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B McKinnon
K Hicks
NA Baltzell
DS Carman
MD Mestayer, et al.

Search for the Θ^+ Pentaquark in the Reaction $\gamma d \rightarrow pK^-K^+n$

B. McKinnon,[13] K. Hicks,[28] N. A. Baltzell,[33] D. S. Carman,[28] M. D. Mestayer,[34] T. Mibe,[28] M. Mirazita,[15] S. Niccolai,[17] P. Rossi,[15] S. Stepanyan,[34] D. J. Tedeschi,[33] P. Ambrozewicz,[10] M. Anghinolfi,[16] G. Asryan,[39] H. Avakian,[34] H. Bagdasaryan,[29] N. Baillie,[38] J. P. Ball,[1] V. Batourine,[21] M. Battaglieri,[16] I. Bedlinskiy,[18] M. Bellis,[3] N. Benmouna,[12] B. L. Berman,[12] A. S. Biselli,[3] S. Bouchigny,[17] S. Boiarinov,[34] R. Bradford,[3] D. Branford,[9] W. J. Briscoe,[12] W. K. Brooks,[34] S. Bültmann,[29] V. D. Burkert,[34] C. Butuceanu,[38] J. R. Calarco,[24] S. L. Careccia,[29] S. Chen,[11] P. L. Cole,[14] P. Collins,[1] P. Coltharp,[11] D. Crabb,[37] V. Crede,[11] D. Dale,[20] R. De Masi,[5] R. DeVita,[16] E. De Sanctis,[15] P. V. Degtyarenko,[34] A. Deur,[34] C. Djalali,[33] G. E. Dodge,[29] J. Donnelly,[13] D. Doughty,[6,34] M. Dugger,[1] O. P. Dzyubak,[33] H. Egiyan,[34,*] K. S. Egiyan,[39] L. Elouadrhiri,[34] P. Eugenio,[11] G. Fedotov,[23] G. Feldman,[12] H. Funsten,[38] M. Gabrielyan,[20] L. Gan,[27] M. Garçon,[5] A. Gasparian,[26] G. Gavalian,[29,*] G. P. Gilfoyle,[32] K. L. Giovanetti,[19] F. X. Girod,[5] J. T. Goetz,[2] A. Gonenc,[10] R. W. Gothe,[33] K. A. Griffioen,[38] M. Guidal,[17] N. Guler,[29] L. Guo,[34] V. Gyurjyan,[34] R. S. Hakobyan,[4] F. W. Hersman,[24] I. Hleiqawi,[28] M. Holtrop,[24] C. E. Hyde-Wright,[29] Y. Ilieva,[12] D. G. Ireland,[13] B. S. Ishkhanov,[23] M. M. Ito,[34] D. Jenkins,[36] H. S. Jo,[17] K. Joo,[8] H. G. Juengst,[29] J. D. Kellie,[13] M. Khandaker,[25] W. Kim,[21] A. Klein,[29] F. J. Klein,[4] M. Kossov,[18] L. H. Kramer,[10,34] V. Kubarovsky,[30] J. Kuhn,[3] S. E. Kuhn,[29] S. V. Kuleshov,[18] J. Lachniet,[29,†] J. Langheinrich,[33] D. Lawrence,[22] K. Livingston,[13] H. Lu,[33] M. MacCormick,[17] B. A. Mecking,[34] C. A. Meyer,[3] K. Mikhailov,[18] R. Miskimen,[22] V. Mokeev,[23] S. A. Morrow,[5,17] M. Moteabbed,[10] G. S. Mutchler,[31] I. Nakagawa,[20] P. Nadel-Turonski,[12] R. Nasseripour,[33] G. Niculescu,[19] I. Niculescu,[19] B. B. Niczyporuk,[34] M. R. Niroula,[29] R. A. Niyazov,[34] M. Nozar,[34] M. Osipenko,[16,23] A. I. Ostrovidov,[11] K. Park,[21] E. Pasyuk,[1] C. Paterson,[13] J. Pierce,[37] N. Pivnyuk,[18] O. Pogorelko,[18] S. Pozdniakov,[18] J. W. Price,[7,‡] Y. Prok,[37,§] D. Protopopescu,[13] B. A. Raue,[10,34] G. Ricco,[16] M. Ripani,[16] B. G. Ritchie,[1] F. Ronchetti,[15] G. Rosner,[13] F. Sabatié,[5] C. Salgado,[25] J. P. Santoro,[36,34,∥] V. Sapunenko,[34] R. A. Schumacher,[3] V. S. Serov,[18] Y. G. Sharabian,[34] E. S. Smith,[34] L. C. Smith,[37] D. I. Sober,[4] A. Stavinsky,[18] S. S. Stepanyan,[21] B. E. Stokes,[11] P. Stoler,[30] I. I. Strakovsky,[12] S. Strauch,[33] M. Taiuti,[16] A. Teymurazyan,[20] U. Thoma,[34,¶] A. Tkabladze,[12] S. Tkachenko,[29] C. Tur,[33] M. Ungaro,[8] M. F. Vineyard,[35] A. V. Vlassov,[18] L. B. Weinstein,[29] D. P. Weygand,[34] M. Williams,[3] E. Wolin,[34] M. H. Wood,[33,**] A. Yegneswaran,[34] L. Zana,[24] J. Zhang,[29] B. Zhao,[8] and Z. Zhao[33]

