Pentaquarks: the latest experimental results

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Abstract. After the claim of the possible discovery of a pentaquark state, many experiments reported positive and negative results opening a discussion about the pentaquark existence. New experiments with high resolution and high statistics are needed in the reaction channels and for the kinematics of the positive results to solve the controversy. Jefferson Lab started a comprehensive program to search for pentaquark in photoproduction at threshold on proton and deuteron targets, collecting more than 10 times the existing statistics. The first experiment on the proton ($g11$) just finished to analyze the data, and the first results of the pentaquark search are reported here.

Keywords: Pentaquark, photoproduction, proton target.

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INTRODUCTION

All known hadronic matter is composed of two kinds of quark configurations: baryons, such as protons and neutrons, which are combinations of 3 quarks (qqq), and mesons, such as pions, which are combinations of a quark and an anti-quark ($q\bar{q}$). However, states of matter consisting of four quarks and an anti-quark ($qqqq\bar{q}$), called pentaquarks, are expected by the theory of Quantum Chromodynamics. In particular, states where the anti-quark has a different flavor with respect to the others have quantum numbers that are not allowed for standard particles and clearly reveal their 'exotic' nature. In the past, experimental searches focused on the search for pentaquark states, did not provide any clear evidence, leading to the conclusion that discoveries in this field would not be possible in the short term. As a consequence, this particular experimental program was abandoned and no further data analysis was pursued for many years. However, the lack of experimental proof left an open question about the physical manifestation of low-energy QCD. In spite of that, theoretical interest in this field has continued and, recently, Diakonov and collaborators [1] made definite predictions about the masses and widths of a decuplet of pentaquark states (the so-called "antidecuplet"). The most intriguing aspect of such a multiplet is the presence of three states with exotic quantum numbers: the Θ^+ , $S = +1$, and the Ξ^{--} and Ξ^+ with $S = -2$. In particular the Θ^+ strangeness, never observed in the baryon sector and not compatible with a qqq state, requires at least a pentaquark configuration of the type $uudd\bar{s}$. The mass of the Θ^+ was predicted to be quite low (1540 MeV) and its widths very narrow (~ 10 -15 MeV) implying that if such state exists it should be directly visible in the measured invariant masses without need for more sophisticated Partial Wave Analysis.

THE POSITIVE RESULTS

The first evidence of the Θ^+ was obtained in the photoproduction measurement performed by the LEPS Collaboration [2]. The signal was found in the reaction $\gamma n \rightarrow K^- \Theta^+ \rightarrow K^- K^+ n$. The target was a CH_2 scintillator located just downstream of the primary hydrogen (LH_2) target. The signal was seen in the missing mass spectrum of the K^- , after cutting out sources of background from ϕ and $\Lambda(1520)$ production. Corrections to compensate for the neutron's Fermi motion in the carbon nucleus were applied. The final peak was found at a mass of 1540 ± 10 MeV, with a width less than 25 MeV, and a gaussian significance of 4.6σ . This result was shortly thereafter confirmed by the CLAS Collaboration [3] who analyzed existing data on deuteron target looking at the channel $\gamma d \rightarrow K^- K^+ np$. Events with the $K^- K^+ p$ in the final state were selected and the missing mass technique was used to identify the neutron. A peak was observed in the nK^+ invariant mass at a value of 1542 ± 5 MeV, with a width less than 21 MeV, and a statistical significance of more than 5σ . Evidence of a Θ^+ candidate was also found in the reaction $\gamma p \rightarrow K^- \pi^+ \Theta^+ \rightarrow K^- \pi^+ K^+ n$ [4]. DIANA Collaboration re-analyzed the old K -Xenon bubble-chamber data [5] ($K^+ n \rightarrow (\bar{K}^0) \Theta^+ \rightarrow (\bar{K}^0) \pi^+ \pi^- p$) and reported a narrow peak (~ 10 MeV), located at 1.54 GeV with a statistical significance of 4σ . The SAPHIR Collaboration reported about the reaction $\gamma p \rightarrow \bar{K}^0 \Theta^+ \rightarrow K_S K^+ (n)$ where a 5σ peak was isolated in the K_S missing mass. The peak was found to be at 1540 ± 5 MeV and a large production cross section of 300 nb was quoted in the paper [6]. Evidence of a narrow structure in the $(K_S p)$ system was also reported in neutrino and anti-neutrino collisions with nuclei [7] at CERN. A peak of less than 20 MeV width resonance was found at a mass of 1533 ± 5 MeV with a statistical significance of 6.7σ . A narrow 4σ peak in the same invariant mass spectrum, located at 1526 ± 3 MeV, was also found by the Hermes Collaboration [8] in the analysis of quasi-real photo production on a deuteron target. Another positive evidence was also found in pp scattering at few GeV beam energy (COSY-TOF Collaboration [9]). Positive results were then reported analyzing collisions of high energy proton beams against electron beam (ZEUS Collaboration [10]) and fixed targets (SVD-2 Collaborations [11]).

Are all these evidences enough to prove that the pentaquark does exist? The possible discovery of a state beyond ordinary matter triggered the interest of the scientific community, resulting in the publication of more than 500 related papers in the past two years.

THE NEGATIVE RESULTS

First doubts on the pentaquark existence, arise from the fact that, the mass of the Θ^+ measured in the different experiments were not compatible within the quoted errors. In particular, there is a systematic difference for the mass value found in the two possible decay modes: reported values were lower for $\Theta^+ \rightarrow p K^0$ than for $\Theta^+ \rightarrow n K^+$. The difference in the background or interference effects that systematically affect the two decay modes in a different way could explain the difference. One can simply assume that the quoted errors on the measured masses were underestimated but a possible indication of a serious concern about the Θ^+ existence should not be ignored.

