1-1-2006

Search for Θ+(1540) Pentaquark in High-Statistics Measurement of γp→K¯¯¯0K+n at CLAS

M. Battaglieri

Angela Biselli
Fairfield University, abiselli@fairfield.edu

CLAS Collaboration

Final publisher version also available at http://prl.aps.org/pdf/PRL/v96/i4/e042001

Peer Reviewed

Repository Citation

Battaglieri, M.; Biselli, Angela; and CLAS Collaboration, "Search for Θ+(1540) Pentaquark in High-Statistics Measurement of γp→K¯¯¯0K+n at CLAS" (2006). *Physics Faculty Publications*. 7.
http://digitalcommons.fairfield.edu/physics-facultypubs/7

Published Citation

M. Battaglieri et al. [CLAS Collaboration], "Search for Θ+(1540) Pentaquark in High-Statistics Measurement of γp→K¯¯¯0K+n at CLAS", Physical Review Letters 96.4 (2006) DOI: 10.1103/PhysRevLett.96.042001

Search for $\Theta^+(1540)$ Pentaquark in High-Statistics Measurement of $\gamma p \to \bar{K}^0 K^+ n$ at CLAS

M. Battaglieri,[1] R. De Vita,[1] V. Kubarovsky,[2] L. Guo,[3] G. S. Mutchler,[4] P. Stoler,[2] D. P. Weygand,[3] P. Ambrozewicz,[14]
M. Anghinolfi,[1] G. Asryan,[38] H. Avakian,[3] H. Bagdasaryan,[31] N. Baillie,[37] J. P. Ball,[5] N. A. Baltzell,[33] V. Batourine,[25]
I. Bedlinskiy,[22] M. Bellis,[2,8] N. Benmouna,[16] B. L. Berman,[16] A. S. Biselli,[8] S. Bouchigny,[20] S. Boiarinov,[3] R. Bradford,[8]
D. Branford,[13] W. J. Briscoe,[16] W. K. Brooks,[3] S. Bültmann,[31] V. D. Burkert,[3] C. Butuceanu,[37] J. R. Calarco,[28]
S. L. Careccia,[31] D. S. Carman,[30] S. Chen,[15] E. Clinton,[26] P. L. Cole,[18] P. Coltharp,[15] D. Crabb,[36] H. Crannell,[9]
J. P. Cummings,[2] D. Dale,[39] E. De Sanctis,[19] P. V. Degtyarenko,[3] A. Deur,[3] K. V. Dharmawardane,[31] C. Djalali,[33]
G. E. Dodge,[31] J. Donnelly,[17] D. Doughty,[11,3] M. Dugger,[5] O. P. Dzyubak,[33] H. Egiyan,[3,*] K. S. Egiyan,[38] L. Elouadrhiri,[3]
P. Eugenio,[15] G. Fedotov,[27] H. Funsten,[37] M. Y. Gabrielyan,[39] L. Gan,[40] M. Garçon,[10] A. Gasparian,[41] G. Gavalian,[28,31]
G. P. Gilfoyle,[32] K. L. Giovanetti,[23] F. X. Girod,[10] O. Glamazdin,[24] J. Goett,[2] J. T. Goetz,[6] E. Golovach,[27] A. Gonenc,[14]
C. I. O. Gordon,[17] R. W. Gothe,[33] K. A. Griffioen,[37] M. Guidal,[20] N. Guler,[31] V. Gyurjyan,[3] C. Hadjidakis,[20]
R. S. Hakobyan,[9] J. Hardie,[11,3] F. W. Hersman,[28] K. Hicks,[30] I. Hleiqawi,[30] M. Holtrop,[28] C. E. Hyde-Wright,[31] Y. Ilieva,[16]
D. G. Ireland,[17] B. S. Ishkhanov,[27] M. M. Ito,[3] D. Jenkins,[35] H. S. Jo,[20] K. Joo,[12] H. G. Juengst,[16,†] J. D. Kellie,[17]
M. Khandaker,[29] W. Kim,[25] A. Klein,[31] F. J. Klein,[9] A. V. Klimenko,[31] M. Kossov,[22] L. H. Kramer,[14,3] J. Kuhn,[8]
S. E. Kuhn,[31] S. V. Kuleshov,[22] J. Lachniet,[8] J. M. Laget,[10,3] J. Langheinrich,[33] D. Lawrence,[26] T. Lee,[28] Ji Li,[2]
K. Livingston,[17] B. McKinnon,[17] B. A. Mecking,[3] J. J. Melone,[17] M. D. Mestayer,[3] C. A. Meyer,[8] T. Mibe,[30]
K. Mikhailov,[22] R. Minehart,[36] M. Mirazita,[19] R. Miskimen,[26] V. Mochalov,[21] V. Mokeev,[27] L. Morand,[10]
S. A. Morrow,[20,10] P. Nadel-Turonski,[16] I. Nakagawa,[42] R. Nasseripour,[14,33] S. Niccolai,[20] G. Niculescu,[23] I. Niculescu,[23]
B. B. Niczyporuk,[3] R. A. Niyazov,[3] M. Nozar,[3] M. Osipenko,[1,27] A. I. Ostrovidov,[15] K. Park,[25] E. Pasyuk,[5] C. Paterson,[17]
J. Pierce,[36] N. Pivnyuk,[22] D. Pocanic,[36] O. Pogorelko,[22] S. Pozdniakov,[22] J. W. Price,[6,7] Y. Prok,[36,‡] D. Protopopescu,[17]
B. A. Raue,[14,3] G. Riccardi,[15] G. Ricco,[1] M. Ripani,[1] B. G. Ritchie,[5] F. Ronchetti,[19] G. Rosner,[17] P. Rossi,[19] F. Sabatié,[10]
C. Salgado,[29] J. P. Santoro,[9,3] V. Sapunenko,[3] R. A. Schumacher,[8] V. S. Serov,[22] Y. G. Sharabian,[3] E. S. Smith,[3]
L. C. Smith,[36] D. I. Sober,[9] A. Stavinsky,[22] S. S. Stepanyan,[25] S. Stepanyan,[3] B. E. Stokes,[15] I. I. Strakovsky,[16]
S. Strauch,[16,§] M. Taiuti,[1] D. J. Tedeschi,[33] A. Teymurazyan,[39] U. Thoma,[3,‖] A. Tkabladze,[16] S. Tkachenko,[31] L. Todor,[32]
C. Tur,[33] M. Ungaro,[2,12] M. F. Vineyard,[34] A. V. Vlassov,[22] L. B. Weinstein,[31] M. Williams,[8] E. Wolin,[3] M. H. Wood,[33,¶]
A. Yegneswaran,[3] L. Zana,[28] J. Zhang,[31] and B. Zhao[12]