(CLAS Collaboration)

[1]*Arizona State University, Tempe, Arizona 85287-1504, USA*
[2]*University of California at Los Angeles, Los Angeles, California 90095-1547, USA*
[3]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[4]*Catholic University of America, Washington, D.C. 20064, USA*
[5]*Service de Physique Nucléaire, CEA-Saclay, F91191 Gif-sur-Yvette, France*
[6]*Christopher Newport University, Newport News, Virginia 23606, USA*
[7]*California State University, Dominguez Hills, Carson, California 90747, USA*
[8]*University of Connecticut, Storrs, Connecticut 06269, USA*
[9]*Edinburgh University, Edinburgh EH9 3JZ, United Kingdom*
[10]*Florida International University, Miami, Florida 33199, USA*
[11]*Florida State University, Tallahassee, Florida 32306, USA*
[12]*The George Washington University, Washington, D.C. 20052, USA*
[13]*University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[14]*Idaho State University, Pocatello, Idaho 83209, USA*
[15]*Laboratori Nazionali di Frascati, INFN, 00044 Frascati, Italy*
[16]*Sezione di Genova, INFN, 16146 Genova, Italy*
[17]*Institut de Physique Nucleaire Orsay, Orsay, France*
[18]*Institute of Theoretical and Experimental Physics, Moscow, 117259, Russia*
[19]*James Madison University, Harrisonburg, Virginia 22807, USA*
[20]*University of Kentucky, Lexington, Kentucky 40506, USA*
[21]*Kyungpook National University, Daegu 702-701, Republic of Korea*
[22]*University of Massachusetts, Amherst, Massachusetts 01003, USA*
[23]*General Nuclear Physics Institute, Moscow State University, 119899 Moscow, Russia*
[24]*University of New Hampshire, Durham, New Hampshire 03824-3568, USA*
[25]*Norfolk State University, Norfolk, Virginia 23504, USA*
[26]*North Carolina A & T State University, Greensboro, North Carolina 27411, USA*
[27]*University of North Carolina, Wilmington, North Carolina 28403, USA*

