Search for the Θ^+ Pentaquark in the Reaction $\gamma d \rightarrow p K^0 \bar{K}^0(p)$ with CLAS

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Abstract. A search for photo-production of the $\Theta^+(1540)$ pentaquark and its decay to $p K^0$ was performed with the CLAS detector system at Jefferson Lab. In the exclusive channel $\gamma d \rightarrow p K^0 \bar{K}^0(p)$, about twenty-thousand events with a slow missing proton, $\pi^+ \pi^-$ decay of the neutral kaon, and photon energy between 1.6 and 3.6 GeV are fully reconstructed. Included are numerous hyperon and meson resonances, with their decays to $p K^-$ and $K^0 \bar{K}^-$ respectively. To understand the possibility of a pentaquark signal amidst the backgrounds, a phenomenological isobar-inspired model of complex Breit-Wigner amplitudes and decay angular distributions for the resonances is fit to the data with a maximum likelihood method. No pentaquark signal is found above the background. The upper limit on the total production cross section is measured to be consistent with other channels published by the collaboration, but systematic studies are still in progress.

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INTRODUCTION

The naïve constituent quark model, with only three-quark and quark-anti-quark states, has been remarkably successful in describing the mass spectra of well-known baryons and mesons. The additional interactions of quantum chromodynamics predict additional states, some of which cannot be described by the simple quark model. The search for these exotic states is a useful tool in testing our understanding of nature as described by the theories. One possible exotic baryon is the Θ^+ pentaquark, which, with a strangeness quantum number of +1, would require at least four quarks and one anti-quark. With a mass of about 1540 MeV/c², it is the lightest member of an anti-decuplet group of pentaquark states as predicted by the chiral soliton¹ and di-quark² models. Positive experimental evidence was first reported in 2003 by the LEPS collaboration³. Since then, numerous searches worldwide have been performed⁴, relating negative results to positive sightings is not simple due to largely varying production mechanisms, energy regimes, and detector acceptance.

EXPERIMENT

Hall-B at Jefferson Lab is a prime facility at which to search for pentaquarks. The large angular and kinematic coverage of the CLAS detector allows for exclusive

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measurement of numerous production and decay modes simultaneously. In 2004, the CLAS collaboration performed two experiments designed for investigation of the Θ^+ . The G10 experiment ran for two months, accumulating almost 50 pb^{-1} of data describing interactions between a tagged bremsstrahlung photon beam and 24 cm liquid deuterium target. Data were taken at two different strengths of the main toroidal magnetic field of the spectrometer. With the ability to reconstruct multi-particle final states and beam energies from threshold up to 3.6 GeV, numerous channels can be measured across a large range of kinematics. The results of two searches for the $n\bar{K}^+$ decay mode of the Θ^+ have already been published from this data set: the $\gamma d \rightarrow p\bar{K}^+K^-n^5$ and $\gamma d \rightarrow \Lambda n\bar{K}^+K^0$ channels. With 95% confidence level upper limits on the production cross section of 3 and 25 nb respectively, neither found evidence for a pentaquark. The G11 experiment immediately followed with a hydrogen target and found no evidence either, reporting a combined upper limit of 0.7 nb for the reactions $\gamma p \rightarrow p\bar{K}^0K^0$ and $\gamma p \rightarrow n\bar{K}^+K^0$ when looking for the $\Theta^+ \rightarrow p\bar{K}^0$ and $\Theta^+ \rightarrow n\bar{K}^+$ decays⁷. CLAS has also published a null search for the Θ^{++} from the same data⁸.

We analyzed the reaction $\gamma d \rightarrow p\bar{K}^+K^0(p)$ for evidence of the Θ^+ decaying to $p\bar{K}^0$ after production off a quasi-free neutron. This channel is particularly advantageous. For one, the four-momentum of the proton, K^- , and $\pi^+\pi^-$ (decayed from the K_s^0) are measured with drift chambers and time-of-flight detectors. This leaves only the slow “spectator” proton undetected and enables the channel to be exclusively reconstructed without requiring a final state interaction to enhance the detector acceptance for such a slow track. Also, the exotic, positive strangeness of the baryonic $p\bar{K}^0$ system is well defined by detection of the charged kaon and strangeness conservation. After selecting events with only four, well-identified $p\bar{K}^+\pi^+\pi^-$ tracks, a kinematic fit constrains the missing proton and K_s^0 masses and requires conservation of energy and momentum between initial and final states.