(CLAS Collaboration)

[1]*Istituto Nazionale di Fisica Nucleare, Sezione di Genova, and Dipartimento di Fisica, Universitá di Genova, 16146 Genova, Italy*
[2]*Rensselaer Polytechnic Institute, Troy, New York 12180-3590, USA*
[3]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[4]*Rice University, Houston, Texas 77005-1892, USA*
[5]*Arizona State University, Tempe, Arizona 85287-1504, USA*
[6]*University of California at Los Angeles, Los Angeles, California 90095-1547, USA*
[7]*California State University, Dominguez Hills, California 90747-0005, USA*
[8]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[9]*Catholic University of America, Washington, District of Columbia 20064, USA*
[10]*CEA-Saclay, Service de Physique Nucléaire, F91191 Gif-sur-Yvette, France*
[11]*Christopher Newport University, Newport News, Virginia 23606, USA*
[12]*University of Connecticut, Storrs, Connecticut 06269, USA*
[13]*Edinburgh University, Edinburgh EH9 3JZ, United Kingdom*
[14]*Florida International University, Miami, Florida 33199, USA*
[15]*Florida State University, Tallahassee, Florida 32306, USA*
[16]*The George Washington University, Washington, District of Columbia 20052, USA*
[17]*University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[18]*Idaho State University, Pocatello, Idaho 83209, USA*
[19]*INFN, Laboratori Nazionali di Frascati, Frascati, Italy*
[20]*Institut de Physique Nucleaire ORSAY, Orsay, France*
[21]*Institute for High Energy Physics, Protvino, 142281, Russia*
[22]*Institute of Theoretical and Experimental Physics, Moscow, 117259, Russia*
[23]*James Madison University, Harrisonburg, Virginia 22807, USA*
[24]*Kharkov Institute of Physics and Technology, Kharkov 61108, Ukraine*