[28]*Ohio University, Athens, Ohio 45701, USA*
[29]*Old Dominion University, Norfolk, Virginia 23529, USA*
[30]*Rensselaer Polytechnic Institute, Troy, New York 12180-3590, USA*
[31]*Rice University, Houston, Texas 77005-1892, USA*
[32]*University of Richmond, Richmond, Virginia 23173, USA*
[33]*University of South Carolina, Columbia, South Carolina 29208, USA*
[34]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[35]*Union College, Schenectady, New York 12308, USA*
[36]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0435, USA*
[37]*University of Virginia, Charlottesville, Virginia 22901, USA*
[38]*College of William and Mary, Williamsburg, Virginia 23187-8795, USA*
[39]*Yerevan Physics Institute, 375036 Yerevan, Armenia*
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A search for the Θ^+ in the reaction $\gamma d \to pK^-K^+n$ was completed using the CLAS detector at Jefferson Lab. A study of the same reaction, published earlier, reported the observation of a narrow Θ^+ resonance. The present experiment, with more than 30 times the integrated luminosity of our earlier measurement, does not show any evidence for a narrow pentaquark resonance. The angle-integrated upper limit on Θ^+ production in the mass range of 1.52–1.56 GeV/c^2 for the $\gamma d \to pK^-\Theta^+$ reaction is 0.3 nb (95% C.L.). This upper limit depends on assumptions made for the mass and angular distribution of Θ^+ production. Using $\Lambda(1520)$ production as an empirical measure of rescattering in the deuteron, the cross section upper limit for the elementary $\gamma n \to K^-\Theta^+$ reaction is estimated to be a factor of 10 higher, i.e., $\sim$3 nb (95% C.L.).

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In the original quark model, first introduced by Gell-Mann and Ne'eman [1], the ground-state baryons have only three valence quarks. Exotic multiquark structures beyond the basic quark model were suggested by Jaffe [2] and others in the 1970s, but it is now thought that these resonances are too wide to be detected by experiments. Recently, the prediction of a narrow pentaquark [3] and an initial report by the LEPS Collaboration [4] have revitalized interest in searches for an exotic baryon with valence quark structure ($uudd\bar{s}$), known as the Θ^+. If the Θ^+ exists, then this presents a challenge to theorists to find a way to describe pentaquarks, using either effective degrees of freedom [5,6] or lattice gauge calculations [7] based on QCD.

The reaction $\gamma d \to pK^-K^+n$ was measured by the CLAS Collaboration [8], showing evidence for the Θ^+ decaying to nK^+ at a mass of about 1.54 GeV/c^2. Considering the important implications of a possible pentaquark state, it was necessary to test the reproducibility of our previous result. In addition, there are several experiments that see evidence for the Θ^+ and many that do not (see the reviews [9]). It is crucial to understand why some experiments see a peak and others do not [10]. For example, a strong peak identified as the Θ^+ was reported for $\gamma p \to \pi^+K^-K^+n$ in Ref. [11]. On the other hand, a high-statistics search for the Θ^+ in the $\gamma p \to K^0K^+n$ reaction reported a null result [12]. We present here a new search for the Θ^+ in the $\gamma d \to pK^-K^+n$ reaction with much improved statistical precision.

The present data were acquired during a two-month period in early 2004 with the CLAS detector [13] and the Hall *B* photon tagging system [14]. The incident electron beam energy was $E_0 = 3.776$ GeV, producing tagged photons in the range from 0.8 to 3.6 GeV. In order to ensure accuracy in the absolute mass scale for the current experiment, the tagging spectrometer was calibrated independently of CLAS using the conversion of photons into e^+e^- pairs in an aluminum foil. The e^+ and e^- were momentum analyzed in a pair spectrometer having a precision field-mapped magnet, so that nonlinear aspects of the photon energy measurement were calibrated, giving an accuracy of $0.1\%E_\gamma$ over the full energy range.

The photon beam was directed onto a 24-cm long liquid-deuterium target. One difference from our previous experiment [8] is that the target was placed 25 cm upstream of the center of the CLAS detector to increase the forward-angle acceptance of negatively charged particles. The trigger required two charged particles detected in coincidence with a tagged photon. The torus magnet was run at two settings, low field (2250 A) and high field (3375 A), each for about half of the run period. The low field setting has slightly better acceptance at forward angles but worse momentum resolution. The high field setting was the same as that used in Ref. [8]. The CLAS momentum resolution is on the order of 0.5%–1.0% (rms) depending on the kinematics. Detailed calibrations of the CLAS detector subsystems were performed to achieve an accuracy of 1–2 MeV/c^2 in the nK^+ invariant mass distribution. An integrated luminosity of about 38 pb^{-1} (for $E_\gamma > 1.5$ GeV) was collected here.

