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Experimental evidence for the pentaquark

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Abstract. The present experimental evidence for the existence of light pentaquarks is reviewed, including both positive and null results. I also discuss the CLAS experiments at Jefferson Laboratory that are forthcoming in the near future to address questions regarding existence, mass, width, and other quantum numbers of these five-quark baryon states.

PACS. 12.39.Mk Glueball and nonstandard multi-quark/gluon states – 14.20.-c Baryons – 14.80.-j Other particles

1 Introduction

The body of new experimental results indicating the possible existence of pentaquark baryons represents one of the most exciting topics to arise in nuclear physics in the past decade. To date there have been nearly a dozen experiments employing various beams and targets that have announced evidence for a narrow state (called Θ^+) with a mass of about 1540 MeV/c^2 and a width of <20 MeV. There are also a similar number of high-energy experiments that see no evidence for such a state. Additionally one experiment has announced evidence for a narrow cascade state (called Ξ_5) at a mass of 1862 MeV/c^2 with a width of <20 MeV.

Speculation regarding baryon states whose minimal quark content cannot be obtained with only three valence quarks has appeared in the literature for more than 30 years, initially in connection with $K-N$ scattering data [1]. These states, initially referred to as Z^* resonances, were included in the Particle Data Group (PDG) listings until 1986, when they were dropped due to a lack of convincing experimental evidence. However a recent theoretical paper by Diakonov [2], which predicted an exotic baryon with minimal quark content $uudd\bar{s}$ at a mass of 1540 MeV/c^2 with a width of 15 MeV in a chiral soliton framework, reawakened the field and has led to a new round of experimental searches. The isoquartet of Ξ_5 states along with the Θ^+ are believed to be part of an anti-decuplet of pentaquark baryon states with spin 1/2 and positive parity. Of important note is that most of these new searches come from mining existing data that were taken for other purposes. This is important to appreciate, especially given the relatively low statistical significance of the published positive results (in the range from 4-7σ).

The experimental concerns regarding the Θ^+ include not only the statistical significance of the observed peaks, but also the apparent discrepancy between the masses measured in the nK^+ and pK^0 isospin decay modes. The differences among the determined Θ^+ mass values must be addressed to ensure there are no experimental problems. However, the mass difference could be attributed to different initial and/or final state interactions or different interference effects in the two decay modes. For the Ξ_5 baryon, only one experiment has been able to see any hint of a signal. Of concern in each of these analyses is the meaning and importance of different analysis cuts used to enhance the signal. However, these cuts could also provide important clues regarding the production dynamics of these exotic states. Providing a definite answer to the question of existence or non-existence of the Θ^+, Ξ_5, and other five-quark baryons is of critical importance in this field in order to better understand QCD and the structure of hadronic matter.

In this talk I focus on the present experiment evidence, including both positive and null results, for the low-mass exotic five-quark Θ^+ and Ξ_5 baryon states. I then focus on several of the key theoretical issues related to these states. Finally I discuss the second generation, high statistics experiments that are being planned with CLAS at Jefferson Laboratory that will be crucial in providing definitive answers regarding the existence and the nature of the pentaquark states.

2 Positive experimental searches

At the current time at least 10 different experiments have announced a positive result for the Θ^+ baryon. A compilation of the mass and decay width from these experiments is presented in Table 1. The estimated statistical significance quoted is given by $N_s/\sqrt{N_b}$, where N_s is the number of counts within $\pm 2\sigma$ of the mean for the Θ^+ peak from a Gaussian fit and N_b is the corresponding number of background events. Each of the experiments has relatively low statistics and the backgrounds beneath the peaks are not completely understood, which obviously affects the

Table 1. Overview of the positive Θ^+ pentaquark experiments. The column labeled "Significance" lists the quoted statistical significance as explained in the text

