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# Observation of an exotic S = +1 baryon in exclusive photoproduction from the deuteron

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# Observation of an Exotic $S = +1$ Baryon in Exclusive Photoproduction from the Deuteron

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In an exclusive measurement of the reaction $\gamma d \rightarrow K^+K^-pn$, a narrow peak that can be attributed to an exotic baryon with strangeness $S = +1$ is seen in the $K^+n$ invariant mass spectrum. The peak is at $1.542 \pm 0.005$ GeV/$c^2$ with a measured width of 0.021 GeV/$c^2$ FWHM, which is largely determined by experimental mass resolution. The statistical significance of the peak is $(5.2 \pm 0.6)\sigma$. The mass and width of the observed peak are consistent with recent reports of a narrow $S = +1$ baryon by other experimental groups.

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High-energy neutrino and antineutrino scattering experiments [1] have established that sea quarks ($q\bar{q}$ pairs) are part of the ground-state wave function of the nucleon. In addition, results from pion electroproduction experiments in the $\Delta$-resonance region, together with other experiments, have shown [2] the presence of a pion "cloud" surrounding the valence quarks of the nucleon. In this sense, five-quark ($qqqq\bar{q}$) configurations are mixed with the standard three-quark valence configuration. However, it is natural to ask whether a five-quark configuration exists where the $\bar{q}$ has a different flavor than (and hence cannot annihilate with) the other four quarks. Such states are not forbidden by QCD [3,4], and definite evidence of pentaquark states would be an important addition to our understanding of QCD. In fact, the question of which color singlet configurations exist in nature lies at the heart of nonperturbative QCD. A baryon with the exotic strangeness quantum number $S = +1$ is a natural candidate for a pentaquark state.

The general idea of a five-quark state has been around since the late 1960s [5]. Recently, symmetries within the chiral soliton model were used by Diakonov, Petrov, and Polyakov [6] to predict an antidecuplet of five-quark resonances with spin and parity $J^\pi = \frac{1}{2}^+$. The lowest mass member, an isosinglet with valence quark configuration $uudd\bar{s}$ giving strangeness $S = +1$ (originally called the $Z^+$ but now renamed as the $\Theta^+$ [7]), has a predicted mass of approximately 1.53 GeV/$c^2$ and a width of ~0.015 GeV/$c^2$. The narrow width, similar to that of the $\Lambda(1520)$ baryon resonance with strangeness $S = -1$, is largely constrained by symmetries of the coupling constants and the phase space of the decay to a $KN$ final state.

The existence of the $\Theta^+$ has been suggested by several recent experiments. The LEPS Collaboration at the SPring-8 facility in Japan recently reported [8] the observation of an $S = +1$ baryon at 1.54 GeV/$c^2$ with a FWHM less than 0.025 GeV/$c^2$ from the inclusive reaction $\gamma n \rightarrow K^-(K^+X)$ 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 [9] recently announced results from an analysis of bubble-chamber data for the reaction $K^+n \rightarrow K^0p$, where the neutron is bound in a xenon nucleus, which shows a narrow peak at $1.539 \pm 0.002$ GeV/$c^2$. The statistical significance of the ITEP result is $4.4\sigma$.

One might wonder how an $(nK^+)$ resonance could have evaded earlier searches. The Particle Data Group has summarized these searches most recently in 1986 [5] saying that the results permit no definite conclusion for an $S = +1$ resonance. A more recent phase shift analysis for $K^+N$ scattering by Hyslop *et al.* [10] finds weak resonance behavior in the $P_{01}$, $D_{03}$, $P_{13}$, and $D_{15}$ partial waves, but none of these "resonancelike structures" (in the words of Ref. [10]) have convincing phase motion. We note that the $K^+n$ database is sparse for low-energy $K^+$ beams, and a narrow resonance could have escaped detection [11].

