Evidence for an Exotic Baryon State, $\Theta^+(1540)$, in Photoproduction Reactions from Protons and Deuterons with CLAS

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Talk at CIPANP 2003, New York, May 19-24, 2003

Abstract

CLAS photoproduction data on deuterium and hydrogen targets have been analyzed in a search for an exotic baryon state with strangeness $S = +1$, the $\Theta^+$ (originally named the $Z^+$). This resonance was predicted recently in theoretical work based on the chiral soliton model as a lowest mass member of an anti-decuplet of 5-quark states. The reaction $\gamma d \rightarrow p K^- K^+ n$, which requires a final state interaction inside the deuteron, was used in the analysis of deuteron data. In the analysis of proton data, the reaction $\gamma p \rightarrow \pi^+ K^- K^+ n$ was studied. Evidence for the $\Theta^+$ state is found in both analyses in the invariant mass distribution of the $nK^+$. Our results are consistent with previously reported results by LEPS/Spring-8 collaboration (Japan), and by the ITEP (Moscow) group.

1 Introduction

Pentaquark resonances have been predicted decades ago and there have been experimental searches for many years. However, no significant signal was found in the early work. Recent theoretical work based on the chiral soliton model [1] made more quantitative predictions for the masses and widths of a spin $s = 1/2$ anti-decuplet of 5-quark states ($qqqq\bar{q}$). Using the $P_{11}(1710)$ resonance as the “anchor” for the masses of the anti-decuplet, the lowest lying member, $\Theta^+$, is predicted to have a mass $1530$ MeV$/c^2$ and a width of $\sim 10$ MeV$/c^2$. It is predicted to be an exotic baryon state with strangeness $S = +1$, and $I = 0$.

The LEPS collaboration at the SPring-8 facility in Japan recently reported [2] the observation of an $S = +1$ baryon at $1.54$ GeV$/c^2$ with a width of $< 25$ MeV$/c^2$ from the reaction $\gamma n \rightarrow K^- K^+ n$ where the target neutron is bound in carbon, and the residual nucleus is assumed to be a spectator. This measurement reported a statistical significance of $4.6 \pm 1.0 \sigma$. Also, the DIANA collaboration at ITEP [3] recently announced results from an analysis of bubble-chamber data for the reaction $K^+ n \rightarrow K^0 p$, where the neutron is bound in a xenon nucleus, which shows a narrow peak at $1539 \pm 2$ MeV$/c^2$. The statistical significance of the ITEP result is $4.4 \sigma$. 

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The data presented here were taken at the Thomas Jefferson National Accelerator Facility with the CLAS detector [5] and the photon tagging system [6] in Hall B. Data from two experiments have been used in these analyses: i) photoproduction on deuterium using tagged photons produced by 2.474 and 3.115 GeV electrons; and ii) photoproduction on protons using tagged photons produced by 4.1 and 5.5 GeV electrons. The exclusive reaction $\gamma d \rightarrow pK^-K^+(n)$ was studied in the analysis of the deuteron data. A peak in the invariant mass distribution of $nK^+$ was found at 1.542 GeV/$c^2$ with a width of 21 MeV/$c^2$ and the statistical significance $5.3 \pm 0.5 \sigma$. The reaction $\gamma p \rightarrow \pi^+K^-K^+(n)$ was studied using the hydrogen data. A peak at 1.537 GeV/$c^2$ with a width of 31 MeV/$c^2$ in the invariant mass distribution of $nK^+$ was found in this reaction as well. The statistical significance of this peak is $4.8 \pm 0.4\sigma$.

