Search for Pentaquark States at CLAS

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After the initial claim of discovery of a possible pentaquark state named $\Theta^+(1540)$, many experiments reported positive and negative results opening a discussion about the existence of such exotic particle. Most of the experimental evidence was obtained from data previously collected for other purposes in many reaction channels and under very different kinematic conditions, so that direct comparison of the results of the different experiments are very difficult. New experiments with high resolution and high statistics are needed to solve the controversy. A comprehensive program to search for pentaquark in photoproduction reaction on proton and deuteron was undertaken at Jefferson Laboratory. These second generation experiments cover the few GeV region where most of the positive evidences were found, collecting more than 10 times the existing statistics. First experiments on proton and deuteron were completed showing no evidence for the $\Theta^+(1540)$ and setting upper limits on the production cross section at the level of few nb.

1. INTRODUCTION

A fundamental issue in hadronic physics is the the possible existence of states beyond the usual qqq and $q\bar{q}$ configuration. In particular search for pentaquarks, i.e. states with minimal $qqqq\bar{q}$ configuration, started several decades ago. The interest in this topic was recently renewed by the prediction by Diakonov and collaborators [1] of a decuplet of such states with relatively low masses (1.5−2.1 GeV) and narrow widths. First evidence for the lower mass pentaquark, an exotic state with positive strangeness named $\Theta^+(1540)$, was reported in 2002 by the LEPS collaboration [2].

After this initial claim, data already collected by several collaboration where analyzed finding both positive results, that confirmed the initial evidence, as well as negative results [3]. The very different kinematic conditions and experimental setups of these experiments make a direct comparison of their results very difficult, leaving therefore an open controversy on whether pentaquarks have been really seen so far.

2. SEARCH FOR PENTAQUARKS AT CLAS

In order to solve the experimental situation, a second generation of dedicated experiments was undertaken at Jefferson Lab with the CLAS detector. These experiments are designed to search for pentaquarks states in photoproduction reactions covering the few GeV region where most of the positive evidences were reported and accumulating at least an order of magnitude more statistics than previous measurements. A first experiment ($g10$) on deuteron target with beam energy in the range 1.0-3.5 GeV was completed in 2004, followed by an experiment on proton target ($g11$) with beam energy in the range $1.6 - 3.8$ GeV. A second run on deuteron target ($eg3$) with beam energy of $4.0 - 5.4$ GeV was completed in 2005, while a second run on proton target ($super - g$) with energies up to 5.7 GeV is planned for the near future. The mass resolutions are of few MeV and the accuracy in the mass determination is of $1 - 2$ MeV, allowing a precise determination of any possible narrow peak in the measured mass spectra.

3. EXPERIMENTAL SETUP

The measurements were performed with the CLAS detector in Hall B [4] using a bremsstrahlung photon beam produced by a continuous electron beam impinging on thin gold foils. The photons, whose energies are determined on event-by-event basis by a tagging system, interact with a liquid hydrogen or deuterium target. Outgoing hadrons were detected by the CLAS spectrometer. The large acceptance of the detector allows the measurement of multi-particle final states. The momentum of charged particles was determined via tracking through three regions of drift chambers immersed in a toroidal magnetic field, with a typical resolution of the order of 0.5-1%. Particle identification was obtained from time-of-flight measurements (TOF), while the photon interaction time was determined by the Start Counter (ST). Coincidences between the photon tagger and CLAS triggered the recording of an event. The CLAS trigger, defined by the coincidences between the TOF and ST system elements, is set to select events with two or more particle tracks. In this way, simultaneous measurement of several different multi-particle final states was possible keeping the same experimental setup.

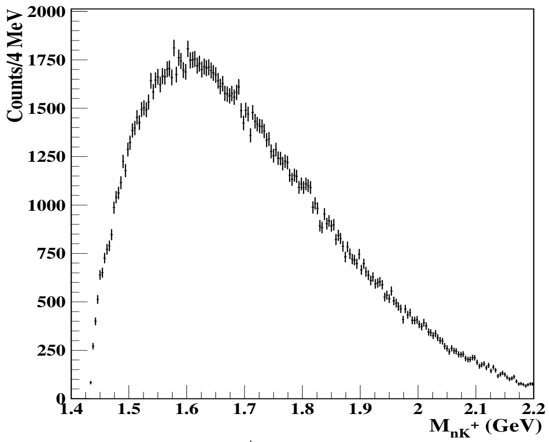

Figure 1. The nK^+ invariant mass spectrum for the reaction $\gamma p \rightarrow \bar{K}^0 K^+ n$. The spectrum is smooth and shows no evidence of a structure or peak that could be associated to the Θ^+ pentaquark.