The present experiment is an exclusive measurement on deuterium for the reaction $\gamma d \rightarrow K^+K^-p(n)$ where the final state neutron is reconstructed from the missing momentum and energy. The data presented here were taken at the Thomas Jefferson National Accelerator Facility with the CLAS detector [12] and the photon tagging system [13] in Hall B. Photon beams were produced by 2.474 and

3.115 GeV electrons incident on a bremsstrahlung radiator of thickness $10^{-4}$ radiation lengths, giving a tagged photon flux of approximately $4 \times 10^6$ $\gamma$'s per second. The maximum tagged photon energy was 95% of the electron beam energy. The integrated tagged photon flux above 1.51 GeV was $1.64 \times 10^{12}$ at 2.474 GeV and $0.70 \times 10^{12}$ at 3.115 GeV. The tagged photon energy is measured with a resolution of between 0.003 and 0.005 GeV, depending on the energy. The photons struck a liquid-deuterium target of thickness 10 cm.

The event trigger was formed when a charged particle hit two scintillator planes [the "start counter" around the target and a "time-of-flight" (TOF) counter a few meters away], in coincidence with an electron detected in the tagging system. The particle identification was performed using the reconstructed momentum and charge from tracking, together with the measured TOF. The analysis focused on events with a 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 ns of the proton's vertex time. Also, the incident photon time at the interaction vertex was required to be within 1.0 ns of the proton (to eliminate accidental coincidences). The missing mass ($MM$) of the selected events is plotted in Fig. 1, which shows a peak at the neutron mass on top of a small background. A fit to the distribution (solid line) yields a mass resolution of $\sigma = 0.009$ GeV$/c^2$.

The reaction $\gamma d \rightarrow K^+ K^- p(n)$ selects the $\Theta^+$ decays to the $K^+ n$ final state. It is likely that production of the $\Theta^+$ in this final state proceeds on the neutron via $t$-channel $K^+$ exchange, similar to the production of the $\Lambda(1520)$ on the proton, where the dominant mechanism is $t$-channel $K^-$ exchange [14]. If the proton is a spectator during $\Theta^+$ production, it will not be seen in our detector due to its small momentum [15]. However, in some fraction of events, the $K^-$ and the proton may be involved in the final state interaction, as shown in Fig. 2. While the production of the $\Theta^+$ does not require a rescattering, such events increase the probability of detecting the $K^-$'s and the protons in the final state by rescattering them into the acceptance region of CLAS. By requiring an exclusive process, we are able to fully reconstruct the unobserved neutron, which aids significantly in reducing background. Another advantage of this exclusive measurement is that no corrections for the Fermi momentum of the neutron are needed, so the width of the neutron peak in Fig. 1 is limited only by the resolution of the CLAS detector system. Events within $\pm 3\sigma$ of the neutron peak were kept for further analysis. The background in this region is about 15% of the total, mostly from pions that are misidentified as kaons.

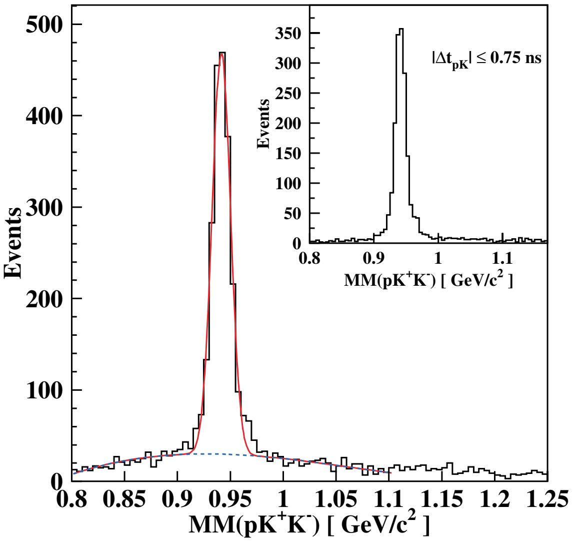

FIG. 1 (color). Missing mass spectrum for the $\gamma d \rightarrow pK^+K^-X$ reaction, after timing cuts to identify the charged particles and the coincident photon, which shows a peak at the neutron mass. There is a small, broad background from misidentified particles and other sources. The inset shows the neutron peak with a tighter requirement on the timing between the proton and kaons.

