Pentaquark Searches at JLab

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Since LEPS collaboration reported the first evidence for a $S=+1$ baryon resonance in early 2003 with a mass of 1.54 GeV, dubbed Θ^+ , more than ten experiments have confirmed this exotic state, among these two carried out at Jefferson Laboratory. At the same time, there are a number of experiments, mostly at high energies, that report null results.

To try to clarify this situation, during the past year, The CLAS Collaboration at Jefferson Laboratory has undertaken a second generation high-statistics experimental program to search for exotics baryons. Here the preliminary results from these experiments are reported.

1. INTRODUCTION

Experimental evidence for a $S=+1$ baryon resonance has been reported for the first time by the LEPS Collaboration [1]. Immediately after, several other groups found evidence for this exotic baryon in both his decaying channels pK^0 and nK^+ [2] analyzing existing data. The reported masses in some cases vary by more than the uncertainties given for the individual experiments, ranging from 1522 to 1555 MeV, with the masses obtained from processes involving nK^+ signals in the initial or final states giving on average 10–15 MeV higher values than those in the pK^0 channel. The observed widths are comprised between $\sim (10 - 30)$ MeV, but in all cases they are dominated by the experimental resolution.

The relatively small statistical significance in every measurement, possibly explained by the fact that all the results come from the analysis of data taken for other purposes, and the discrepancy in mass determination are not the only problems to face to overcome the reticence to accept the existence of the pentaquark. In fact, a major problem is that several experiments at high statistic and high energies reported negative results in searches for the Θ^+ [3].

To clarify this situation a second generation experimental program has been undertaken at Jefferson Laboratory.

2. EXPERIMENTAL PROGRAM IN HALL B AT JLAB

The superconducting electron accelerator at Jefferson Laboratory delivers simultaneously 100% duty-cycle electron beam to three different experimental Halls A, B and C. The maximum energy is 5.8 GeV and the maximum current is 200 μ A. Hall B is equipped with a tagged photon facility [4] and the CLAS detector [5]. The tagger system is able to tag photons in the energy range $(0.20 - 0.95)E_0$ with an energy resolution of 0.1% E_0 . The CLAS spectrometer is built around six superconducting coils producing a toroidal magnetic field. The coils naturally separate the detector into six sectors each instrumented with 3 sets of multi-wire drift chambers for track reconstruction, one layer of scintillator counters for time-of-flight measurements, Cherenkov counters and electromagnetic calorimeters for particle identification.

The CLAS Collaboration at Jefferson Laboratory has published two papers on the experimental evidence for the Θ^+ , based on the analysis of previously collected CLAS photoproduction data from hydrogen and deuterium. The new dedicated experiments, whose main features are summarized in Table 1, aim to improve the statistical accuracy of the measurements by at least one order of magnitude.

Table 1

Summary table of the new dedicated experiments in Hall B at JLab for the search of exotics baryons.

EXP.	SEARCH	TARGET	RUNNING	E (GeV)
E03-113 [6] (<i>g10</i>)	Θ^+	LD_2	3/13 - 5/16/04	$E_\gamma = 0.8 - 3.6$
E04-021 [7] (<i>g11</i>)	$\Theta^+, \Theta^{+*}, \Theta^{++}$	LH_2	5/22 - 7/25/04	$E_\gamma = 1.6 - 3.8$
E04-010 [8] (<i>eg3</i>)	Ξ_5	LD_2	11/20/04 - 1/31/05	$E_{e^-} = 5.7$
E04-017 [9] (<i>super g</i>)	Θ^+, Ξ_5	LH_2	2006	$E_\gamma = 1.5 - 5.4$

3. PHOTOPRODUCTION OF Θ^+ ON A DEUTERIUM TARGET: *g10* experiment

This experiment ran during spring 2004 using a 24 cm length liquid deuterium target, tagged photons in the energy range (0.8 - 3.59) GeV and with the CLAS torus magnetic field set at 2 different values. The run with lower magnetic field has increased the acceptance for forward ongoing negative particles (which allow us to perform an analysis similar to LEPS for inclusive reactions) while the one with higher magnetic field has the same geometrical acceptance and single track resolution as the published CLAS result on deuterium. Under this conditions an integrated luminosity of 50 pb^{-1} was achieved (roughly shared between the two magnetic field configurations). This value is a factor 20 greater than the published data (from now on we refer to the published result as the *g2a* result).