4. RESULTS ON THE $\Theta^+(1540)$ SEARCH

The first result was obtained from the reaction $\gamma p \rightarrow \bar{K}^0 K^+ n$ searching for evidence of the $\Theta^+ \rightarrow nK^+$ [5]. The K^+ was detected by the spectrometer, the $\bar{K}^0$ was reconstructed via its K_S component decay to $\pi^+\pi^-$ and the neutron was reconstructed with the missing mass technique. After rejection of known hyperons ($\Sigma^\pm$, $\Lambda^*(1520)$) decaying to the same final state a total of 160 000 events were retained. The nK^+ invariant mass spectrum is shown in Fig. 1. The spectrum is smooth and structureless showing no evidence of a structure that could be associated with the $\Theta^+(1540)$. From the analysis of the mass spectrum, an upper limit on the production cross section at the 95% Confidence Level of 0.5-1.2 nb was set in the mass range $1.5 - 1.6$ GeV. This result directly contradicts the SAPHIR experiment [6] that reported a cross section of 50 nb. In the CLAS data $\sim$ 99 000 $\Lambda^*(1520)$ were observed, corresponding to a ratio of the Θ^+ to $\Lambda^*(1520)$ yields of less than 0.22% (95% C.L.).

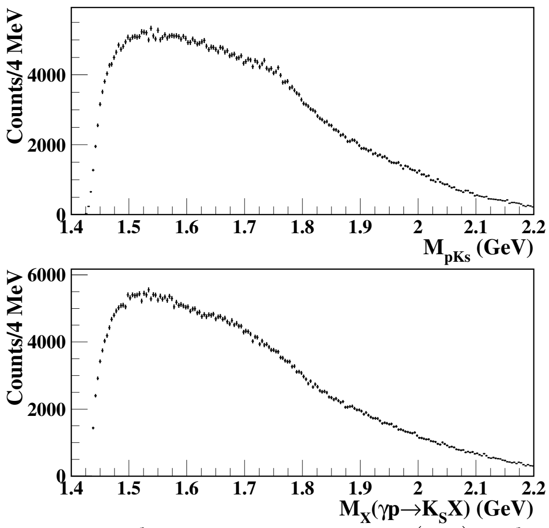

Figure 2. The pK_S invariant mass (top) and K_S missing mass (bottom) for the reaction $\gamma p \rightarrow \bar{K}^0 K^0 p$. Shoulders corresponding to excited Σ states are visible in both spectra.

These results were then confirmed by the analysis of the reaction $\gamma p \rightarrow \bar{K}^0 K^0 p$ where the Θ^+ was searched in the decay to pK^0 [7]. In this case the proton was detected in CLAS and a K_S meson was reconstructed from its $\pi^+\pi^-$ decay. The second neutral kaon was reconstructed via the missing mass technique. After rejection of the reaction $\gamma p \rightarrow p\phi \rightarrow pK_L K_S$ and $\gamma p \rightarrow \Lambda(1116)\pi^+ K^0 \rightarrow p\pi^-\pi^+ K^0$, approximately 550 000 events were obtained. Since the selected final state has two neutral kaons, the Θ^+ peak could appear both in the invariant mass spectrum of the pK_S system as well as in the missing mass spectrum of the K_S. Both spectra are shown in Fig. 2 with no evidence of a narrow peak or enhancement. The combined analysis of the spectra from the reactions $\gamma p \to \bar{K}^0 K^+ n$ and $\gamma p \to \bar{K}^0 K^0 p$ yielded to a final upper limit on the production cross section for the reaction $\gamma p \to \bar{K}^0 \Theta^+$ of 0.7 nb at the 95% Confidence Level.

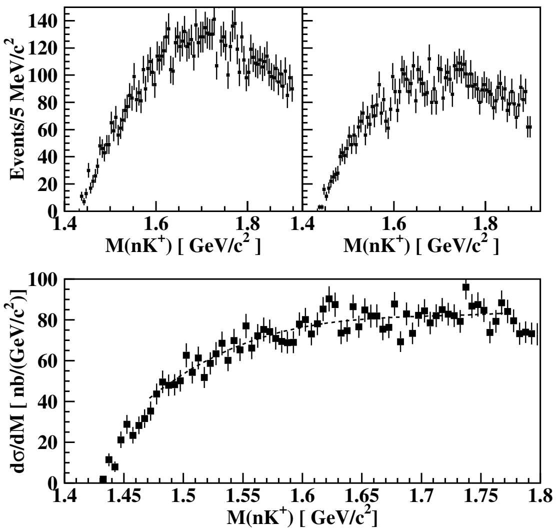

Figure 3. Top: the nK^+ invariant mass spectrum for the reaction $\gamma d \to pK^+K^-(n)$ for two magnetic field settings of the spectrometer. Bottom: cross section for mass bin along with a polynomial fit.