BACKGROUND ANALYSIS

Various intermediate states are possible in the $\gamma d \rightarrow p\bar{K}^+K^0(p)$ reaction, and understanding their contributions is important when searching for an unconfirmed resonance. It has been suggested that some published exotic sightings are actually reflections produced by combinations of kinematic constraints imposed in the analysis⁹. A variety of resonant backgrounds are present in our data set, the most prominent being the $\Lambda(1520)$, decaying to $p\bar{K}^-$ in an $l=2$ state of angular momentum. Due to its narrow width and a mass close to the minimum allowed by its daughters, it can easily be removed from the data. However, many more massive Λ and Σ states with four-star PDG particle listings are visible (Figure 1). Also present is evidence of mesons decaying to the $K\bar{K}^0$ system, including the $a_2(1320)$ and sub-threshold $a_0(980)$. Unfortunately, it is impossible to efficiently remove any significant amount of the broader, overlapping backgrounds.

FIGURE 1. The production of hyperons can proceed through the reaction $\gamma d \rightarrow Y^* K^0(p)$ and is a prominent source of background. The invariant mass-squared (left), showing a narrow peak for $\Lambda(1520)$ and broad, higher mass states, and momentum transfer to the pK^- system (right) are kinematic variables included in the model (red line). The vertical axis is normalized yield.

To understand these contributions, a simple multi-dimensional model is developed and fit to the data with an un-binned maximum-likelihood method. The probability for the reaction is described as the sum of the complex amplitudes of each resonant process, and the relevant variables are invariant mass, momentum transfer, and daughter decay angle for the pK^- and $K^0 K^-$ systems. A single resonance's amplitude is defined to be the product of a complex relativistic Breit-Wigner mass distribution, a spherical harmonic for the decay angular distribution in the helicity rest frame, and an exponentially decaying t -channel weighting. An additional factor is introduced to distribute the momentum of the target neutron inside the deuteron according to the Bonn potential. To account for energy dependence of the resonant cross-sections, the data is divided into five photon energy bins, and each bin is fitted with the model independently. The mass and width parameters for each resonance are chosen according to the PDG¹⁰, and their relative normalizations and phases are allowed to vary. After fitting the free parameters to the data, the model becomes a source of events for detector acceptance and resolution studies and a background distribution with which to estimate the existence of the Θ^+ .

RESULTS, CONCLUSIONS

A pentaquark signal should exhibit itself in the invariant mass spectrum of the pK^0 system, as shown in Figure 2 and overlayed with the background model description. No obvious sign exists in any mass region. Only the portion of the data with the lower torus field setting is shown, due to its larger statistics. The upper limit on its cross-section is estimated by holding the background shape fixed while scanning the centroid of a Gaussian with the width of the experimental resolution across the mass spectrum and finding the strength of the Gaussian that minimizes the χ^2 . The yield in the hypothetical peak and its uncertainty will be interpreted via standard statistical techniques of Feldman and Cousins¹¹. The resulting preliminary upper limit on the cross section of $\gamma d \rightarrow \Theta^+ K^-(p)$ is measured to be consistent with analyses of the other channels published by the CLAS Collaboration, but systematic studies are still in progress.

FIGURE 2. The total cross section [nb/5.5 MeV/c²] for the reaction $\gamma d \rightarrow p K^0 K^-(p)$ as a function of the invariant mass of the $p K^0$ system. Five photon energy ranges, as well as the full spectrum (bottom right), are shown. The model description is indicated by the black line.

In this search for the Θ^+ , a good understanding of the background shape is achieved with a systematic fitting approach to model the data. No evidence for the pentaquark is found, and the quantitative results will be published in the near future. The value of the upper limit on the production cross-section of a Θ^+ is sensitive to the assumed background shape, and preliminary results are in agreement with already published analyses.

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