Expt.	**Reaction**	**Mass** (MeV/c^2)	**Width** Γ (MeV)	**Significance**	**Ref.**
LEPS	$\gamma C \to K^+K^-X$	1540 ± 10	< 25	4.6σ	[3]
DIANA	$K^+Xe \to K_s^0pX$	1539 ± 2	< 9	4.4σ	[4]
CLAS-d	$\gamma d \to K^+K^-p(n)$	1542 ± 5	< 21	5.2σ	[5]
SAPHIR	$\gamma p \to K^+K_s^0(n)$	1540 ± 6	< 25	4.8σ	[6]
CLAS-p	$\gamma p \to K^+\pi^+\pi^-(n)$	1555 ± 10	< 26	7.8σ	[7]
ITEP	$\nu A \to K_s^0pX$	1533 ± 5	< 20	6.7σ	[8]
SVD	$p + A \to pK_s^0X$	1526 ± 3	< 24	5.6σ	[9]
HERMES	$e^+d \to K_s^0pX$	1526 ± 3	13 ± 9	$\sim 5\sigma$	[10]
ZEUS	$ep \to K_s^0pX$	1522 ± 3	8 ± 4	$\sim 5\sigma$	[11]
COSY	$pp \to K_s^0p\Sigma^+$	1530 ± 5	< 18	$\sim 5\sigma$	[12]

quoted statistical significance. The first group of experiments from the LEPS, DIANA, CLAS, and SAPHIR collaborations have searched for evidence of the Θ^+ using different beams, energies, detector configurations, and assumptions regarding the reaction mechanism. As each was carried out using data collected for other purposes, each is statistically and systematically limited. In this section I focus on selected aspects of these different measurements.

The LEPS experiment at SPring-8 employed a photon beam with tagged energies between 1.5 and 2.4 GeV. The $\gamma n \to K^+K^-n$ reaction was studied on carbon from a scintillator target [3]. Cuts were made to remove the dominant $\phi \to K^+K^-$ decay channel and backgrounds from $\gamma p \to K^+K^-p$. Corrections were made for the Fermi momentum of the target nucleon, leading to a Θ^+ signal at a mass of 1540 MeV/c^2 with 19 counts above a background of 17 counts. This analysis assumed that the remainder of the nucleus acted as a spectator to the interaction. This work has since been followed up with a dedicated run on a deuterium target. Preliminary results announced at the N^*2004 conference indicate a consistent result with roughly a factor of four increase in statistics [13].

The DIANA experiment at ITEP employed a K^+ beam of 750 MeV/c incident on a xenon-filled bubble chamber [4]. The analysis focussed on $K^+Xe \to K_s^0pX$ charge-exchange events with $K_s^0 \to \pi^+\pi^-$, where the strangeness of the final state K_s^0 is known as the K^+ has strangeness +1. The analysis employed cuts to remove low momentum p and K_s^0 tracks and cuts on the K_s^0p opening angle to reduce effects of rescattering within the nucleus (which is claimed to be an important effect). The final spectrum shows 29 events in the Θ^+ peak (concentrated into a single bin) over a background of 44 events.

The CLAS experiment on deuterium (CLAS-d), $\gamma d \to K^+K^-p(n)$ (the neutron was not detected), was the first exclusive reaction for the Θ^+ [5]. One of the strengths of an exclusive analysis is the reduction of background channels and the fact that no Fermi momentum correction is required. This experiment used a tagged-photon beam with energies from 1.5 to 3.1 GeV. The analysis required a rather complicated secondary rescattering mechanism of the final state K^- and p to increase the acceptance for these particles in CLAS (see Fig. 1). As a result of this assumption (which was found to be required to explain $\Lambda(1520)$ production in the same final state), the shape of the background is difficult to estimate and may include some degree of kinematic reflections [14]. This experiment claims 42 counts in its Θ^+ spectrum at a mass of 1542 MeV/c^2 and a width of 21 MeV. Another CLAS photoproduction experiment was on a proton target (CLAS-p) [7] $\gamma p \to K^+\pi^+\pi^-(n)$ (the neutron was not detected), and claimed evidence for a Θ^+ with an impressive statistical significance of 7.8 σ (see Fig. 2). This experiment employed tagged photons from 3.0 to 5.5 GeV. The final

