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SEARCH FOR PENTAQUARKS: THE EXPERIMENTAL PROGRAM AT CLAS*

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Experimental evidences for the existence of exotic 5-quark baryons have been reported recently by several groups. These data may open new perspectives in hadron spectroscopy as well as in QCD. However, the statistical significance of these results is quite low, and the pentaquark signal has not been seen in various other experiments. The new dedicated experiments currently underway at CLAS will hopefully give a clearer answer on the existence and, possibly, on the properties of pentaquarks. This paper summarizes the results obtained so far in the search for 5-quark states and describes the characteristics and goals of the new experiments running at CLAS.

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1. Introduction

Since the first public announcement of the observation of the new state $\Theta^+(1540)$ in the year 2003 [1], the existence of exotic baryons, that have quantum numbers which require a minimum quark content $qqqq\bar{q}$, has excited the hadronic physics community. Although the idea of exotic pentaquark states was introduced originally in the early 70's, the specific predictions for both a mass of 1530 MeV and a narrow width of less than 15 MeV, which motivated the first measurement at LEPS/SPring-8 [1], were made in 1997 by Diakonov *et al.* [2]. Within the framework of their Chiral Soliton Model, they predicted the Θ^+ to be an isosinglet member of a $J = \frac{1}{2}^+$ anti-decuplet of ten pentaquark states (see Fig. 1), three of which having exotic flavour quantum numbers, Θ^+ ($S = 1$), Ξ_5^{--} ($S = -2$, $Q = -2$) and Ξ_5^+ ($S = -2$, $Q = +1$). The other non-exotic members of the anti-decuplet are two N_5^* and three Σ_5 states.

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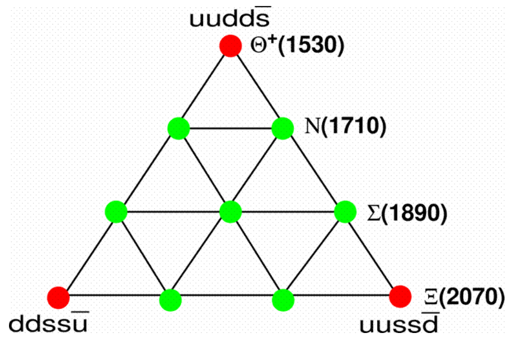

Fig. 1. The pentaquark antidecuplet in the Chiral Soliton Model [2]. At the vertices of the triangle are the three exotic states, Θ^+ ($S=1$), Ξ_5^{--} ($S=-2$, $Q=-2$) and Ξ_5^+ ($S=-2$, $Q=+1$).

2. Published results

Evidence for the Θ^+ state has been claimed in 10 published works (see Table I). As already mentioned, the first observation was reported by the LEPS experiment at SPring-8 [1]. Studying the reaction $\gamma^{12}\mathrm{C} \to K^+K^-X$, after Fermi-motion corrections and cuts applied to select quasi-free production on the neutron, a peak at 1.540 GeV/c^2 was found in the K^- missing mass. The statistical significance was estimated to be 4.6σ (Fig. 2) and an upper limit to the width of 25 MeV was given, fully due to the experimental resolution. This result was followed by the one obtained by the DIANA collaboration [3], that reanalized old data taken with K^+ beam on a xenon bubble chamber, finding a narrow peak ($\Gamma < 9$ MeV) in the K^0p invariant mass spectrum from the charge-exchange reaction $K^+\mathrm{Xe} \to K^0pX$.

TABLE I

Summary of the experimental observations of Θ^+ published at today.

Experiment	Reaction	Decay	M(MeV/c^2)	Γ(MeV)	Sign.
LEPS [1]	$\gamma n(^{12}\mathrm{C}) \to \Theta^+K^-$	nK^+	1540 ± 10	< 25	4.6σ
DIANA [3]	$K^+\mathrm{Xe} \to \Theta^+X$	pK^0	1539 ± 2	< 9	4.4σ
CLAS-d [4]	$\gamma d \to \Theta^+K^-p$	nK^+	1542 ± 5	< 21	5.2σ
CLAS-p [7]	$\gamma p \to \Theta^+K^-\pi^+$	nK^+	$1555 \pm 1 \pm 10$	< 26	7.8σ
SAPHIR [8]	$\gamma p \to \Theta^+K^0$	nK^+	$1540 \pm 4 \pm 2$	< 25	4.8σ
HERMES [9]	$\gamma^*d \to \Theta^+X$	pK^0	$1528 \pm 2.6 \pm 2.1$	17 ± 9	4–6 σ
ITEP [11]	$\nu A \to \Theta^+X$	pK^0	1533 ± 5	< 20	6.7σ
SVD-2 [12]	$pA \to \Theta^+X$	pK^0	1526 ± 3	< 24	5.6σ
COSY-TOF [13]	$pp \to \Theta^+\Sigma^+$	pK^0	1530 ± 5	< 18	4–6 σ
ZEUS [10]	$\gamma p \to \Theta^+X$	pK^0	1522 ± 3	8 ± 4	4.6σ