The $g10$ deuteron data set was analyzed searching for the $\Theta^+ \to nK^+$ in the reaction $\gamma d \to pK^-K^+n$ [8] with the aim of verifying the previous CLAS observation of a narrow resonance in the same reaction [9]. The integrated luminosity of the present measurement was more than 30 times larger than the previous experiment. The proton, K^+ and K^- were detected in the spectrometer and the neutron was reconstructed from the overdetermined kinematics. As in the other analyses, contribution from ϕ-meson and $\Lambda^*(1520)$ production were removed to reduce the background. The nK^+ invariant mass spectra obtained with two different magnetic field settings of the spectrometer are shown in the top panels of Fig. 3. The spectra show no indication of a peak or structure. The two spectra were corrected for the detector acceptance and integrated luminosity and them combined obtaining the mass dependent cross section shown in the bottom panel of Fig. 3. The analysis of this spectrum sets an upper limit (95% C.L.) on the $\gamma d \to pK^-\Theta^+$ of 0.3 nb in the mass range $1.52 - 1.56$ GeV. Using an phenomenological approach based on $\Lambda^+(1520)$ production to empirically measure the re-scattering of the proton in the deuteron, this upper limit was converted into an upper limit on the elementary process $\gamma n \to K^-\Theta^+ \to K^-K^+n$ of ~ 3 nb (95% C.L.). These results clearly contradict the previous low statistics data. In order to understand this discrepancy, the new data were analyzed using the same event selection and photon energy range of the previous analysis. The comparison of the two spectra showed that in the previous analysis the background in the signal region was underestimated. The significance of the original structure was determined using a background distribution extracted from the new high statistic run obtaining $\sim 3.1\sigma$ compared to the $(5.2 \pm 0.6)\sigma$ published.

The same data set was also analyzed searching for evidence of the reaction $\gamma d \to \Lambda\Theta^+ \to \Lambda n K^+$ [10]. As for the other reaction channels no evidence for Θ^+ production was observed and upper limits on the total cross section were set between 5 and 25 nb, depending on the production model assumed.

5. SEARCH FOR THE Θ^{++} STATE

The new high statistics CLAS data have been analyzed searching for evidence of other pentaquark states as the Θ^{++}, the isospin partner of the Θ^+, and Ξ^{--}. Results on the Θ^{++} search in the $g11$ data set were recently published [11]. Evidence for the $\Theta^{++} \to pK^+$ was searched in the reaction $\gamma p \to K^-K^+p$. This final state was selected either detecting the three charged particles in CLAS or detecting only the proton and K^+ and reconstructing the K^- via the missing mass technique. The pK^+ invariant mass spectra for these two event topologies are shown in Fig. 4. Both spectra are smooth and show no evidence of narrow structures in the mass range 1.5−2.0 GeV. In the same data set approximately 1 000 000 $\Lambda^*(1520) \to pK^-$ were observed. From the bottom panel of Fig. 4 the 95% Confidence Level upper limit on the total production cross section for the reaction $\gamma p \to K^-\Theta^{++}$ was extracted. This was found to be 0.15 nb on average in the mass range 1.5 − 2.0 GeV, corresponding to $\sigma(\Theta^{++})/\sigma(\Lambda^*(1520)) < 2.3 \times 10^{-4}$ (95% C.L.). This negative result challenges the positive observation recently reported by the STAR Collaboration [12] putting very strong limits on the possible production of an isovector pentaquark.

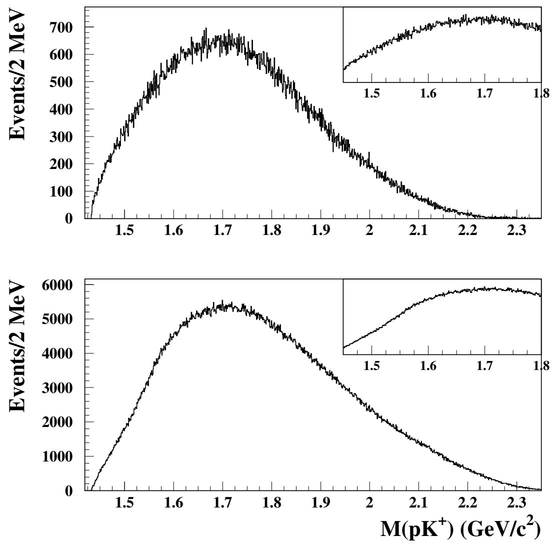

Figure 4. The pK^+ invariant mass spectrum for the reaction $\gamma p \to K^-K^+p$ when all three final state particles are detected (top) or when only the proton and K^+ are detected (bottom). The insets show an enlargement of the mass region of the previously reported Θ^+.

6. CONCLUSIONS

A comprehensive physics program to search for evidence of pentaquark states in photoproduction reaction is in progress at Jefferson Lab with the CLAS detector. These new experiment were explicitly designed to provide high statistics and high resolution data in the few GeV energy region were positive evidence for pentaquark states was reported. The analyses of several reaction channels on proton and deuteron show no evidence of the Θ^+ pentaquarks setting upper limits on the total production cross section at the few nb level. Search for the isovector Θ^{++} pentaquark on proton target also yields a null result. Further searches for pentaquark states in other reaction channels and in wider kinematic range are planned in the near future. These include the search for $\gamma p \to K^+\pi^-\Theta^+$, $\gamma p \to K^*\Theta^+$, and $\gamma d \to K^+K^+p\Xi^{--}$ up to a maximum photon energy of 5.7 GeV. These new analyses together with the results presented above could clear up the debate on the pentaquark existence.

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