2 Photoproduction on deuterium

In the photoproduction on deuterium the $\Theta^+$ can be produced directly on the neutron in the reaction $\gamma n \rightarrow \Theta^+K^-$, similar to the reaction mechanism used by the LEPS collaboration. While the proton is a spectator in the direct production reaction and will not be detected in most cases, there are other ways to excite the $\Theta^+$. Due to the final state interactions the proton can obtain high momentum and be detected. Fig.1 shows rescattering diagrams that may contribute to the production of the $\Theta^+$ in the photoproduction on deuterium. For identification of such reactions the $p$, $K^+$, and $K^-$ are detected, and the neutron is identified in the missing mass analysis. Although these reactions have a smaller cross section compared to the direct production because of an additional rescattering, they have the following advantages: i) the $K^-$'s that are produced predominantly in the forward direction in the direct production mechanism will scatter at larger angles and will have higher probability of detection in CLAS; ii) the kinematics of such exclusive reactions puts additional constraints on the event selection that help to clean up the event sample significantly, and iii) due to the exclusive kinematics no Fermi momentum corrections are needed for the correct calculation of $M(nK^+)$. 

![Rescattering Diagrams](image)

Figure 1: Rescattering diagrams that can contribute to the production of the $\Theta^+$ in the exclusive reaction.

The analysis focused on events with one detected proton, $K^+$ and $K^-$ (and no other charged particles) in the final state. Either the $K^+$ or the $K^-$ in the event was required to have a time at the interaction vertex within 1.5 nsec of the proton's vertex time. Also, the incident photon time at the interaction vertex was required to be within 1.0 nsec of the proton to eliminate
accidental coincidences. The missing mass ($MM$) distribution of selected events with the $pK^+K^-$ final state is shown in Fig. 2, where a clear peak at the neutron mass is seen. For further analysis events within ±3σ of the neutron peak were kept. Background contributions due to particle misidentification are estimated at about ∼15%. The inset in Fig. 2 shows the $MM$ distribution of events with a tighter cut on the vertex time for kaons. Both kaons were required to be within 0.75 nsec of the proton vertex time. Practically no background remains under the neutron peak in this case.

There are several known reactions, such as photoproduction of mesons (that decay into $K\bar{K}$) or excited hyperons (that decay into a $pK^-$ or $nK^-$), that contribute to the same final state. The $\phi$ meson at $M(K^+K^-) = 1.02$ GeV/$c^2$, and the Λ(1520) at $M(pK^-) = 1.518$ GeV/$c^2$ are cleanly seen in our event sample. Events from these resonances have been removed from the final sample.

Two other event selection requirements are applied, based on kinematics. First, the missing momentum of the undetected neutron must be greater than 80 MeV/c. For momenta below this value, the neutron is likely a spectator to other reaction mechanisms. Our studies show that increasing the value of this cutoff does not change the final results – in particular it does not eliminate the peak shown below – but does reduce the statistics in the $M(nK^+)$ spectrum. Second, events with $K^+$ momentum greater than 1.0 GeV/c were removed. This cutoff is based on Monte Carlo simulations of the $\Theta^+$ decay from an event distribution uniform in phase space, which show that the $K^+$ momentum rarely exceeds 1.0 GeV/c. The data also show that $K^+$ momenta greater than 1.0 GeV/c are associated with an invariant mass of the $nK^+$ system, $M(nK^+)$, above 1.7 GeV/$c^2$. The second requirement reduces this background.

The final $M(nK^+)$ spectrum is shown in Fig. 3 along with a fit to the peak at 1.542 GeV/$c^2$ and a Gaussian plus constant term fit to the background. The panel on the left shows the distribution for all selected events. The spectrum of events removed by the Λ(1520) cut
photoproduction on the proton

3 Photoproduction on the proton

In this analysis the reaction $\gamma p \to \pi^+ K^- K^+ n$ was studied. Possible diagrams contributing to the photoproduction of the $\Theta^+$ from the proton are presented in Fig. 4. An estimate of the cross section for $\Theta^+$ production in the reaction $\gamma p \to K^*0 \Theta^+$ was made by M. Polyakov [7]. The $d\sigma/d\cos\theta_{cm}$ distribution ($\theta_{cm}$ is the angle between the $\pi^+ K^-$ momentum and photon beam in the center of mass system) peaks in the forward direction (small $t$ region), as expected for the $t$-channel exchange mechanism (see Fig. 4). About 80% of the events lie in the region with $\cos\theta_{cm} > 0.5$ (for a photon energy at 4 GeV), which appears to be a natural cut for the extraction of the $\Theta^+$ signal from a proton target. This important feature of the cross section can be used for the signal selection and the background reduction in photoproduction reactions.