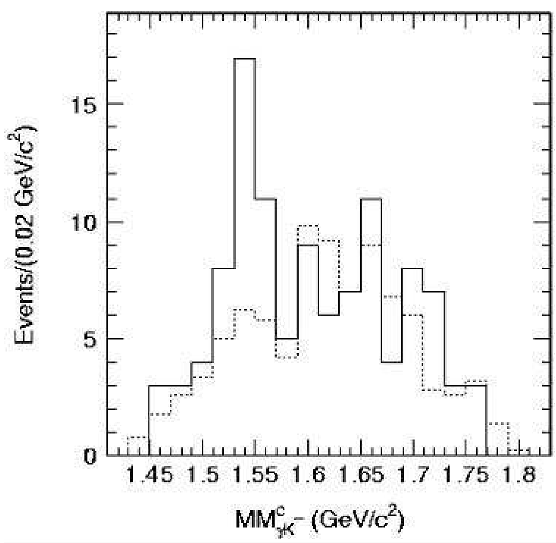

Fig. 2. SPring-8 experiment [1]: K^- missing mass spectrum for the signal sample (solid line) and for events from LH_2 (dashed line).

The first exclusive measurement of photoproduction of Θ^+ was then performed by the CLAS collaboration [4]. Data were taken during the summer of 1999 using tagged photons [5] with a maximum energy of 3 GeV impinging on a 10 cm long liquid-deuterium target. The reaction $\gamma d \to K^- p K^+ n$ was exclusively measured by detecting the three charged particles in CLAS [6] and identifying the proton with the missing-mass technique. In order to be able to detect the spectator proton in CLAS, that has a momentum threshold of 200 MeV/c for detecting protons, a final-state interaction between the scattered K^- and the proton was assumed for the Θ^+ production mechanism. Cuts on the pK^- invariant mass and on the K^+K^- invariant mass were imposed to eliminate the competing reactions of photoproduction of, respectively, $\Lambda(1520)$ and ϕ, leading to the same final state. An additional cut on the neutron momentum ($p_n >$ 80 MeV/c) was applied to remove the events with a spectator neutron. The resulting nK^+ invariant-mass spectrum, shown in Fig. 3, had a peak at a mass of 1.542 ± 0.005 GeV/c^2 with a width of 0.021 GeV/c^2, compatible with the resolution of the detector. After studying the background underneath the peak using a Monte Carlo simulation which takes into account the contribution from three-body (pK^-K^+) and four-body (pK^-K^+n) phase-space kaon photoproduction on the deuteron, the statistical significance of the peak was estimated to be 5.2σ. However, a recent reanalisys of the same data set using a different technique finds that the significance of the peak may not be as large as in the published work.

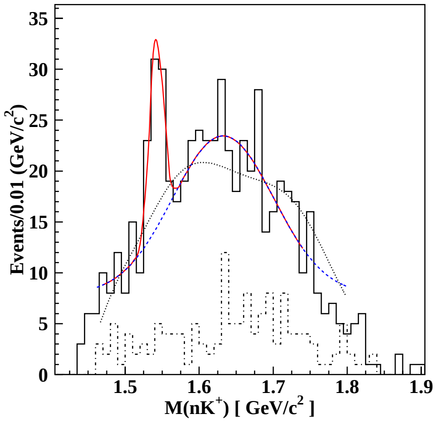

Fig. 3. CLAS-d experiment [4]: invariant mass of nK^+. The dashed–dotted line shows the spectrum of events associated with $\Lambda(1520)$ production. The two fits to the background are done with a gaussian curve (solid line), which has been used to computed the statistical significance, and a curve obtained from Monte Carlo simulations (dotted line).