0031-9007/06/96(4)/042001(6)$23.00

[25]*Kyungpook National University, Daegu 702-701, South Korea*
[26]*University of Massachusetts, Amherst, Massachusetts 01003, USA*
[27]*Moscow State University, General Nuclear Physics Institute, 119899 Moscow, Russia*
[28]*University of New Hampshire, Durham, New Hampshire 03824-3568, USA*
[29]*Norfolk State University, Norfolk, Virginia 23504, USA*
[30]*Ohio University, Athens, Ohio 45701, USA*
[31]*Old Dominion University, Norfolk, Virginia 23529, USA*
[32]*University of Richmond, Richmond, Virginia 23173, USA*
[33]*University of South Carolina, Columbia, South Carolina 29208, USA*
[34]*Union College, Schenectady, New York 12308, USA*
[35]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0435, USA*
[36]*University of Virginia, Charlottesville, Virginia 22901, USA*
[37]*College of William and Mary, Williamsburg, Virginia 23187-8795, USA*
[38]*Yerevan Physics Institute, 375036 Yerevan, Armenia*
[39]*University of Kentucky, Lexington, Kentucky 40506, USA*
[40]*University of North Carolina, Wilmington, North Carolina 28403, USA*
[41]*North Carolina Agricultural and Technical State University, Greensboro, North Carolina 27455, USA*
[42]*The Institute of Physical and Chemical Research, RIKEN, Wako, Saitama 351-0198, Japan*

(Received 22 October 2005; published 31 January 2006)

The exclusive reaction $\gamma p \rightarrow \bar{K}^0 K^+ n$ was studied in the photon energy range between 1.6 and 3.8 GeV searching for evidence of the exotic baryon $\Theta^+(1540) \rightarrow nK^+$. The decay to nK^+ requires the assignment of strangeness $S = +1$ to any observed resonance. Data were collected with the CLAS detector at the Thomas Jefferson National Accelerator Facility corresponding to an integrated luminosity of 70 pb^{-1}. No evidence for the Θ^+ pentaquark was found. Upper limits were set on the production cross section as function of center-of-mass angle and nK^+ mass. The 95% C.L. upper limit on the total cross section for a narrow resonance at 1540 MeV was found to be 0.8 nb.

DOI: 10.1103/PhysRevLett.96.042001 PACS numbers: 12.39.Mk, 13.60.Rj, 14.20.Jn, 14.80.−j

Following the announcement by the LEPS collaboration [1] in 2003, many experiments [2–11] reported evidence of a new exotic baryon with strangeness quantum number $S = +1$ and valence quark structure $udud\bar{s}$. The renewed interest in pentaquarks was motivated by a prediction within the Chiral Soliton Model [12] for a $S = +1$ baryon at a mass of 1530 MeV and width of less than 15 MeV. If it exists, this would be the first observation of a baryon state that is not made up of a simple 3-quark (qqq) valence configuration. The observation of a second pentaquark, the Ξ^{--} with $dsds\bar{u}$ structure, was reported by the NA49 collaboration [13] and the first evidence for an anticharmed pentaquark, Θ_c, was found by the H_1 collaboration [14]. On the other hand, in the past year reanalyses of data collected in high-energy experiments [14–27] show no evidence for pentaquarks, casting doubt on their existence. The experimental evidence, both positive and negative, was obtained from data previously collected for other purposes in many reaction channels and under very different kinematic conditions, which likely involved dissimilar production mechanisms. Thus, direct comparisons of the results of the different experiments are very difficult, preventing a definitive conclusion about the pentaquark's existence. A second generation of dedicated experiments, optimized for pentaquark searches, was undertaken at the Thomas Jefferson National Accelerator Facility. These photo-production experiments cover the few GeV beam energy region where most of the positive results have been reported, and collect at least an order of magnitude more statistics than any of the previous measurements. The mass resolution is of the order few MeV and the accuracy of the mass determination is approximately 1–2 MeV, allowing precise determination of any possible narrow peaks in the decay distributions. This Letter presents the first result from this program. We searched for the Θ^+ in the $\gamma p \rightarrow \bar{K}^0 K^+ n$ reaction, where the $K^+ n$ decay mode identifies a baryon with strangeness +1. This channel was previously investigated at ELSA by the SAPHIR collaboration [4] in a similar photon energy range, finding positive evidence for a narrow Θ^+ state with $M = 1540$ MeV and full width at half maximum (FWHM) $\Gamma < 25$ MeV. A total production cross section on the order of 300 nb (reduced later to 50 nb as reported in Ref. [28]) was reported. For the first time, our new results put previous positive findings to a direct test. This measurement was performed using the CLAS [29] detector at Jefferson Lab in the experimental Hall-B with a bremsstrahlung photon beam produced by a primary continuous electron beam of energy $E_0 = 4.0$ GeV. A bremsstrahlung tagging system [30], which measures the energy of each interacting photon with resolution of 0.1% E_0, was used to tag photons in the energy range 1.6–3.8 GeV. The target consisted of a 40 cm long cylindrical cell containing liquid hydrogen. Outgoing hadrons were detected and identified in CLAS. Momentum information for charged particles was obtained via tracking through three regions of multiwire drift chambers [31] inside a toroidal magnetic field (~0.5 T), which was generated by six superconducting coils. The CLAS momentum resolution is on the order of 0.5–1% (σ) depending on the kinematics. The detector geometrical acceptance for each positive particle in the relevant kinematic region is about 40%. It is somewhat less for low-energy negative hadrons, which can be lost at forward angles because they are bent out of the acceptance by the toroidal field. The field was set to bend the positive particles away from the beam into the acceptance region of the detector. Time-of-flight scintillators were used for hadron identification [32]. The interaction time between the incoming photon and the target was measured by the start counter [33], consisting of a set of 24 2.2 mm thick plastic scintillators surrounding the hydrogen cell. Coincidences between the photon tagger and two charged particles in the CLAS detector triggered the recording of the events. An integrated luminosity of about 70 pb^{-1} was accumulated in 50 days of running. In total, about 20 TB of data were collected.