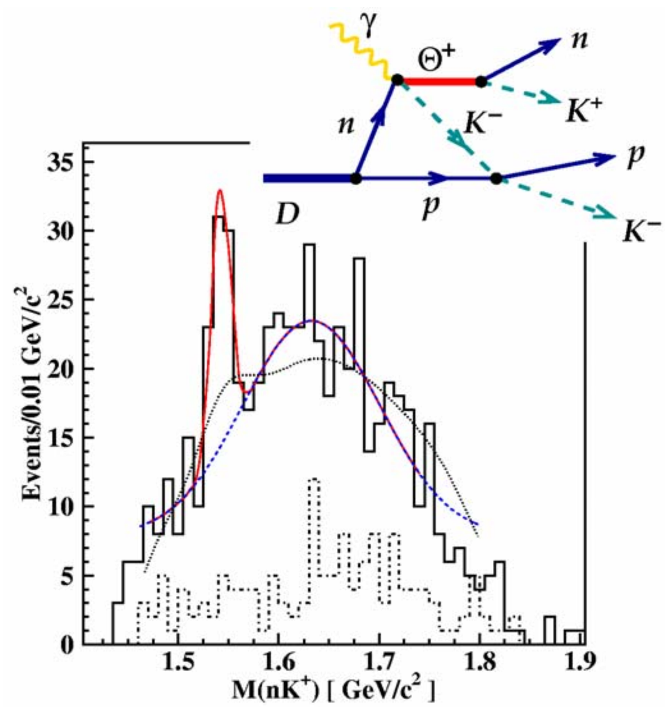

Fig. 1. Published CLAS-d result [5] for the reaction $\gamma d \to K^+K^-p(n)$ showing evidence for the Θ^+ peak. The *curves* include two different assumptions for the underlying background. The *inset* represents one possible rescattering diagram

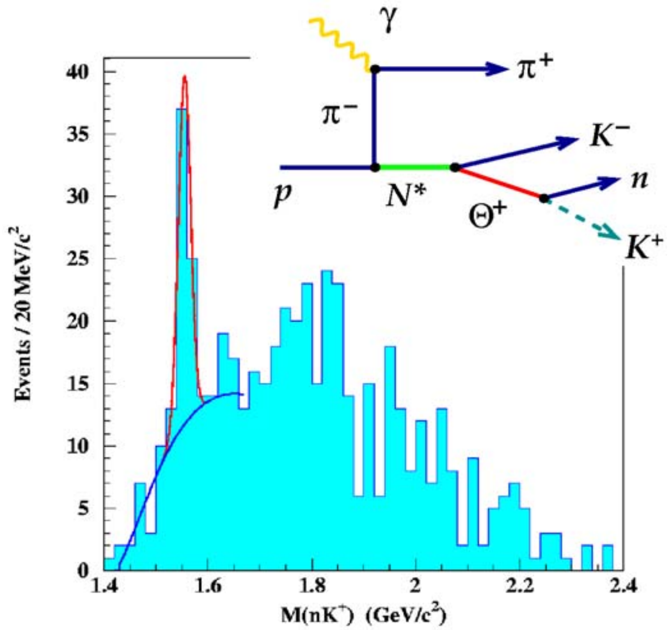

Fig. 2. Published CLAS-p result [7] for the reaction $\gamma p \rightarrow K^+\pi^+\pi^-(n)$ showing evidence for the Θ^+ peak. The *inset* represents the assumed reaction mechanism

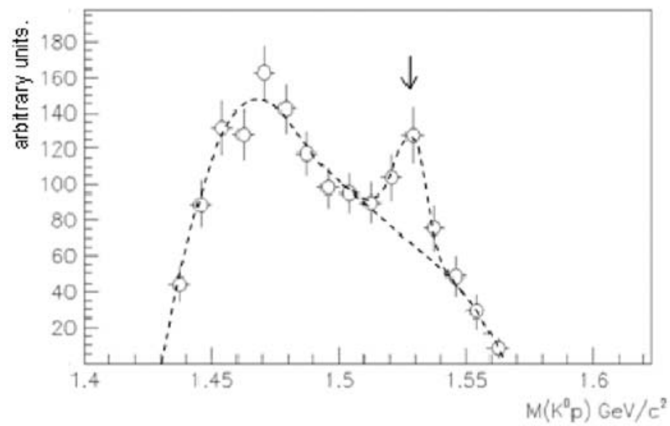

Fig. 3. Published COSY-TOF result [12] for the reaction $pp \rightarrow \Sigma^+ K_s^0 p$ showing evidence for the Θ^+ peak

event sample is enriched by requiring angular cuts to select events with a forward-going π^+ ($\cos\theta_\pi^{CM} > 0.8$) and a backward-going K^+ ($\cos\theta_K^{CM} < 0.6$). These cuts were designed to remove the dominant background from meson production reactions and enhance the s-channel production mode for the Θ^+. These data were examined by a partial wave analysis where the amplitudes of each partial wave were fit over the full angular coverage of CLAS, hence fixing the background under the Θ^+ peak. The analysis claims 41 events in the Θ^+ peak at a mass of 1555 MeV/c^2, which is ∼15 MeV higher than the CLAS-d result.