The other Θ^+ signal observed by the CLAS collaboration [7] was found analyzing data taken in 1999 and 2000 using a 18 cm long hydrogen target and tagged photon beam in the energy range $3.0 < E_\gamma < 5.45$. The reaction measured was $\gamma p \to \pi^+ K^- K^+ n$, and also in this case the exclusivity was ensured by detecting all charged particles and identifying the neutron by its missing mass. After selecting the π^+ t-channel process by applying the cuts $\cos\theta^*_{\pi^+} > 0.8$ and $\cos\theta^*_{K^+} < 0.6$ — $\theta^*_{\pi^+}$ and $\theta^*_{K^+}$ being the angles between the π^+ and the K^+ mesons and the photon beam in the center-of-mass system — a peak appeared in the nK^+ invariant mass spectrum, as can be seen in Fig. 4. The mass of the observed peak is 1.555 ± 0.010 GeV$/c^2$, and its statistical significance is $(7.8 \pm 1.0)\sigma$.

Several other experiments, from medium to high energy, reported observation of Θ^+ signals, using various kinds of beams and targets: in photoproduction on the proton at SAPHIR [8]; in quasi-real photon–deuteron and photon–proton scattering by, respectively, the HERMES [9] and ZEUS [10] collaborations; in neutrino and anti-neutrino collisions with nuclei from bubble-chamber experiments at CERN and Fermilab [11]; in hadron–hadron collisions at SVD-2 [12] and COSY-TOF [13].

As it can be seen in the summary of Table I, the observed Θ^+ masses range from 1.522 to 1.555 GeV$/c^2$, a variation which is much bigger than the experimental errors quoted by the various experiments. The widths, in all cases dominated by the experimental resolutions, are between 10 and 30 MeV.

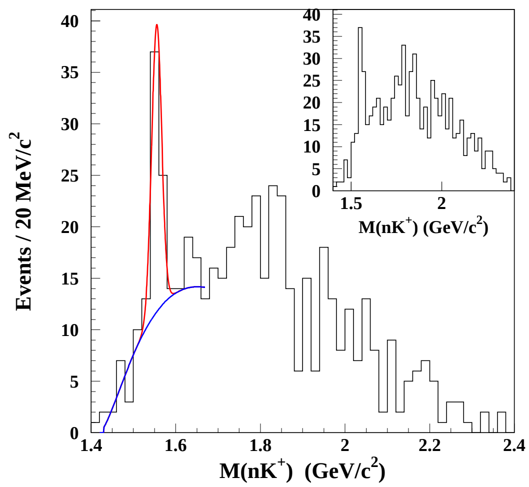

Fig. 4. CLAS-p experiment [7]: invariant mass of nK^+ in the reaction $\gamma p \to \pi^+ K^+ K^- n$, with the cuts $\cos\theta^*_{\pi^+} > 0.8$ and $\cos\theta^*_{K^+} < 0.6$. The background function used for the fit was obtained by Monte Carlo simulation. The insert shows the nK^+ invariant mass spectrum with only the $\cos\theta^*_{\pi^+} > 0.8$ cut.

An observation of other possible 5-quarks states belonging to the anti-decuplet of Fig. 1 came from NA49 [14]. A narrow baryon resonance with mass 1.862 ± 0.002 GeV$/c^2$, width of about 0.018 GeV, and statistical significance of 4σ was found in the invariant mass spectra of $\Xi^-\pi^-$, and a similar enhancement was also seen in the $\overline{\Xi}^+\pi^+$ effective mass (see Fig. 5). This state has been claimed to be a candidate for the Ξ_5^{--} exotic baryon with $S = -2$, $I = \frac{3}{2}$ and quark content $(dsds\bar{u})$. At the same mass a peak was observed also in the $\Xi^-\pi^+$ spectrum, thus a possible non-exotic Ξ_5^0, isospin partner of $\Xi^-\pi^-$, with quark content $(dsus\bar{d})$. However, as of today no other experiment has confirmed these observation.