The reaction $\gamma p \rightarrow \bar{K}^0 K^+ n$ was isolated as follows. The K^+ was detected directly, and the K_S component of the $\bar{K}^0$ was reconstructed from its $\pi^+\pi^-$ decay. The momentum of the neutron was reconstructed from the known incident photon energy and measurements of all other particles in the event. Calibrations of all detector components, and especially the tagger system, were performed achieving a precision of 1–2 MeV in the nK^+ invariant mass determination. The quality of the channel identification is shown in Fig. 1 where the $\bar{K}^0$ and the missing neutron peaks are seen above a small background.

Reactions involving hyperon decays also contribute to the same final state. The most significant are $\gamma p \rightarrow K^+ \Lambda^*(1520) \rightarrow K^+ \bar{K}^0 n$, $\gamma p \rightarrow \pi^- K^+ \Sigma^+$, and $\gamma p \rightarrow \pi^+ K^+ \Sigma^-$. These backgrounds are easily removed in our analysis with cuts around the known masses. They also serve as checks of our analysis procedure, e.g., by comparing their production cross sections with the world data. Figure 2 shows the background peaks: $\Lambda^*(1520)$ in the K^+ missing mass spectrum and the Σ^+ and Σ^- peaks in the $n\pi^+$ and $n\pi^-$ invariant mass spectra, respectively. The mass region of each of these peaks was excluded from the final data set. After all cuts, the data sample contained approximately 0.17×10^6 events out of the 7×10^9 in the original data set. The resulting nK^+ invariant mass distribution is shown in Fig. 3. The spectrum is smooth and structureless. In particular, no evidence for a peak or an enhancement is observed at masses near 1540 MeV, where signals associated with the Θ^+ were previously reported.

To enhance our sensitivity to a possible resonance signal not visible in the integrated distribution, we considered the two-body reaction $\gamma p \rightarrow \bar{K}^0 \Theta^+(1540)$ and selected different K_S ($\bar{K}^0$) center-of-mass angle intervals. Monte Carlo studies of the CLAS acceptance for this reaction showed that we could detect events over the entire angular range (0°–180°), with some reduction of efficiency at forward angles ($\theta^{\text{c.m.}}_{\bar{K}^0} < 30°$). No structures were found in the distribution when specific angular ranges were selected.