The quality of the detector calibrations and cross section normalization factors was verified using the reaction $\gamma d \to \pi^- pp$. The differential cross sections in the photon energy range near 1.1 GeV were compared with the same reaction measured by the Hall *A* Collaboration [15], and also the world data, with good agreement (within ~10% over most of the angular range).

The event selection here is similar to that of Ref. [8], requiring detection of one proton, one K^+, one K^-, and up to one neutral particle. All had vertex times within ~1.0 ns of the tagged photon. The missing mass of the $\gamma d \to pK^-K^+X$ reaction and the invariant mass of the detected pK^- particles $M(pK^-)$ are shown in Fig. 1. The missing mass was required to be within $\pm 3\sigma$ of the neutron mass, where σ is the mass resolution ($\simeq$8 MeV) of the peak shown. Also, the missing momentum (not shown) was required to be greater than 0.20 GeV/c in order to remove spectator neutrons. Simulations of the decay $\Theta^+ \to nK^+$ show that this cut does not affect the Θ^+ detection efficiency. Events corresponding to ϕ-meson production were cut by requiring the K^+K^- mass to be above 1.06 GeV/c^2, and, similarly, the $\Lambda(1520)$ was cut by removing events from $1.495 < M(pK^-) < 1.545$ GeV/c^2; see Fig. 1. Variations of these event selection cuts were studied and yield results consistent with those given below.

In Fig. 1, both the low field setting (top) and the high field setting (bottom) are independent data sets. The $M(pK^-)$ spectra show a prominent peak for the $\Lambda(1520)$ and also strength at higher mass corresponding to well known Λ^* resonances at 1.67, 1.69, and 1.82 GeV. These Λ^* resonances are suppressed in the final data sample due to the neutron momentum cut, since in $\gamma p \to K^+\Lambda^*$ the neutron is a spectator. Also, Λ^* production is not necessarily incompatible with Θ^+ production, as the $\gamma d \to \Lambda^*\Theta^+$ reaction still conserves strangeness. A narrow pentaquark peak with a sufficient cross section would still be visible on top of the broad background from the Λ^* resonances projected onto the nK^+ mass spectrum.

The spectra of the invariant mass of the nK^+ system $M(nK^+)$ are shown in Fig. 2, after applying the above analysis cuts. These spectra were constructed using the neutron mass as an explicit constraint (as contrasted with the missing mass of the pK^- in Ref. [8], which did not use this constraint). A kinematic fitting approach gives nearly identical mass spectra (but using a more elaborate procedure). The $M(nK^+)$ spectra in Fig. 2 do not show any evidence for a narrow peak near 1.54 GeV/c^2.

The $M(nK^+)$ spectra at the top of Fig. 2 were then corrected for the CLAS detector acceptance and normalized by the luminosity, resulting in the combined data shown in the bottom plot. The acceptance correction comes from a Monte Carlo simulation that matches the exponential t dependence of the measured K^+ and K^- momenta and was fitted to the experimental neutron momentum distribution in the range $p_n > 0.2$ GeV/c. Using this Monte Carlo simulation, the angle-resolved acceptance of the CLAS detector ranges from 0.7% to 1% in the final data sample for both the high and low field settings.