The small statistical significance of the reported Θ^+ signals — due to the fact that all the results come from the analysis of data taken for other purposes — the discrepancy between the measured masses, and, moreover, the null results reported — but still unpublished — by various high-energy and high-statistics experiments, still leave a question mark on the actual existence of pentaquarks. Solving this issue is fundamental for our understanding of QCD, and therefore it has become central in the experimental program of many facilities. In particular, at Jefferson Lab, a broad experimental program dedicated to the search for pentaquarks has been approved and is currently underway. The CLAS detector has been chosen for this scope, because its large acceptance and its capability of detecting exclusive processes with multi-particle final states with good resolution make it a powerful tool for hadron spectroscopy.

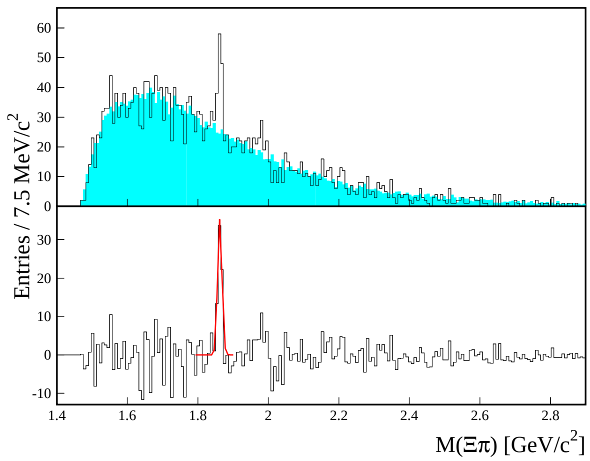

Fig. 5. NA49 experiment [14]: (Top) Sum of the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\overline{\Xi}^+\pi^-$, and $\overline{\Xi}^+\pi^+$. The shaded histogram is a mixed-event background. (Bottom) Background-subtracted spectrum with a Gaussian fit to the peak.

3. Pentaquark program at CLAS

The primary goal of the series of new CLAS experiments (see Table II) dedicated to the search for pentaquark states is to improve the statistical accuracy of the published measurements by at least one order of magnitude. In

TABLE II

Summary of the new CLAS experiments dedicated to the search for exotic baryons.

Experiment	Goal	Target	Running period	E (GeV)
E03-113 (G10) [15]	Θ^+	LD_2	3/13/04-5/16/04	$E_\gamma = 0.8 - 3.6$
E04-021 (G11) [16]	Θ^+,Θ^{+*},Θ^{++}	LH_2	5/22/04-7/25/04	$E_\gamma = 0.8 - 3.8$
E04-010 (EG3) [17]	Ξ_5	LD_2	11/20/04-1/31/05	$E_e = 5.7$
E04-017 (SuperG) [18]	Θ^+,Ξ_5	LH_2	2006	$E_\gamma = 1.5 - 5.4$

the experiment **G10** [15], that ran during spring 2004, tagged photons with energies from 0.8 to 3.59 GeV were impinging on a 24 cm long liquid deuterium target. Two different values for the CLAS torus magnetic field were chosen for the halves of the experiments. The run with lower magnetic field had higher acceptance for negative particles in the forward direction, thus allowing to reproduce the experimental conditions of the LEPS/SPring-8 experiment and measure the inclusive reaction $\gamma d \to K^- X$; the run with high magnetic field had instead the same acceptance and track resolution of the data used for the CLAS published result on the deuteron. An integrated luminosity of 50 pb^{-1} was achieved. An example of the quality of these data can be seen in Fig. 6. In addition to aiming to reproduce and improve the published result on the $\gamma d \to pK^+K^-n$ reaction and the SPring-8 measurement, other channels will be analyzed, such as $\gamma d \to \Lambda K^+ n$, $\gamma d \to \Lambda K^0 p$, and $\gamma d \to pK^0K^-p$.

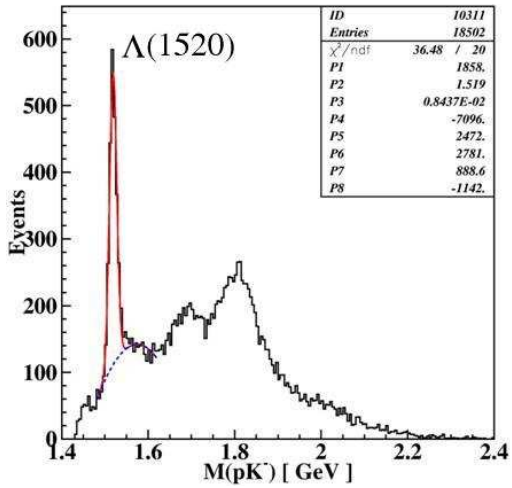

Fig. 6. CLAS G10 experiment [15]: invariant mass of pK^-, showing a peak at the mass of $\Lambda(1520)$. A small subset of the data processed with preliminary calibrations of the detector were used for this plot.