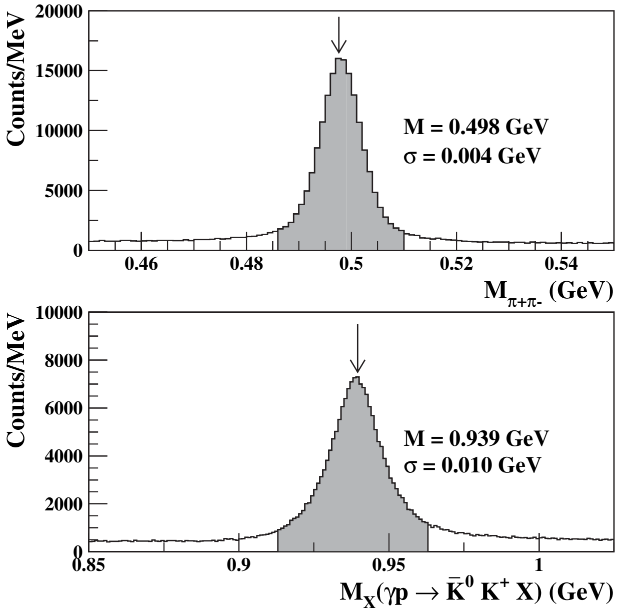

FIG. 1. Top: $\pi^+\pi^-$ invariant mass and the $\bar{K}^0$ peak. Bottom: missing mass for the reaction $\gamma p \rightarrow \bar{K}^0 K^+ X$ after $\bar{K}^0$ selection showing a peak at the neutron mass. The mass positions and widths of the measured peaks are given. For comparison, the arrows indicate the accepted value [36] for the mass position. The shaded area corresponds to the events used in the analysis.

Since no signal was found, an upper limit for the Θ^+ production cross section in this reaction channel was extracted. The unbinned nK^+ mass spectrum was fit in the range 1.45–1.8 GeV using a maximum likelihood procedure, with the sum of a narrow Gaussian function and a 5th-order polynomial that parameterizes, respectively, the Θ^+ contribution and a smooth background. To derive the corresponding event yields, the fitted functions were integrated over $\pm 3\sigma$ around a fixed mass position. The fit procedure was repeated varying the resonance position from 1520 to 1600 MeV in 5 MeV steps while the width σ was fixed at 3.5 MeV. This value was derived by Monte Carlo simulation assuming a negligible intrinsic width as suggested from recent analyses of KN scattering data [34] and therefore dominated by the CLAS experimental resolution. The validity of the Monte Carlo simulations in reproducing the experimental data was checked by comparing the predicted with measured widths of narrow states such as the Σ^+ and Σ^-. The data set was independently analyzed by three groups, each one deriving an estimate of the Θ^+ and background yields. The three analyses differ in the reaction selection cuts, in the background rejection criteria, and in the fit to the mass spectra. The three results were found to be consistent. They were combined by taking the average of both the signal and background yield, assuming totally correlated measurements. These values were then used to evaluate an upper

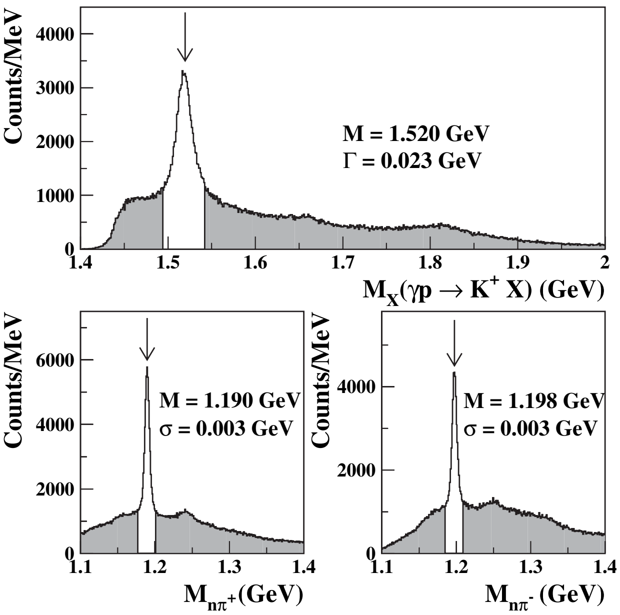

FIG. 2. Top: K^+ missing mass distribution with the $\Lambda^*(1520)$ peak. Bottom: $n\pi^+$ (left) and $n\pi^-$ (right) invariant mass distributions with $\Sigma^+(1189)$ and $\Sigma^-(1197)$ peaks. The mass position and width of the measured peaks are indicated. For comparison, the arrows indicate the accepted value [36] for the mass position. The shaded area corresponds to the events used in the analysis.