The SAPHIR experiment was the first to present evidence for the Θ^+ from a proton target from the exclusive reaction $\gamma p \rightarrow K^+ K_s^0(n)$ [6] (the neutron was not detected). They employed a tagged-photon beam with energy between 0.8 and 2.6 GeV. To enhance the Θ^+ signal, they employed a cut on forward-going kaons ($\cos\theta_K^{CM} > 0.5$) and observed 63 events in their Θ^+ peak. The large cross section that they estimated from their data conflicted with the data from CLAS for the same reaction. A re-analysis of the SAPHIR data now suggests a smaller cross section, but the result is still under investigation [15].

Following these papers, several other experiments measured the pK_s^0 invariant mass via inclusive reactions on nuclei and claimed to see evidence for the Θ^+. One of the experiments collected data from 120k 40-100 GeV ν and $\bar{\nu}$ charged-current events on hydrogen, deuterium, and neon-filled bubble chambers [8]. Two others experiments from the HERA accelerator employed electroproduction data. The result from HERMES [10] employed a fixed-target e^+d experiment at 28 GeV. The result from ZEUS [11] used $e-p$ collisions at $\sqrt{s} \approx$310 GeV. The SVD experiment focussed on $p+A$ collisions at 70 GeV/c at the IHEP accelerator requiring $\cos\theta_{pK_s^0} \geq 0$ [9]. Of importance in these experiments is that the K_s^0 is a mixture of both strangeness +1 and -1 eigenstates, so the invariant mass spectra could include both Σ^{*+} and Θ^+ peaks. However, it has been reasoned that a peak at a pK_s^0 mass where there are no known Σ^{*+} states can be interpreted as evidence for the strangeness +1 Θ^+. It is also interesting that these four experiments each report a Θ^+ mass which is about 10 MeV below those experiments reporting a Θ^+ from nK^+ reconstructions. Furthermore, most of the null experiments for the Θ^+ come from analyses using the same method of measuring the pK_s^0 invariant mass. The inherent weakness in not knowing the strangeness of a particle, coupled with the uncertainty in the associated backgrounds, clearly raises an important concern with these experiments. To reduce these doubts, it is important to confirm the pK_s^0 peak in experiments where the final state strangeness is cleanly tagged.

Another more recent result with strong evidence for the Θ^+ is from the COSY-TOF experiment [12] which employed the exclusive hadronic reaction $pp \rightarrow \Sigma^+ K_s^0 p$ reaction at $p_p = 2.95$ GeV (see Fig. 3). Here the strangeness of the $K_s^0 p$ combination is tagged by the accompanying final state Σ^+. Particle identification is done entirely by geometric reconstruction, which is quite accurate for this near threshold reaction. This analysis yielded a consistent result from the 2000 and 2002 data sets for the Θ^+ mass of 1530 MeV/c^2 and a cross section of 0.4 μb. This collaboration has plans to acquire additional data with improved detector resolution within the next year.

There is one other relevant and potentially exciting analysis. The NA49 experiment at CERN claims to see evidence for the exotic Ξ_5^{--} pentaquark state decaying into $\Xi^-\pi^-$ with a mass of 1862 MeV/c^2 and a width of 18 MeV via pp reactions at $\sqrt{s}$=17.2 GeV [16]. This analysis finds 38 Ξ_5^{--} candidates above a background of 43 events (see Fig. 4). This mass is in disagreement with the chiral soliton predictions of Diakonov [2] and the diquark model predictions of Jaffe and Wilczek [17]. No other experiments that have searched for this exotic state have been able to confirm this result. There is also additional