The cross section spectrum of Fig. 2 (lower) was fit with a third-degree polynomial, as shown. This curve was then held fixed, and the excess (or deficit) above (or below) the

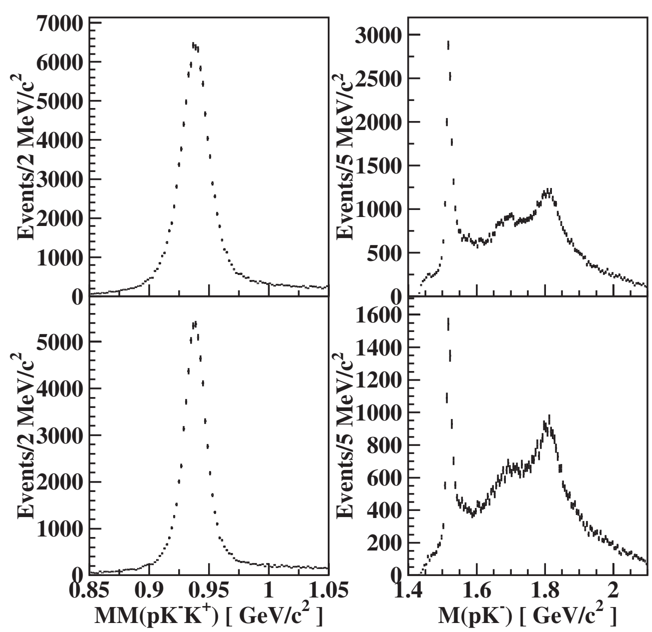

FIG. 1. The raw data for the missing mass $MM(pK^-K^+)$ of the reaction $\gamma d \to pK^-K^+X$ showing a clean neutron peak (left). The invariant mass spectra of the detected pK^- (right) show the $\Lambda(1520)$ peak along with higher mass hyperons. The data are shown separately for the low field (top) and high field (bottom) settings of the CLAS torus magnet.

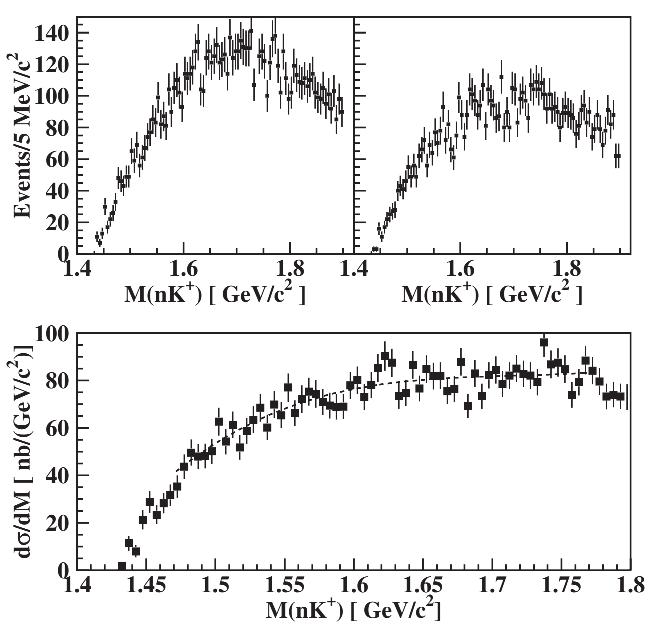

FIG. 2. The invariant masses of the nK^+ system for both the low field (top left) and high field (top right) data sets, after applying all event selection cuts. The cross section per mass bin for the combined data (bottom) is shown along with a polynomial fit.

polynomial was used to determine the cross section upper limit by standard methods [16]. The upper limit was also checked on both the low and high field data separately, giving consistent results. We emphasize that this upper limit is for the $\gamma d \rightarrow pK^-\Theta^+$ reaction and not for the elementary cross section on the neutron.

The angle-integrated upper limit for the $\gamma d \rightarrow pK^-\Theta^+$ reaction, shown in Fig. 3 (top), is calculated to be less than 0.3 nb in the mass range of 1.5–1.6 GeV/c^2. This estimate assumes that our Monte Carlo simulation corrects for the CLAS detector acceptance in unmeasured kinematic regions, such as for very forward-angle kaons. As mentioned above, our acceptance calculation assumes an exponential t dependence, giving kaons preferentially at forward angles.