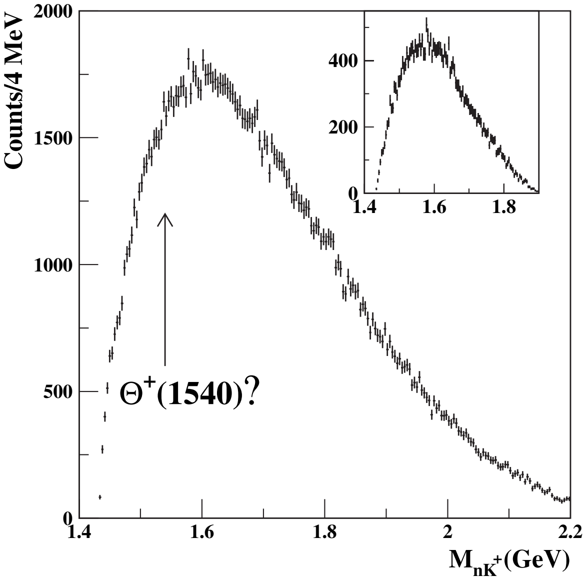

FIG. 3. The nK^+ invariant mass distribution after all cuts. It is smooth and no narrow structures are evident. The arrow shows the position where evidence for the Θ^+ was found by previous experiments. The inset shows the nK^+ mass distribution with specific cuts to reproduce the SAPHIR analysis [4] as described in the text.

limit at 95% C.L. on the Θ^+ yield using the Feldman and Cousins approach [35].

The upper limit on the yields was then transformed into an upper limit on the Θ^+ production cross section taking into account the luminosity of incident photons and target, the CLAS detection acceptance, the $\bar{K}^0 \to K_S \to \pi^+\pi^-$ branching ratios of 50% × 69% [36], the assumed Θ^+ branching ratio to nK^+ of 50%, and several models for the production mechanism. The CLAS acceptance for the detection of the Θ^+ in this reaction was obtained by means of detailed Monte Carlo studies which included knowledge of the detector geometry and response to traversing particles. In the simulation the $\gamma p \to \bar{K}^0\Theta^+ \to \pi^+\pi^-K^+n$ distributions were generated assuming five different Θ^+ production mechanisms: t-exchange dominance (the $\bar{K}^0$ is mainly produced at forward angles in the center-of-mass system), u-exchange dominance (at backward angles), uniformly distributed, and using the predictions of the model in Ref. [37] (with and without K^* exchange process). For the t-exchange hypothesis we used the same angular distribution as for $\gamma p \to K^+\Lambda^*(1520)$ production, which exhibits a typical t-channel forward peaking behavior [38]. The u-exchange distribution was generated the same way but interchanging the center-of-mass angles of the $\bar{K}^0$ and Θ^+. The CLAS overall detection efficiencies obtained with different production mechanisms varied between 2.8% for the t-exchange hypothesis and 5.2% for the angular distribution of Ref. [37] when no K^* exchange process is included. All the upper limits reported in this article were derived in the most conservative scenario, i.e., in the t-exchange hypothesis.

The upper panel in Fig. 4 shows the upper limit on the total cross section as a function of the Θ^+ mass. An upper

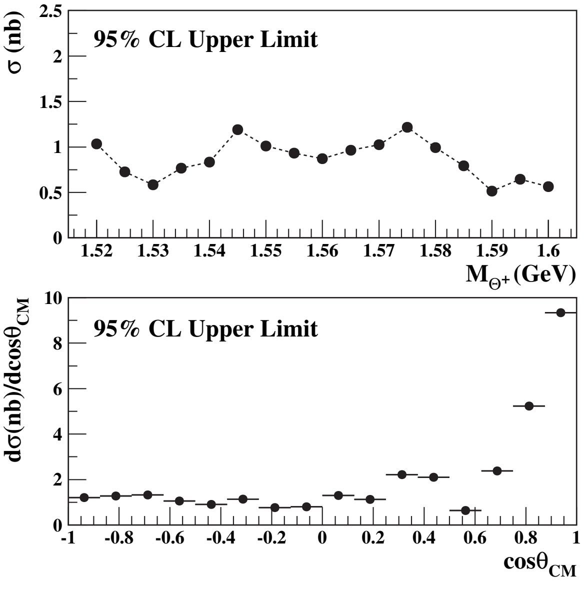

FIG. 4. The 95% C.L. upper limit on the total cross section as a function of the Θ^+ mass (top) and on the differential cross section $d\sigma/d\cos\theta^{\bar{K}^0}_{\mathrm{c.m.}}$ (bottom) for the reaction $\gamma p \to \bar{K}^0\Theta^+$ for an assumed Θ^+ mass of 1540 MeV. The dotted line in the top plot is to guide the eye.