There are several known reactions, such as photoproduction of mesons (that decay into $K\bar{K}$) or excited hyperons (that decay into $pK^-$), that contribute to the same final state. We now discuss the explicit cuts we have made to remove the main background sources from our final event sample in order to enhance our signal relative to background. The $\phi$ meson at 1.02 GeV$/c^2$, which decays into a $K^+$ and $K^-$, is produced primarily at forward angles [16]. These events are easily identified using the invariant mass of the $K^+K^-$ pair, $M(K^+K^-)$, as shown in Fig. 3 (top). In order to remove the $\phi$ mesons, events with $M(K^+K^-) < 1.07$ GeV$/c^2$ are rejected.

Similarly, the $\Lambda(1520)$ resonance can be produced by the $\gamma p \rightarrow K^+\Lambda$ reaction with a subsequent decay of the $\Lambda$ to a proton and $K^-$. A peak corresponding to the $\Lambda(1520)$ is seen in the invariant mass spectrum of the $pK^-$ system, $M(pK^-)$, as shown in Fig. 3 (bottom). Unlike $\phi$ mesons, $\Lambda(1520)$'s can be produced in conjunction with $\Theta^+$'s and still conserve net strangeness. However, even though there is a large cross section for producing $\Lambda(1520)K^+$ on the proton followed by $K^+n$ rescattering, the kinematics is a poor match for $\Theta^+$ production, since, as was described

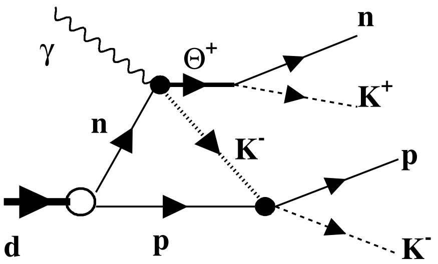

FIG. 2. A rescattering diagram that could contribute to the exclusive reaction mechanism that produces the $\Theta^+$ and an energetic proton through final state interactions. Note that the $\Theta^+$ is produced independently of the secondary scattering.

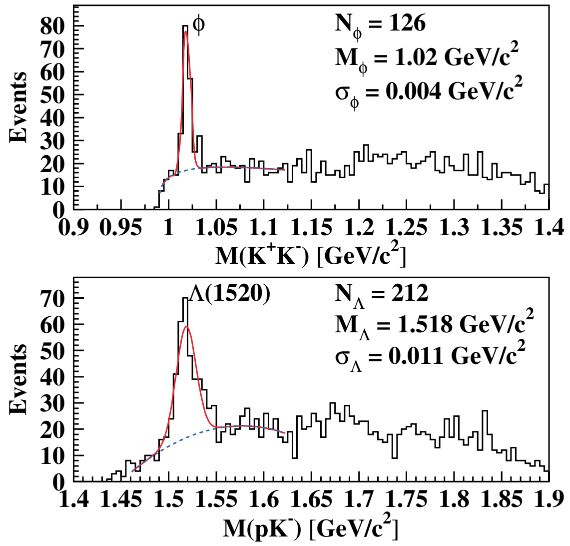

FIG. 3 (color). Invariant mass of the $K^+K^-$ system (top) and the $pK^-$ system (bottom) showing peaks at the mass of known resonances. These resonances are removed in the analysis by placing cuts on the peaks shown. Results for the number of counts ($N$), the mass ($M$), and the widths ($\sigma$) from fits are also given.