The most important dynamical variable that affects the acceptance is the angular dependence of the cross section. The upper limit for the differential cross section is shown in the bottom half of Fig. 3 as a function of $\cos\theta^*$, where θ^* is the angle of the nK^+ system, corresponding to the Θ^+ decay particles, in the center-of-mass frame relative to the beam direction. The solid line denotes the maximum upper limits in the mass range from 1.52 to 1.56 GeV/c^2 for a given bin of $\cos\theta^*$. The dashed line is the upper limit at a particular mass of 1.54 GeV/c^2. The corresponding acceptance in CLAS covers the full angular region and is only a factor of 2 smaller at forward angles of the K^- (i.e., Θ^+ at $\cos\theta^* < -0.75$) as compared with midrange angles ($\cos\theta^* \sim 0$).

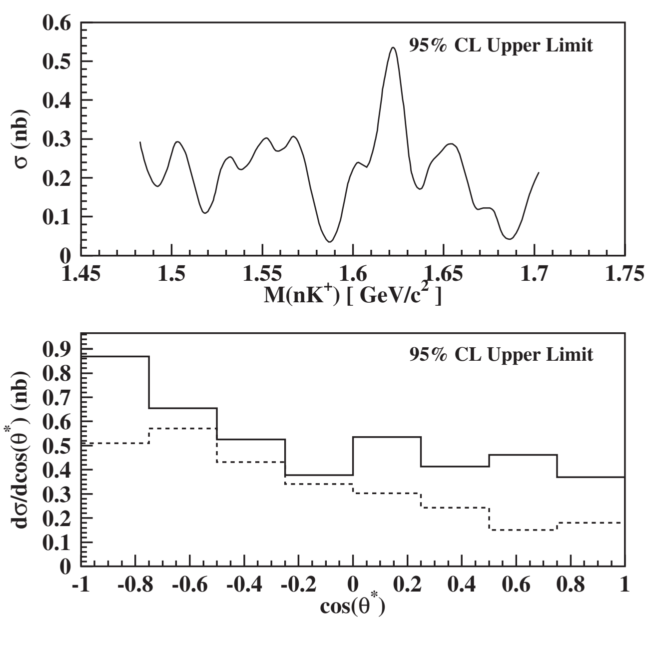

FIG. 3. The 95% confidence limit (C.L.) upper limit cross sections for the $\gamma d \rightarrow pK^-\Theta^+$ reaction using the combined low and high field data. The top plot is a function of mass, whereas the lower plot shows the maximum upper limit for the given θ^* bin, for a mass range between 1.52 and 1.56 GeV/c^2 (solid line) or just at mass 1.54 GeV/c^2 (dashed line).

In determining the upper limit, systematic uncertainties need to be studied. The dominant uncertainty is the unknown angular dependence of possible Θ^+ production. For example, if the Θ^+ were produced primarily with forward-angle K^-, as suggested by Ref. [17], then we need only to consider the first angular bin in Fig. 3 (lower). The upper limit (95% C.L.) for the differential cross section $d\sigma/d(\cos\theta^*)$ in this bin ($\cos\theta^* < -0.75$) is about 0.5 nb for a mass of 1.54 GeV/c^2, and, after integrating over $\cos\theta^*$ (assuming zero contribution outside this bin), the upper limit on the Θ^+ total cross section is about 0.125 nb. The upper limit is well defined for a given set of assumptions about the Θ^+ mass, angular dependence, etc., and we believe that the limits given above cover most of the reasonable alternatives. Fluctuations in the upper limits due to other systematic effects are smaller [18].

The connection between our upper limits from deuterium and those from the elementary reaction on a free neutron is now explored. There is no involvement of a proton in $\gamma n \rightarrow K^-\Theta^+ \rightarrow K^-K^+n$, but a proton was required in our deuterium analysis. To be detected in CLAS, a proton must have a momentum of at least 0.35 GeV/c, and, hence, a mechanism to gain this momentum must be modeled. In order to set upper limits for Θ^+ production off the neutron, we need to correct for rescattering of the spectator proton in deuterium. For example, there could be rescattering of the K^- from the proton.

