long deuterium target \[4\]. The studied reaction $\gamma d \rightarrow K^- K^+ pn$ was isolated by detecting the three charged particles in the final state and selecting the neutron with the missing mass technique. The $\Theta^+$ was reconstructed from the $K^+ n$ invariant mass. Since detection of the proton was required to insure exclusivity, a final state interaction involving the spectator proton was required in order to provide it with enough momentum to be detected. The minimum proton momentum which was detected was 200 MeV/c. A possible reaction diagram is shown in Fig. 5.

Cuts were applied to eliminate background from known resonances: the $\phi(1020)$ mesons (in the $K^+ K^-$ decay mode) and $\Lambda(1520)$ baryons (in the $pK^-$ decay mode). The result is shown in Fig. 6. A peak is seen at a mass $1542 \pm 5$ MeV. The background under the peak was estimated by two methods, a Gaussian fit and Monte-Carlo simulation. The quoted statistical accuracy of the fitted peak was 5.2 $\sigma$. An analysis of this data using a different technique finds that the significance may not be as large as presented in the published work. We expect a definitive answer from a much larger statistics data set that is currently being analyzed (see below).

**Photoproduction on a Proton Target.** The proton experiment used tagged photons with a maximum energy of 5.45 GeV, incident on a hydrogen target \[5\]. The reaction studied was $\gamma p \rightarrow \pi^+ K^- K^+ n$, with the neutron again identified by missing mass. Several possible reaction mechanisms were considered, $\gamma p \rightarrow K^0 \Theta^+$ with a forward cut in the $K^0$ direction, and $\gamma p \rightarrow \pi^+ K^- \Theta^+$ with a forward cut in the $\pi^+$ direction, illustrated in Fig. 7. It was found that the signal was most evident in the channel with a forward going $\pi^+$. The resulting mass spectrum is shown in Fig. 8. A full partial wave analysis was performed on the reaction $\gamma p \rightarrow \pi^+ K^- K^+ n$ to rule out the possibility of a meson reflection in the $nK^+$ mass system and to determine the background shape under the observed resonance structure. The mass of the observed peak is $1555 \pm 10$ MeV. The statistical accuracy is quoted at about $7.8 \pm 1 \sigma$.

The invariant mass of the $\Theta^+ K^-$ system was calculated, yielding the distribution shown in Fig. 9. The observed peak at a mass near 2.4 GeV is suggestive of a possible narrow resonance.
state which decays into $\Theta^+K^-$, as illustrated in Fig. 7. Of course at this stage this is mere speculation.

3.2. New Dedicated Experiments
Based on the observations described here, the JLab CLAS and Hall A collaborations have undertaken a series of experiments to try to corroborate the existence of pentaquarks. These are described in the following.

Photoproduction of $\Theta^+$ from neutrons ($g10$) [22]. This experiment, which was run during spring 2004, measured the exclusive reaction $\gamma d \rightarrow \pi^+K^-p\pi^+$ in order to verify our published result with an order of magnitude increase in statistics. Data taking was successfully completed in May 2004. The experiment utilized a maximum tagged photon beam energy of 3.6 GeV with two different magnetic field settings for the CLAS spectrometer. The target was shifted upstream 25 cm from the nominal position to increase the acceptance in the forward direction. The run with lower magnetic field has increased acceptance for forward going negative particles, which allows us to perform an analysis similar to Spring-8 for inclusive reactions. The run with high magnetic field had the same geometrical acceptance and single track resolution as the published CLAS result. The higher integrated luminosity was achieved by means of a longer target, improved trigger scheme, and longer data taking time. The total luminosity was about 50 $pb^{-1}$ compared with about 2.5 $pb^{-1}$ for the originally published data. The first pass of the detector calibration and performance check has already been completed. Preliminary examples of missing mass and invariant mass distributions based on a small fraction of the statistics, shown in Fig. 8 and 9, give an indication of the quality of the obtained data. The missing mass spectra of the reaction $\gamma d \rightarrow K^+K^-pX$ are shown in Fig. 10 for two different particle ID cuts. The mass resolution ($\sigma = 12$ MeV/$c^2$) and background under
Figure 9. The $M_{K^- nK^+}$ mass distribution for events selected from the $\Theta^+$ peak. The inset shows the distribution for the events outside the $\Theta^+$ region.

The neutron peak are in agreement with the previous measurements. The $pK^-$ and $K^+ K^-$ invariant mass spectrum in Fig. 11 clearly shows the $\Lambda(1520)$ baryon and $\phi$ meson, which are backgrounds that have to be removed in the final analysis.

The results. The possible reaction and decay modes which are the object of the analysis are shown in Table 2. Both decay modes, $pK^0$ and $nK^+$, are being analyzed in missing mass and invariant mass distributions. The results are expected to be released before the end of 2004.

Search for the Ground and Excited States from Protons ($g_{11}, \text{super-g}$) [23, 24]. This consists of two experiments, each with an order of magnitude more statistics than was available for our previously published result on the proton [5] and preliminary (unpublished) lower energy data [19].

The first ($g_{11}$, which utilized a tagged photon maximum energy of 4 GeV successfully completed data taking at the end of July 2004. The goal was primarily to check for the existence of the $\Theta^+$ and other possible members of the anti-decuplet on a proton target.