The first addressed question was whether under similar experimental conditions it would be possible to reproduce the published peak with higher statistics. So the new data events were selected with $E_\gamma < 2.35 \text{ GeV}$ and $E_\gamma < 2.96 \text{ GeV}$ with ratio 2.5 : 1 to match the photon spectrum used in the published result and also the same kinematical cuts in the analysis were applied. In Fig. 1 the published missing mass of the pK^- distribution (points with error bars) is shown together with results from the *g10* analysis (histogram). The *g10* spectrum is scaled by a factor of 0.17, corresponding to the ratio of the final number of events in these distributions. The shapes of these two dis-

tributions are in reasonable agreement. There is a discrepancy in the region of masses 1.54 - 1.55 GeV/c^2 where Θ^+ signal was reported. Statistical analysis, Kolmogorov and χ^2 test, has been applied to these two distributions resulting in statistical compatibility.

Because one of the weak points of all the published results claiming the existence of the Θ^+ is the poor knowledge of the background, the statistical significance of the peak found in the *g2a* data have been re-evaluated using as background function the one used to fit the background of the *g10* missing mass distribution. The *g2a* published spectrum was fit using a sum of a Gaussian function and the polynomial function from *g10* scaled by 5.82. Fit parameters were the number of events in the Gaussian distribution, the mean and the width of the Gaussian function. Within error of the fit the peak position and the width are the same as in the published spectrum. Calculating in the same way as in published data, the statistical significance of the Gaussian peak is 3.6σ in the mass region of $1.54 \text{ GeV}/c^2$. With this we conclude that the quoted high significance of the peak in the *g2a* published data is an unlucky coincidence of the statistical fluctuation and the underestimate of the background.

Since no signal was found, an upper limit for the cross section has been extracted. To do this the *g10* missing mass distribution was fit with a third-order polynomial in the mass range from 1.45 to 1.7 GeV/c^2 . A Gaussian function was added to the polynomial for the final fit. The mean and the width of the Gaussian function were fixed. The

width was taken as $\sigma=0.0065 \text{ GeV}/c^2$ based on the fit to the experimental missing mass distribution of the neutron, $M(pK^+K^-)$, and on the simulated resolution. The only parameter in the fit was the number of events in the Gaussian distribution. These values were then used to evaluate an upper limit at 95% CL using the Feldman and Cousins approach. Finally the upper limit on the yield was transformed into an upper limit on the Θ^+ production cross section for the reaction $\gamma d \rightarrow pK^+K^-(n)$ taking into account the luminosity of incident photons and target, the CLAS detection acceptance (evaluated using a Monte Carlo simulation) and the $\Theta^+ \rightarrow nK^+$ branching ratio. A value of $\sim 400 \text{ pb}$ has been found at $1.526 \text{ GeV}/c^2$. In Fig. 2 the upper limit of the total cross section as a function of the Θ^+ mass for the elementary process $\gamma n \rightarrow K^+K^-n$ is reported. If the Fermi momentum is assumed to be the only source of the energetic spectator proton, the value of the cross section upper limit is $\sim 20 \text{ nb}$ at $1.529 \text{ GeV}/c^2$ (dotted line). This value decrease to $\sim 4 \text{ nb}$ if one assumes a more sophisticated model for an energetic spectator and take the $\Lambda(1520)$ production as a guide (solid line).

Figure 1. The $MM(pK^-)$ distribution for $g10$ (histogram) together with $g2a$ published distribution (points with error bars).