We use a phenomenological approach to estimate the rescattering of the spectator nucleon using the t-channel symmetry between $\Lambda(1520)$ and Θ^+ production. The first-order t-channel diagrams are shown at the bottom of Fig. 4. For $\Lambda(1520)$ production, the neutron is a spectator in this t-channel diagram, whereas for Θ^+ production, the proton is a spectator. Assuming that the t channel dominates both $\Lambda(1520)$ and Θ^+ production, a direct measure of rescattering of the neutron for $\Lambda(1520)$ production can be used to estimate the amount of rescattering of the proton in Θ^+ production. This is a conservative estimate, since the K^+n scattering cross section is smaller than that for K^-p. In addition, the Θ^+ would likely have a larger radius than the $\Lambda(1520)$ and, thus, a larger cross section for final state interactions.

The fraction of cross section for $K^+\Lambda(1520)$ production as a function of the neutron momentum cut is shown by the solid points in Fig. 4. This ratio is unity when no momentum cut is applied, and only 10% of the cross section survives for neutron momenta greater than 0.35 GeV/c, as shown by the arrow. For comparison, the solid line in Fig. 4 shows the same fraction calculated using Fermi motion of the neutron in deuterium, based on the Paris potential [19]. The points are higher than the line, indicating substantial rescattering due to final state interactions. Assuming a similar reduction factor in Θ^+ production for *protons* above 0.35 GeV/c, the upper limit for $\gamma n \rightarrow \Theta^+K^-$ is estimated to be a factor of 10 higher than the upper limits presented in Fig. 3.

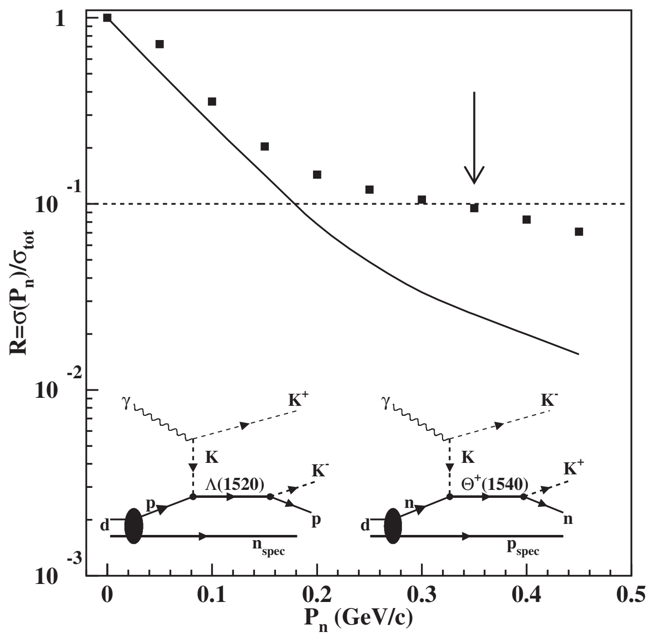

FIG. 4. The relative cross section fraction for $\Lambda(1520)$ production as a function of the neutron momentum from our data (points). A cutoff of 0.35 GeV/c on the horizontal axis corresponds to a factor of 10 loss in detection of the $\Lambda(1520)$ compared with no cut. Also shown by the solid curve is the fraction calculated using only the Fermi motion of the neutron. The reaction diagrams at the bottom show the symmetry between t-channel production for $\Lambda(1520)$ and Θ^+ reactions.