The reaction $\gamma p \to \pi^+ K^- K^+ n$ was studied at Jefferson Lab with photon energy from 3 to 5.25 GeV using an energy tagged photon beam. The final state particles, $\pi^+$, $K^-$ and $K^+$, were detected in the CLAS detector [5], and the neutron was identified using the missing mass
technique. There are 13.6K events, each having a positive pion and two kaons of opposite sign in the final state, which were selected for the analysis of the reaction $\gamma p \rightarrow \pi^+ K^- K^+ n$. The missing mass distribution for the reaction $\gamma p \rightarrow \pi^+ K^- K^+ X$ is shown in Fig. 5. A neutron peak is clearly seen in this distribution. There is a 27% background under the peak. The arrows indicate the $\pm 3\sigma$ cut for the neutron selection.

There are about 40 $\phi$ mesons in the selected sample. A cut on the $M_{K^+ K^-}$ invariant mass with $M_{K^+ K^-} > 1.040$ GeV/$c^2$ was applied to remove $\phi$ mesons. The $M_{nK^+}$ invariant mass spectrum of the remaining 3699 events is presented in Fig. 6.

To suppress background and extract the signal for the $\Theta^+$ photoproduction, we used the general properties of the production mechanism of $\Theta^+$ from a proton target (see Fig. 4). In the tree diagrams the $K^- \pi^+$ system moves along the photon beam in the center of mass system and $nK^+$ moves in the opposite direction. In order to select the $t$-channel process illustrated in Fig. 4 only events with $\cos\theta_{cm} > 0.5$ were taken for further analysis. Since we want to retain
both the resonance $K^{*0}$ production and non-resonance $K^-\pi^+$ continuum no cuts on $M_{K^-\pi^+}$ were applied.

Fig. 6 (the right panel) presents the $nK^+$ invariant mass spectrum of the events with $\cos \theta_{cm} > 0.5$. This distribution was fitted by a Gaussian function and a smooth background. As suggested by data from this experiment the shape of the $nK^+$ invariant mass distribution in the reaction $\gamma p \to \pi^+K^-K^+n$ does not change significantly as a function of the $\theta_{cm}$ angle. For this reason the shape of the background was obtained from the full data set of the events (left panel in Fig. 6). The resulting fit yields 27 counts in the peak with the mass $M = 1.54$ GeV/c$^2$ and width $FWHM = 32$ MeV/c$^2$. The mass scale uncertainty is estimated as $\pm 10$ MeV/c$^2$. This uncertainty is mainly due to the energy calibration of the CLAS detector and the electron accelerator. The statistical significance of this peak is $4.8 \pm 0.4 \sigma$ calculated over a window of 80 MeV/c$^2$. The mass resolution is close to the experimental resolution of CLAS.

As a check, a side band subtraction was carried out using events from the neutron peak ($\pm 3\sigma$) and background events left and right of the neutron peak. No resonance structures were found in the side band distribution and the peak parameters of the fit did not change after the side band subtraction.

4 Summary

Analyses of CLAS photoproduction data firmly establish the existence of a narrow $S = +1$ exotic baryon in the $nK^+$ system with a mass approximately at 1.54 GeV/c$^2$. The statistical significance of the peak in the invariant mass distribution of the $nK^+$ is $4.8\sigma$ for the analysis of the reaction $\gamma p \to \pi^+K^-K^+n$, and is $5.3\sigma$ for the analysis of the reaction $\gamma d \to pK^-K^+n$. These results are consistent with the $S = +1$ state reported by LEPS and DIANA collaborations, and with the 5-quark ($uudd\bar{s}$) baryon predicted in the chiral soliton model.
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