limit of 0.8 nb was found for $M = 1540$ MeV. The process to extract the yield was repeated for each angular bin to derive the 95% C.L. upper limit on the $\Theta^+(1540)$ differential cross section $d\sigma/d\cos\theta_{\mathrm{c.m.}}^{\bar{K}^0}$. The result is shown in the lower panel of Fig. 4. The cross section upper limit remains within about 1–2 nb for most of the angular range and rises at forward angles due to the reduced CLAS acceptance. As a check on our procedure, we extracted the differential and the total cross section for several known reactions from the same data set, finding overall good agreement within experimental uncertainties with the existing world measurements. These results will be reported elsewhere.

Another measure of the strength of the pentaquark signal is to compare the upper limit on the yield to the number of $\Lambda^*(1520)$ events produced in the reaction. The 95% C.L. upper limit on the number of Θ^+ events at a mass of 1540 MeV for our data sample is 220 events. The number of observed $\Lambda^*(1520)$ events, shown in the upper panel of Fig. 2, was determined using a Breit-Wigner resonance shape fit to be 100 k. Thus, the ratio is less than $220/100$ k $= 0.22\%$ (95% C.L.).

Our upper limit on the cross section is in clear disagreement with the findings of Ref. [4] which reported a Θ^+ signal of 63 events at a mass of 1540 MeV corresponding to the published total cross section of 300 nb. In order to better compare with that experiment, we repeated the analysis applying the same cuts reported in that paper: the photon energy was limited to 2.6 GeV, only events with a forward-emitted $\bar{K}^0$ ($\theta_{\mathrm{c.m.}}^{\bar{K}^0} > 60°$) were used and no cuts were made to exclude hyperons. The resulting mass distribution is shown in the inset of Fig. 3: it remains smooth and structureless. Another way to show the inconsistency of the two experiments is to compare the ratio of the upper limit of the number of Θ^+ with the number of the observed $\Lambda^*(1520)$. Applying again the same specific cuts to reproduce the SAPHIR analysis, we evaluated a 95% C.L. limit on the Θ^+ yield of less than 100 events. In the same photon energy range (1.6–2.6 GeV) we observed $\sim 53\,000 \Lambda^*(1520)$'s, compared with a Θ^+ yield of 63 and $630 \Lambda^*(1520)$'s, respectively, reported in Ref. [4]. The ratios obtained in the two experiments differ by more than a factor 50.

In conclusion, this is the first result of a dedicated set of high-statistics and high-resolution experiments undertaken at Jefferson Lab to elucidate the debate on the existence of the pentaquark. The reaction $\gamma p \rightarrow \bar{K}^0 K^+ n$ was studied in search for evidence of the Θ^+ pentaquark in the nK^+ decay channel. The final state was isolated detecting the K^+, the $\bar{K}^0$ by its $\pi^+\pi^-$ decay, and identifying the neutron by means of the missing mass technique. The direct measurement of the K^+ allows one to define the strangeness of any baryon resonance observed in this final state. The nK^+ mass distribution was found to be smooth and structureless. No evidence for a narrow resonance was found in the mass range 1520–1600 MeV. An upper limit of 0.8 nb (95% Confidence Level) on the total production cross section for a Θ^+ mass of 1540 MeV was set. This is in disagreement with previously reported evidence for a resonance in the same reaction channel, and sets stringent upper limits on the models which predict these long-lived pentaquark states.

We would like to acknowledge the outstanding efforts of the staff of the Accelerator and the Physics Divisions at Jefferson Lab that made this experiment possible. This work was supported in part by the Italian Istituto Nazionale di Fisica Nucleare, the French Centre National de la Recherche Scientifique and Commissariat à l'Energie Atomique, the U.S. Department of Energy and National Science Foundation, and the Korea Science and Engineering Foundation. The Southeastern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under Contract No. DE-AC05-84ER40150.