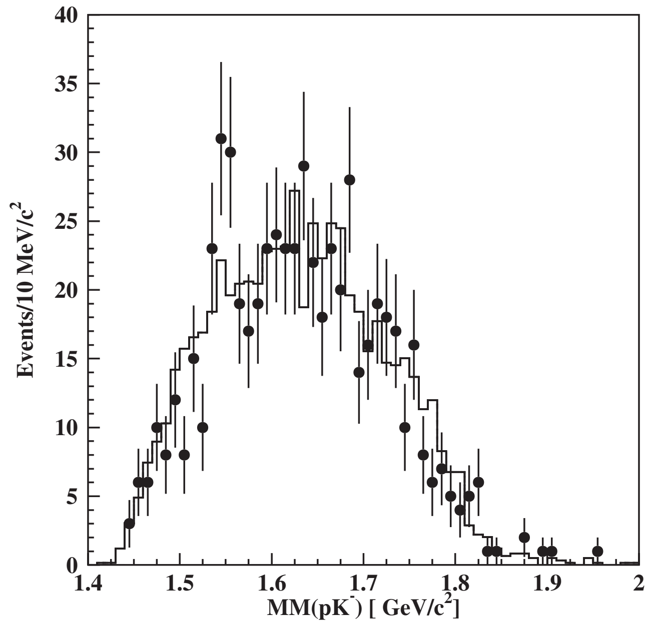

FIG. 5. Comparison of the previously published [8] result (points) with the current result (histogram) normalized (by a factor of 1/5.92) to get the same total number of counts.

A comparison of the current results with our previous report [8] is instructive. To do this, the current data were constrained, by software, to use the same event selection and the same photon energy region as was used in Ref. [8]. Only the high field data are used here. This analysis will be called the "repeat study," since the analysis conditions are essentially unchanged from Ref. [8].

In Fig. 5, the results of Ref. [8] (points with statistical error bars) are compared with the results of the repeat study (histogram), rescaled for comparison by the ratio of the total counts. The peak at 1.54 GeV/c^2 from Ref. [8] is not reproduced in the repeat study. For comparison, the number of $\Lambda(1520)$ events scales, within statistical uncertainties, with the ratio of exclusive pK^-K^+n events (current/previous) [20].

Assuming that the histogram in Fig. 5 represents the true shape of the background, a smooth third-degree polynomial was fit to the histogram over the range from 1.45 to 1.75 GeV/c^2, giving a reduced $\chi^2 \simeq 1.15$. A Gaussian peak, with width fixed at 7.0 MeV (the CLAS detector resolution) at a mass of 1.542 GeV/c^2, was fit on top of the polynomial background shape to the solid points in Fig. 5, giving 25 ± 9 counts in the peak. The significance of a fluctuation is given by $S/\sqrt{B+V}$, where S is the signal above background, B is the background, and V is the variance in the background [21]. The variance of the background is difficult to estimate precisely, unless the shape is known. Using the polynomial fit parameters, the values of B and V in the region from 1.53–1.56 GeV/c^2 are 57 and 7, respectively. This gives a new statistical significance of 3.1σ. In hindsight, the original signal size estimate of $5.2 \pm 0.6\sigma$ in our previous publication was due to a significant underestimate of the background.

In summary, the reaction $\gamma d \to pK^-K^+n$ has been measured using the CLAS detector where the neutron was identified by missing mass. A search for a narrow Θ^+ resonance decaying into nK^+ was done in the mass range of 1.48–1.7 GeV/c^2. The upper limit (95% C.L.) for the total cross section of Θ^+ production ranges from 0.15–0.3 nb, depending on its angular distribution, for a mass of 1.54 GeV/c^2. An upper limit for the elementary process $\gamma n \to K^-\Theta^+$ requires a correction for the proton momentum cutoff. The size of this correction was estimated from a phenomenological model based on $\Lambda(1520)$ production to be a factor of 10, giving an upper limit for the elementary $\gamma n \to K^-\Theta^+$ reaction estimated at ~3 nb. The current null result shows that the nK^+ invariant mass peak of Ref. [8] could not be reproduced and puts significant limits on the possible production cross section of a narrow Θ^+.

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*Current address: University of New Hampshire, Durham, NH 03824-3568, USA.

†Current address: Carnegie Mellon University, Pittsburgh, PA 15213, USA.

‡Current address: University of California at Los Angeles, Los Angeles, CA 90095-1547, USA.

§Current address: Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA.

‖Current address: Catholic University of America, Washington, D.C. 20064, USA.

¶Current address: Physikalisches Institut der Universitaet Giessen, 35392 Giessen, Germany.

**Current address: University of Massachusetts, Amherst, MA 01003, USA.

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