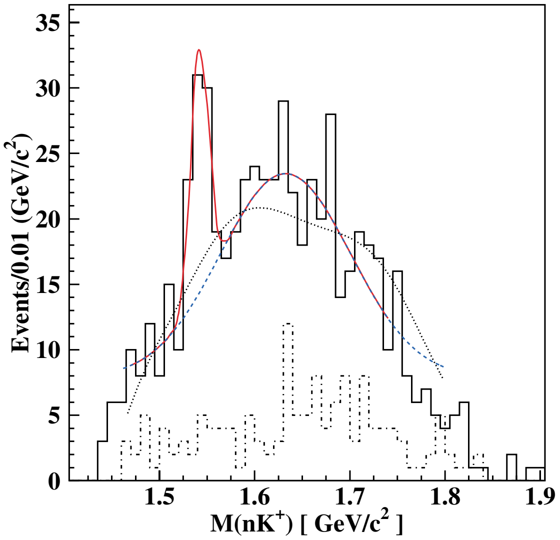

FIG. 4 (color). Invariant mass of the $nK^+$ system, which has strangeness $S = +1$, showing a sharp peak at the mass of 1.542 GeV/$c^2$. A fit (solid line) to the peak on top of the smooth background (dashed line) gives a statistical significance of 5.8$\sigma$. The dotted curve is the shape of the simulated background. The dash-dotted histogram shows the spectrum of events associated with $\Lambda(1520)$ production.

above, this is likely a $t$-channel process with forward production of the $K^+$ in the c.m. frame. In our kinematics the average momentum for the $K^+$ in the production of the $\Lambda(1520)$ is ~0.8 GeV/$c$, while for the production of the $\Theta^+$ in the $K^+n$ interaction, the average momentum of the kaon should be approximately 0.45 GeV/$c$. For this reason, we reject events with $1.485 < M(pK^-) < 1.551$ GeV/$c^2$ ($\pm 3\sigma$ cut from the peak) to improve our signal to background ratio.

Two other event selection requirements were applied, based on kinematics. The first one requires that the missing momentum of the undetected neutron must be greater than 0.08 GeV/$c$. 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. The second requirement concerns the $K^+$ momentum. Monte Carlo simulations of the $\Theta^+$ decay from an event distribution uniform in phase space 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 above ~1.7 GeV/$c^2$. Events with a $K^+$ momentum above 1.0 GeV/$c$ were removed to reduce this background.

The final $nK^+$ invariant mass spectrum, $M(nK^+)$, is shown in Fig. 4 [17], along with a fit (solid line) to the peak and a Gaussian plus constant term fit to the background (dashed line). For the fit given, there are 43 counts in the peak at a mass of $1.542 \pm 0.005$ GeV/$c^2$ with a width (FWHM) of 0.021 GeV/$c^2$. The width is consistent with the instrumental resolution. The uncertainty of 0.005 GeV/$c^2$ in the mass is due to calibration uncertainties of the photon tagging spectrometer [13], the electron beam energy, and the momentum reconstruction in CLAS. The statistical significance of this peak is estimated based on fluctuations of the background over a $\pm 2\sigma$ window centered on the peak, giving $43/\sqrt{54} = 5.8\sigma$. The spectrum of events removed by the $\Lambda(1520)$ cut is shown in Fig. 4 by the dash-dotted histogram and does not appear to be associated with the peak at 1.542 GeV/$c^2$.

The shape of the expected $M(nK^+)$ mass spectrum was investigated by a Monte Carlo simulation using GEANT [18] based simulation tools for the CLAS detector and the algorithm used for the data analysis. We studied four-body phase space production of the $pK^+K^-n$ final state and the production of the three-body phase space in the $pK^+K^-$ final state ($K^+K^-$ in $s$-wave). No peaklike structures were visible in the $M(nK^+)$ distributions of these two final states. We used the shapes of these distributions to fit the experimental $M(nK^+)$ spectrum. The fitted shape of the background is shown by the dotted line in Fig. 4. The relative weights of three-body and four-body phase space events determined by the fit was 3:1. The statistical significance of the peak at 1.542 GeV/$c^2$ in the fit using this simulated background was 4.8$\sigma$.