Figure 2. The 95% cross section upper limit for the total cross section as a function of the Θ^+ mass for the elementary process $\gamma n \rightarrow K^-K^+n$. See the text for the explanation of the two curves.

4. PHOTOPRODUCTION OF Θ^+ ON A HYDROGEN TARGET: $g11$ experiment

The $g11$ experiment ran soon after the $g10$ one and finished to take data at the end of July 2004. Data were taken using a 40 cm length liquid hydrogen target and tagged photons in the energy range (1.6 - 3.8) GeV. An integrated luminosity of 70 pb^{-1} was achieved.

The first reaction studied was $\gamma p \rightarrow \bar{K}^0 K^+(n)$, which is not the one published by CLAS on the proton. It was identified by detecting the K^+ and the π^- and π^+ from the decay of the K_s component of the $\bar{K}^0$. The momentum and energy of the neutron were reconstructed as missing mass from the measurement of all the other particles in the event and the known incident photon energy. The reactions which involve the decays of hyperons and which contribute to the same final state were removed with cuts around the known hyperon masses. After all cuts the resulting nK^+ invariant mass distribution is shown in Fig. 3. The spectrum is smooth and structureless and no evidence for a peak or an enhancement is observed at masses near 1540 MeV, where signals associated with the Θ^+ were previously reported.

Since no signal was found, an upper limit for the Θ^+ production cross section was extracted. Also in this case, the nK^+ mass spectrum was fit using a narrow Gaussian function (the θ^+ contribution) with a 5-th order polynomial which parametrizes the background. The position of the gaussian peak was varied from 1520 and 1600 MeV in 5 MeV steps while the width σ was fixed at 3.5 MeV and for each step the corresponding event yield under the peak was extracted. These values were then used to evaluate an upper limit at 95% CL using the Feldman and Cousins approach. Finally the upper limit on the yield was transformed into an upper limit on the Θ^+ production cross section taking into account the luminosity of incident photons and target, the CLAS detection acceptance (evaluated using a Monte Carlo simulation) and the $\bar{K}^0 \rightarrow K_s \rightarrow \pi^+\pi^-$ branching ratio. The upper panel in Fig. 4 shows the upper limit on the total cross section as a function of the Θ^+ mass. As can be seen an upper limit of 0.8 nb was found for $M = 1540$ MeV. The process to extract the yield was repeated for each angular bin to derive the 95% CL upper limit on the $\Theta^+(1540)$ differential cross section $d\sigma/d\cos\theta_{CM}^{\bar{K}^0}$. The result is shown in the lower panel of Fig. 4. The cross section upper limit remains within about 1-2 nb for most of the angular range and rises at forward angles due to the reduced CLAS acceptance. The check of the all adopted procedure was done by extracting the differential and the total cross section for several known reaction from the same data set finding overall good agreement within experimental uncertainties with the existing world measurements.

The found upper limit on the cross section is strongly in disagreement with the value reported by the SAPHIR collaboration (Barth et. al in [2]) which published a total cross section value of 300 nb.

5. CONCLUSION

The preliminary results of the first two experiments at high-statistic and high-resolution of a dedicated program undertaken in the Hall B of Jefferson Laboratory for the search of exotic baryons have been reported. They have been

Figure 3. The nK^+ invariant mass distribution after all cuts. It is narrow and no narrow structures are evident

Figure 4. The 95% cross section upper limit on the total cross section as a function of the Θ^+ mass (top) and on the differential cross section $d\sigma/d\cos\theta_{CM}^{\bar{K}^0}$ (bottom) for the reaction $\gamma p \rightarrow \bar{K}^0 \Theta^+$, for an assumed Θ^+ mass of 1540 MeV. The dotted line in the top plot is to guide the eye.

performed using a deuterium target ($g10$ experiment) and an hydrogen target ($g11$ experiment). None of the experiments found evidence for the exotic Θ^+ baryon.

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