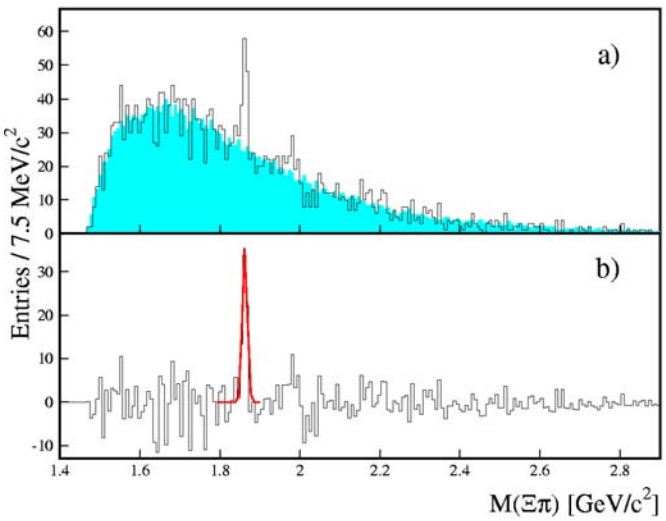

Fig. 4. Published NA49 result [16] for **a**. the sum of the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\overline{\Xi}^+\pi^-$ and $\overline{\Xi}^+\pi^+$ invariant mass spectra. The shaded histogram shows the normalized mixed-event background. **b** Background subtracted spectrum with the Gaussian fit to the peak

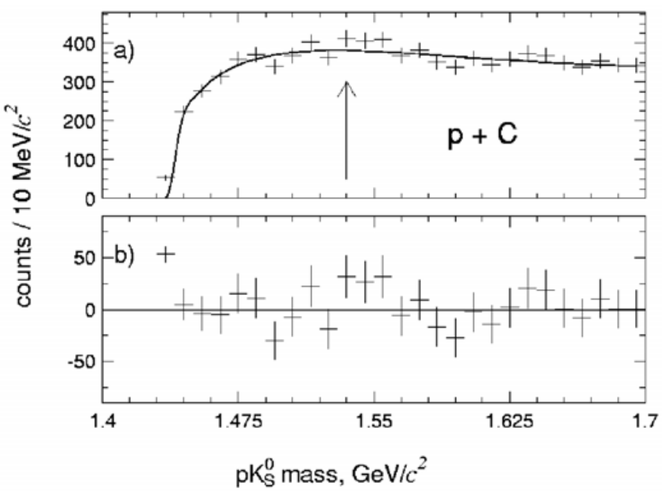

Fig. 5. Published HERA-B result [19] for the pK_s^0 invariant mass from $p + C$ collisions at 920 GeV. **a** Shows background determined from event mixing as the solid line. **b** Background subtracted data

controversy from within the NA49 collaboration itself that leads to doubt about this result [18]. Thus confirmation of this signal awaits and is in fact crucial to understand the nature and dynamical underpinnings of the Θ^+ itself.

3 Null experimental searches

During the course of the past year a number of null results for the Θ^+ and Ξ_5 states have been presented at various conferences. These experiments have been compiled in Table 2, and mainly report null results in high energy reactions (see Fig. 5 for the HERA-B result). These experiments see many of the well known hadronic resonances, but are mainly from high multiplicity, inclusive analyses (with the exception of the Fermilab E690 experiment). Because of the difficulty in detecting neutrons in these experiments, they have typically focussed on reconstructions of the pK_s^0 invariant mass, just as in the HERMES and ZEUS experiments.

Initially one might expect that if the Θ^+ exists, it should be produced in both high-energy electroproduction and in high-energy hadron collisions. However, reconstruction of the Θ^+ (and the Ξ_5 as well) must also be intimately connected with understanding the production mechanism for such states, as well as in understanding the underlying background processes. One of the most obvious differences between experiments reporting evidence for the Θ^+ and experiments that report a null result is the different kinematics in the experiments. The differences between the different experiments must surely provide strong clues as to why exclusive measurements at medium energy show a potential Θ^+ peak, whereas this signal is not equally apparent in high-energy inclusive measurements. One potentially relevant argument may be that the reaction mechanism is indeed through excitation of an intermediate crypto-exotic N^* state as hinted at by the CLAS-p analysis [7].

Whatever the final explanation is, it is clear that more data and theoretical input is required to address all of the questions raised. From my viewpoint I am entirely convinced that the peaks seen in the positive pentaquark experiments in Table 1 are not statistical fluctuations. However, it is not yet fully apparent what has given rise to these signatures, whether they are due to kinematic reflections, detector inefficiencies, final state interactions, interference effects, or true pentaquark states.