The second ($\text{super-g}$) will be a comprehensive

| Reaction          | The $\Theta^+$ decay mode | Detected final state |
|-------------------|---------------------------|----------------------|
| $\gamma d \to pK^+K^- n$ | $nK^+$                  | $pK^+ K^-$          |
| $\gamma d \to \Lambda K^+ n$ | $nK^+$                  | $p\pi^- K^+$       |
| $\gamma d \to \Lambda K^0 p$ | $pK^0_S$                | $pp\pi^-$          |
| $\gamma d \to ppK^0 nK^-$ | $pK^0_S$                | $p\pi^+ \pi^- K^-$ |
| $\gamma^* n' \to K^+ K^- n$ | $nK^+$                  | $K^+ K^-$          |
study of exotic baryons from a proton target with a maximum photon energy of about 5.5 GeV, with $5 \times 10^7$ s$^{-1}$ tagged photons rate, and broad kinematic coverage for a variety of channels. Its goal is to corroborate the previously published results at a similar energy, to get information about the pentaquark spin by measuring decay angular distributions, and its reaction mechanism by measuring its t-dependence. We will also investigate the possibility of an intermediate resonance near $W=2.4$ GeV as we reported in Ref. [5]. Another goal is to try to verify the existence of exotic cascades which were reported by NA49 [14]. The experiment is scheduled to run mid to late 2005.

To achieve the goals of these experiments it was necessary to design, fabricate and assemble a new longer target (40 cm) and new detectors around the target to provide improved event triggering and particle identification.

As mentioned, the first run ($g11$) was successfully completed. There are $6.9 \times 10^9$ events collected with 80 pb$^{-1}$ integrated luminosity. The calibration of the different CLAS detectors, and checking of the CLAS performance is under way. We expect to have the first physics result near the beginning of 2005. The reactions under study are: $\gamma p \rightarrow \bar{K}^0 K^+ n$, $\gamma p \rightarrow K^0 K^0 p$, $\gamma p \rightarrow K^- \pi^+ K^+ n$, $\gamma p \rightarrow K^- \pi^+ K^0 p$, $\gamma p \rightarrow K^+ \pi^+ \Sigma^-$, $\gamma p \rightarrow K^+ \pi^- \Sigma^+$, and $\gamma p \rightarrow K^- K^+ p$.

The performance of the CLAS setup is demonstrated in Figs.12 and 13. The missing mass resolution ($\sigma = 10$ MeV/c$^2$) and invariant mass resolution for the $K^0$ meson ($\sigma = 4.5$ MeV/c$^2$) is in agreement with spectrometer specifications. The background under the missing mass peaks will be reduced after the detector will be fully calibrated.

The search for exotic cascades using an untagged virtual photon beam ($eg3$) [25]. The NA49 evidence for the $\Xi^- \Xi^+$ and the $\Xi^0 \Xi^0$ at a mass of 1.86 GeV [14] was obtained from reconstruc-
tion of their decay products using the decays $\Xi_5^- \to \pi^- \Xi^-$ and $\Xi_0^0 \to \pi^0 \Xi^-$. To date no other experiments have been able to confirm this observation. $eg3$ is a new CLAS experiment searching for exotic cascades using an untagged virtual photon beam. The experiment is most sensitive to the $\Xi_5^-$ and $\Xi_5$, by means of reconstruction from their decay products. The main goal of the experiment will be to search for $\Xi_5^- \to \pi^- \Xi^-$, $\Xi_5^0 \to \pi^0 \Xi^-$ and $\Xi_5^- \to \pi^- \Xi^0$. Other decay modes are detectable with lower sensitivity.

The experiment is designed to utilize the highest luminosity possible with CLAS. It will use a 5.7 GeV electron beam incident on a deuterium target but without detecting the scattered electron. The untagged photon beam is necessary to achieve sufficient sensitivity to the expected small cross sections. The sequence of weakly decaying daughter particles provides a powerful tool to pick out the reactions of interest. The sensitivity of the experiment is expected to be 46 detected events per nb, and is scheduled to take data in December 2004.

**High Resolution search for $\Sigma_0^0$ and $\Theta^{++}$ in Hall A [25]**. The experiment has already completed data taking in June 2004. It used a liquid hydrogen target and detected a forward $K^-$ (or $K^+$) and scattered electron using the 2-arms of the high resolution spectrometers of Hall-A [27]. The reactions under study are $e^- p \to e^- K^+ X$ and $e^- p \to e^- K^- X$. The missing mass system then had the characteristics of doubly-positive-charged ($K^-$ forward) or neutral ($K^+$ forward) pentaquark states predicted in certain theoretical models. An excellent missing mass resolution provides the tool to search for narrow-width states. The online spectrum is presented in Fig. 14. Once again, data analysis is underway, with results expected in Fall 2004.

**Figure 13.** The missing mass spectrum in the $\gamma p \to K_0^0 K^+ X$ reaction. The neutron peak is clearly seen. (Preliminary CLAS data).

**Figure 14.** Preliminary Hall A data. The missing mass spectrum in the $e^- p \to e^- \pi^+ X$ reaction. The neutron is seen (left peak). The missing mass spectrum in the $e^- p \to e^- K^+ X$ reaction (right peaks). The $\Lambda$, $\Sigma^0$, and $\Lambda(1520)$ peaks are seen.

### 4. CONCLUSION

Many laboratories are involved in the search for pentaquarks, using a wide variety of beams, targets and final states. Several laboratories have reported positive observation of the signal, but
with rather low statistical precision, while others observe null results. Most, but not all, positive observations were made at lower energy facilities and in exclusive reactions, while almost all of the null results have been at high energy facilities with inclusive reactions. Thus, at this time the existence of a narrow pentaquark state is not fully confirmed.

The question of whether pentaquarks exist can only be resolved by a second generation of high statistics experiments. JLab is in a unique position to address this. The experimental program which we have begun is expected to increase the integrated luminosity by more than an order of magnitude for each experiment over what was previously reported. Data for three of these experiments is already in hand, and we expect to present first results of the series of high-statistics experiments by the end of 2004. Stay tuned!

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