A separate Monte Carlo study was carried out to examine the production of known resonances via the reaction $\gamma d \to K^+Y^*N$, where the $Y^*$ decays to a $K^-N$ followed by one of the kaons rescattering off the spectator nucleon. This study [19] was unable to produce structures narrower than about 4 times the CLAS resolution and

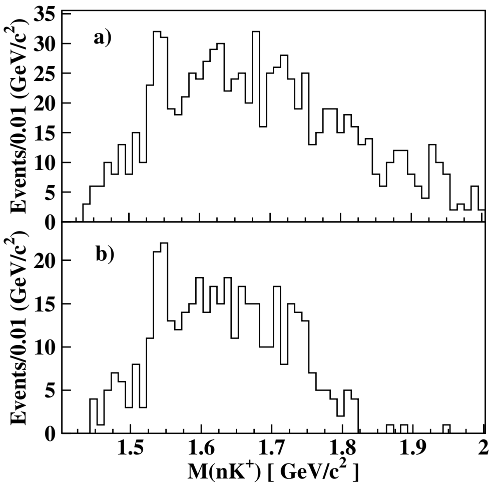

FIG. 5. Spectra of the $(nK^+)$ invariant mass for different cuts: (a) no cut on the $K^+$ momentum; (b) tight cut on proton-kaon vertex time. See the text for details.

concluded that these rescattering processes are not responsible for such a narrow structure in the $M(nK^+)$ spectrum.

The sensitivity of the peak to the placement of event selection cuts was studied, and the conclusion is that the peak at 1.542 GeV$/c^2$ is very robust. For example, removing the $K^+$ momentum limit results in the spectrum shown in Fig. 5(a). Alternatively, tightening the cuts on proton-kaon timing, $|\Delta t_{pK}| < 0.75$ ns, allows less background into the spectrum, as shown in the inset of Fig. 1. The shape of the $M(nK^+)$ spectrum for this selection is shown in Fig. 5(b) and remains essentially unchanged from Fig. 4. In all we tried ten variations of event cut placement and/or different fitting functions. All fits reproduce the measured data with reduced $\chi^2$ in the range between 0.6 and 1. The estimated statistical significance in those ten cases ranges from $4.6\sigma$ to $5.8\sigma$, which we use to derive the conservative estimate for the statistical significance of our result of $5.2 \pm 0.6\sigma$.

A neutron and $K^+$ can couple to both isospin zero and isospin one states. If the $\Theta^+$ has $I = 1$, then there should be two other members of the isotriplet, a neutral and a doubly charged state. The doubly charged state would couple to $pK^+$. We examined the invariant mass $M(pK^+)$ using the same event selection as before. The statistics are limited, but there is no clear peak in the signal region. It should be noted that the CLAS acceptance for the $pK^+$ system is not the same as for the $nK^+$ system, so the two spectra are not directly comparable. The featureless $M(pK^+)$ spectrum (not shown) suggests that the peak at 1.542 GeV$/c^2$ in the $M(nK^+)$ spectrum is an isosinglet, but it is difficult to draw a firm conclusion based on the current data.

These results from CLAS, together with other experiments [8,9], now provide convincing evidence for the existence of an $S = +1$ baryon state at a mass of 1.542 GeV$/c^2$ with a small intrinsic width. In this Letter we presented evidence for this state with a statistical significance in the range of $5.2 \pm 0.6\sigma$, depending on estimates of the background and on the event selection criteria. However, more studies are needed before this $S = +1$ state can be conclusively identified with the $\Theta^+$ predicted in Ref. [6]. Further evidence for the $\Theta^+$ should be searched for in a variety of reactions, in addition to the ones mentioned here. Spin, isospin, and parity of this state remain to be established in future experiments.

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