The **G11** [16] experiment, that ran immediately after G10, has taken data until the end of July 2004. Photons in the energy range (0.8–3.8) GeV and a 40 cm long liquid hydrogen target were used. A new start counter was installed around the target to improve particle identification and event trigger. Under these conditions an integrated luminosity of 80 pb^{-1} was obtained. The data are currently being calibrated and processed, and their quality can be checked in Fig. 7. The goal of this experiment is first of all to verify the existence of Θ^+ through the analysis of several different final states, but also to investigate on possible excited states (Θ^{+*}) and isospin partners (Θ^{++}).

The goal of the **EG3** [17] experiment is to measure the production of the cascade (Ξ) pentaquark states, using a 5.7 GeV electron beam incident on a thin deuterium target (0.5 cm long), but without detecting the scattered electron (untagged virtual-photon beam). The cascades will be searched through the decay modes: $\Xi^{--} \to \pi^-\Xi^-$, $\Xi^- \to \pi^0\Xi^-$, $\Xi^- \to \pi^0\Xi^-$. 20 days of running time should give a luminosity of 10 nb, leading to an estimate of 460 Ξ_5^{--} detected. The EG3 experiment took data from the beginning of December 2004 to the end of January 2005.

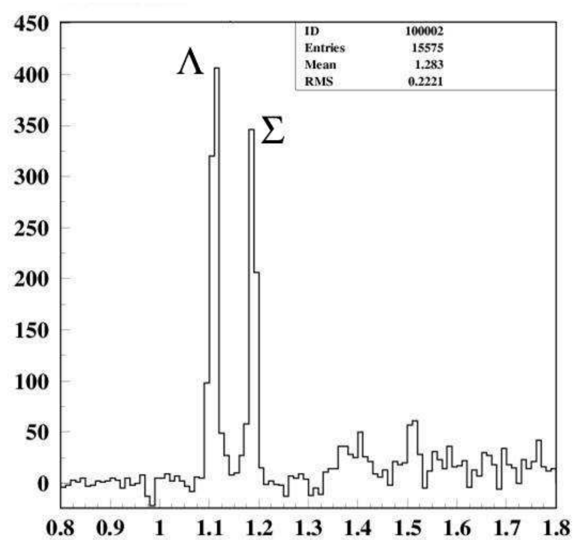

Fig. 7. CLAS G11 experiment [16]: missing mass of K^+, clearly showing peaks at the Λ and Σ masses. A small fraction of the data processed after the first detector calibration pass was used for this plot.

Finally, the **SuperG** [18] experiment aims to perform a comprehensive study of photoproduction of exotic baryons on a proton target, up to photon energies of about 5.5 GeV. Thanks to the wide kinematical coverage for a variety of final states, this experiment will measure spin, decay angular distributions and reaction mechanisms of the produced exotic baryons. The scheduled time for the SuperG run is during the year 2006.

4. Conclusions

The existence of baryon states beyond the classical qqq configuration is one of the open questions in the physics of the strong interactions. Even though such states are not forbidden by QCD, no experimental evidence was found until recently. After the LEPS collaboration reported the first evidence, in 2003, for a narrow baryon state with positive strangeness, named Θ^+, nine other experiments confirmed this result. One experiment reported also the observation of other two pentaquarks, Ξ_5^{--} and Ξ_5^0. However, several reports of non-observation are also coming along. Moreover, the statistical significances of the observed Θ^+ peaks are rather low, and there are discrepancies in the measured masses. The still open question on the existence of five-quarks baryons can therefore be addressed only by performing a second generation of dedicated, high-statistic experiment. CLAS is currently pursuing high-statistic searches for the Θ^+ on hydrogen and deuterium, and in various final states. The experiments are conducted under kinematical conditions similar to the previous measurements. The much higher statistics will allow more definitive conclusions as to the existence of Θ^+ and Ξ_5^{--}.

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