4 Θ^+ width

One of the most intriguing aspects of the Θ^+ is its apparent narrow width. Within any model of five quarks moving independently in an effective mean field potential, the pentaquark state would fall apart rapidly with a width of ~100 MeV. Thus if the Θ^+ truly exists, it must be exotic dynamically, as well as in its quantum numbers.

The chiral soliton model of Diakonov [2] predicts a narrow width for the Θ^+ based on the underlying symmetries of the model. However the predicted width has significant model dependence. Quark models can also obtain widths on the order of $\leq$10 MeV if there are non-trivial quark rearrangements within the Θ^+ wavefunction. For example the diquark model of Jaffe and Wilczek [17] proposes that the Θ^+ is composed of a pair of scalar ud diquarks and a strange anti-quark. Another example is the diquark-triquark model of Karliner and Lipkin [25] where two color non-singlet clusters are kept apart by the p-wave angular momentum barrier.

The recent data for the Θ^+ suggest that the state is so narrow that most experiments can only set an upper bound on its width of ~20 MeV, consistent with experimental resolutions. Recent detailed analysis of the $K-N$

Table 2. Overview of null pentaquark experiments. Of the entries in this list, only the E690 experiment from Fermilab is an exclusive reaction

Expt.	Reaction	Ref.
HERA-B	$p + A$ at 920 GeV, $\sqrt{s}$=41.6 GeV	[19]
BES	$e^+e^- \to \psi(2s)$ or $J/\psi \to \Theta^+\bar{\Theta}^-$; B.R.<$10^{-5}$	[20]
CDF	$p\bar{p}$ at low and high p_t	[21]
BaBar	e^+e^- at $\sqrt{s} = 11$ GeV	[22]
ALEPH,DELPHI,OPAL	$e^+e^- \to Z \to q\bar{q}$ at $\sqrt{s} = 91$ GeV	[22]
FNAL E690	$pp \to pK^-\pi^+\Theta^+$ at 800 GeV; exclusive reaction	[23]
HyperCP	Mixed beam π, K, p at 120-250 GeV	[24]
PHENIX	$d + Au$ at $\sqrt{s} = 200$ GeV $\bar{\Theta}^- \to \bar{n}K^-$	[22]

scattering database indicates that the width of the Θ^+ pentaquark would have to be less than several MeV to have escaped detection [26,27]. On the other hand, the $K-N$ database is quite sparse in this interesting energy range. In fact an important future need is high resolution measurements of the $K^+d \to K^0_s p(p)$ charge-exchange cross section for p_{K^+} in the range of 400-500 MeV/c as a function of the final state $K^0_s p$ mass.

To date two experiments have measured a width that is more than an upper limit. The HERMES experiment has quoted a width for the Θ^+ of 13±9 MeV [10], which is larger than their experimental resolution of 4-6 MeV. The ZEUS experiment measured an intrinsic width for the Θ^+ of 8±4 MeV [11], which is above their experimental resolution of 2 MeV. These widths, however, depend on the assumptions for the background shape.

If the Θ^+ (and the Ξ_5 as well) really is narrow as a few MeV, then the present chiral soliton and quark models will have a difficult time providing a complete dynamical explanation. Another important question regards the Θ^+ production mechanism if its width is indeed ~1 MeV. For photoproduction, the most straightforward calculation of the production mechanism is via t-channel kaon exchange, where the width is related to the coupling constant $g_{K\Theta N}$ and the phase space for production. If the width is 1 MeV, then this diagram is suppressed, although K^* exchange is still possible [28]. Another intriguing possibility is production through a crypto-exotic N^* resonance, first suggested by the CLAS proton data [7]. If this production mode is dominant, then this might provide a natural explanation for some of the null results. However, there are still many more questions than answers and we must await further studies to make progress.

5 Second generation experiments

As noted earlier, nearly all of the pentaquark analysis results obtained to date have resulted from data sets initially acquired for other experiments. In most cases this has resulted in data that are not entirely sufficient to exclude that the observed signals are due to statistical fluctuations, kinematic reflections, or other subtle experimental artifacts. The limited statistics do not permit detailed checks of systematic dependencies.

Table 3. Overview of new pentaquark experiments at CLAS.