---

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

[†] Current address: Old Dominion University, Norfolk, VA 23529, USA

[‡] Current address: Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA

[§] Current address: University of South Carolina, Columbia, SC 29208, USA

[||] Current address: Physikalisches Institut der Universität Gießen, 35392 Giessen, Germany

[¶] Current address: University of Massachusetts, Amherst, MA 01003, USA

[1] T. Nakano *et al.*, Phys. Rev. Lett. **91**, 012002 (2003).
[2] V. V. Barmin *et al.*, Phys. At. Nucl. **66**, 1715 (2003).
[3] S. Stepanyan *et al.*, Phys. Rev. Lett. **91**, 252001 (2003).
[4] J. Barth *et al.*, Phys. Lett. B **572**, 127 (2003).
[5] V. Kubarovsky *et al.*, Phys. Rev. Lett. **92**, 032001 (2004).
[6] A. E. Asratyan, A. G. Dolgolenko, and M. A. Kubantsev, Phys. At. Nucl. **67**, 682 (2004).
[7] A. Airapetian *et al.*, Phys. Lett. B **585**, 213 (2004).
[8] S. Chekanov *et al.*, Phys. Lett. B **591**, 7 (2004).
[9] A. Aleev *et al.*, Phys. At. Nucl. **68**, 481 (2005).
[10] M. Abdel-Bary *et al.*, Phys. Lett. B **595**, 127 (2004).
[11] P. Z. Aslanyan, V. N. Emelyanenko, and G. G. Rikhkvitzkaya, Nucl. Phys. **A755**, 375 (2005).
[12] D. Diakonov, V. Petrov, and M. Polyakov, Z. Phys. A **359**, 305 (1997).
[13] C. Alt *et al.* (NA49 Collaboration), Phys. Rev. Lett. **92**, 042003 (2004).
[14] A. Aktas *et al.*, Phys. Lett. B **588**, 17 (2004).
[15] S. Schael *et al.*, Phys. Lett. B **599**, 1 (2004).
[16] B. Aubert *et al.*, hep-ex/0408064.
[17] K. Abe *et al.*, hep-ex/0411005.
[18] J. Z. Bai *et al.*, Phys. Rev. D **70**, 012004 (2004).

[19] I. V. Gorelov, hep-ex/0408025; D. O. Litvintsev, Nucl. Phys. B, Proc. Suppl. **142**, 374 (2005).

[20] K. Stenson, Int. J. Mod. Phys. A **20**, 3745 (2005).

[21] I. Abt *et al.*, Phys. Rev. Lett. **93**, 212003 (2004); K. T. Knopfle, M. Zavertyaev, and T. Zivko (HERA-B Collaboration), J. Phys. G **30**, S1363 (2004).

[22] M. J. Longo *et al.*, Phys. Rev. D **70**, 111101(R) (2004).

[23] J. Napolitano, J. Cummings, and M. Witkowski, hep-ex/0412031.

[24] S. R. Armstrong, Nucl. Phys. B, Proc. Suppl. **142**, 364 (2005).

[25] C. Pinkenburg, J. Phys. G **30**, S1201 (2004).

[26] Y. M. Antipov *et al.*, Eur. Phys. J. A **21**, 455 (2004).

[27] M. I. Adamovich *et al.*, Phys. Rev. C **70**, 022201 (2004).

[28] M. Ostrick, Prog. Part. Nucl. Phys. **55**, 337 (2005).

[29] B. Mecking *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **503**, 513 (2003).

[30] D. I. Sober *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **440**, 263 (2000).

[31] M. D. Mestayer *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **449**, 81 (2000).

[32] E. S. Smith *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **432**, 265 (1999).

[33] Y. G. Sharabian *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **556**, 246 (2006).

[34] R. A. Arndt, I. I. Strakovsky, and R. L. Workman, Phys. Rev. C **68**, 042201(R) (2003); R. N. Cahn and G. H. Trilling, Phys. Rev. D **69**, 011501(R) (2004); J. Haidenbauer and G. Krein, Phys. Rev. C **68**, 052201(R) (2003); W. R. Gibbs, Phys. Rev. C **70**, 045208 (2004); A. Sibirtsev *et al.*, Phys. Lett. B **599**, 230 (2004).

[35] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).

[36] S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).

[37] Y. Oh, H. Kim, and S. H. Lee, Phys. Rev. D **69**, 014009 (2004).

[38] D. Barber *et al.*, Z. Phys. C **7**, 17 (1980).