Run	Energy	Reactions	Running
g10	3.8 GeV	$\gamma d \to \Theta^+ K^- p$ $\gamma d \to \Theta^+ \Lambda$ $\gamma n \to \Theta^+ K^-$	Completed
g11	4.0 GeV	$\gamma p \to \Theta^+ \bar{K}^0$ $\gamma p \to \Theta^+ K^- \pi^+$	Completed
eg3	5.7 GeV	$\gamma_v p \to \Xi_5^{--} X$ $\gamma_v p \to \Xi_5^{+} X$	Dec. 2004
g12	5.7 GeV	$\gamma p \to \Theta^+ K^- \pi^+$ $\gamma p \to \Theta^+ \bar{K}^0$ $\gamma p \to K^+ K^+ \Xi_5^-$	2005

Given the importance of coming to a definitive conclusion regarding the Θ^+ and other pentaquark baryons, the CLAS experiment at Jefferson Laboratory has dedicated the majority of its beam time in 2004-2005 to focus on providing answers. An overview of the approved experiments is contained in Table 3.

The g10 experiment which took data in the spring of 2004 will focus on Θ^+ production via $\gamma d \to pK^-\Theta^+$, $\gamma d \to K^-\Theta^+$, and $\gamma d \to \Lambda\Theta^+$. The g11 experiment, which completed data taking immediately after the g10 experiment, will focus on the reactions $\gamma p \to \Theta^+\bar{K}^0$ and $\gamma p \to \Theta^+ K^-\pi^+$. Both g10 and g11 will look for Θ^+ decays into nK^+ and pK^0. These experiments have collected more than an order of magnitude more statistics than the existing published CLAS data [5,7]. Both experiments have implemented procedures to reduce the uncertainty in the reconstructed $M(NK)$ mass spectra to the few MeV level, which will be important to study any possible mass differences between the Θ^+ decay modes.

The anti-decuplet of five-quark states within the chiral soliton or quark models contains an isoquartet of Ξ_5 states, two of which are manifestly exotic, the Ξ_5^{--} $(ddss\bar{u})$ and Ξ_5^+ $(uuss\bar{d})$. Evidence for such states has been seen in only one experiment to date [16]. It is imperative to either confirm or refute these data with a high statistics analysis. At CLAS, two new experiments are planning to take data toward this end during the next year.

The eg3 experiment will use an untagged photon beam to study reactions producing Ξ_5^{--} and Ξ_5^{+} pentaquark states by reconstructing the final state from the cascade decay chain. A crucial technique to reduce the combinatoric backgrounds in this experiment is to reconstruct the different detached vertices with CLAS. The second CLAS Ξ_5 experiment is part of the g12 experiment, which will focus on the production reaction instead of the decay process as in eg3. Here the Ξ_5^- will be studied via the missing mass in the reaction $\gamma p \to K^+K^+X$. CLAS has already successfully analyzed the $\Xi(1320)$ ground state with this technique in existing lower energy data.

6 Summary

With roughly equal amounts of positive and null evidence for the exotic Θ^+ and Ξ_5 pentaquarks from a variety of experiments under a broad variety of conditions, one cannot conclude whether these states and other non-*qqq* baryon states exist. Furthermore, the theoretical difficulties in explaining a width perhaps as small as 1 MeV, suggest that if these states do exist, they are very usual. At this point in time the guidance from lattice gauge theory is not particular elucidating as the available calculations come to widely different conclusions. It is clear that the burden to unequivocally prove or disprove the existence of these baryon states is an experimental task. Presently the PDG has listed the Θ^+ as a 3-star resonance, although many feel that this assignment is premature given all of the apparently conflicting data.

At the present time several second generation high statistics detected pentaquark experiments have either completed data taking or are scheduled at various facilities including CLAS. If either or both of the Θ^+ and Ξ_5 pentaquark states can be established experimentally, the new data will allow for significant progress on the development of a detailed program of pentaquark spectroscopy. These data can prove invaluable in establishing the spin, parity, and isospin quantum numbers of these states, as well as providing valuable insight into the associated production mechanisms. It is also essential to study evidence for other spin-orbit partners of these states, as well as evidence for the other non-exotic pentaquarks and to understand how five-quark states couple to and mix with ordinary three-quark states.

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