In the past year reanalysis of data collected in high energy experiments [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25] show no evidence for pentaquarks. Data were collected in different laboratories (SLAC, DESY, CERN, FERMILAB, BNL) using a variety of different probes (e^+e^- colliders, heavy-ion and high-energy proton-proton and proton-nuclei interactions) and, for the most part of the results, analyzing a huge statistics.

Was it enough to prove that the pentaquark did not exist? The answer is not so simple. As an example we report the argument to exclude the significance of the e^+e^- experiments. It is well known that hadroproduction abundance in e^+e^- collisions as a function of the produced hadron mass has a very steep slope that depends on the number of quark-pairs that have to be generated from the vacuum. Pseudo-scalar mesons (one $q\bar{q}$ pair) are produced with a slope of $\sim 10^{-2}/\text{GeV}$ while baryons (two $q\bar{q}$ pairs more) have $\sim 10^{-4}/\text{GeV}$. Following this logic, one can predict that pentaquarks (four $q\bar{q}$ pairs more) should have a slope of $\sim 10^{-8}/\text{GeV}$ that makes the huge statistics collected by e^+e^- colliders, useless to draw any conclusion.

SECOND GENERATION EXPERIMENTS

In summary, twelve different laboratories, using different probes (photons, electrons, protons, neutrinos) and targets (protons, neutrons, nuclei) reported positive results. Some of them, with a high statistical significance. Limiting aspects of the so-called 'low energy' experiments were: the most part of the observed structures contained only few counts, all peaks did not show at the same mass, the background shape, necessary to define a possible signal over it, was not theoretically understood and the limited statistics prevented to derive a smooth curve directly from the data. Moreover many analyses used strong kinematic cuts to enhance the signal-to-background ratio that may distort the spectra and some experiment did not tag the strangeness of the final state.

Ten 'high energy' experiments reported null results analyzing high statistics data sets deriving stringent upper limits on the Θ^+ production but the different kinematic conditions, which likely involved dissimilar production mechanisms, the unknown relative weight of background reactions that could blind the small pentaquark production at high energies, and the different acceptance of the different detectors make very difficult direct comparisons of the results of the different experiments, preventing a definitive conclusion about the pentaquark's existence.

A second generation of dedicated experiments, optimized for the pentaquark search, was undertaken at Jefferson Lab. These experiments cover the few GeV beam energy region where most of the positive evidence were reported, with each collecting at least an order of magnitude more statistics than any of the previous measurements. The mass resolutions are approximately a 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. All used real photon in different energy ranges and different targets. Two experiments (g10 and eg3) were in the range 1.0-3.0 GeV and 4.0-5.4 GeV respectively and used a liquid deuteron target while one experiment (g11) used a proton target with a photon beam of 1.6-3.8 GeV. The three experiments collected data and now they are completing the physics analyses.

FIGURE 1. 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 for the mass position. The shaded area corresponds to the events used in the analysis.

THE G11 EXPERIMENT AT JLAB

Here we present the first result of the g11 experiment reporting the result of the exclusive measurement of the reaction $\gamma p \rightarrow \bar{K}^0 K^+ n$. The reconstruction of all participating particles (exclusive measurement) allows one to tag the strangeness of the reaction which clearly identifies the exotic nature of the baryon produced in association with the $\bar{K}_0$. This channel was previously investigated at ELSA by the SAPHIR collaboration in a similar photon energy range, finding positive evidence for a narrow Θ^+ state with $M=1540$ MeV and full width half maximum (FWHM) $\Gamma < 25$ MeV. They originally quoted a total production cross section of the order of 300 nb (later reduced to 50 nb [26]). For the first time, the new results put previous findings to a direct test.

The measurement was performed using the CLAS detector in Hall B with a bremsstrahlung photon beam produced by a continuous 60 nA electron beam of $E_0 = 4.0$ GeV impinging on a gold foil 8×10^{-5} radiation lengths thick. A bremsstrahlung tagging system with a photon energy resolution of 0.1% E_0 was used to tag photons in the energy range from 1.6 – 3.8 GeV. A liquid hydrogen target was contained in a mylar cylinder cell 4 cm in diameter and 40 cm long. Outgoing hadrons were detected in the

FIGURE 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 for the mass position. The shaded area corresponds to the events used in the analysis.

CLAS [27] spectrometer. Momentum information for charged particles was obtained via tracking through three regions of multi-wire drift chambers immersed in a toroidal magnetic field (~ 0.5 T), which was generated by six superconducting coils. The field was set to bend the positive particles away from the beam into the acceptance region of the detector. Time-of-flight scintillators (TOF) were used for hadron identification. The interaction time between the incoming photon and the target was measured by the Start Counter (ST), consisting of a set of 24, 2.2 mm thick plastic scintillators surrounding the hydrogen cell. The CLAS momentum resolution is of the order of 0.5-1% 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. Coincidences between the photon tagger and the CLAS detector triggered the recording of the events. The trigger in CLAS was defined requiring the coincidence between the TOF system and the ST in at least two sectors. We took data for 50 days during June and July 2004 collecting more than 7G triggers corresponding to an integrated luminosity of 70 pb^{-1} . This is probably the highest statistics ever collected in experiments with tagged photons.

FIGURE 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 [6] as described in the text.

FIRST RESULTS

The reaction $\gamma p \rightarrow K^- \Theta^+ \rightarrow \bar{K}^0 K^+ n$ was isolated as follows. The K^+ was detected directly in the magnetic spectrometer, and the K^0 was reconstructed from its $\pi^+ \pi^-$ decay. The momentum and energy of the neutron were reconstructed from the known incident photon energy and measurements of all other particles in the event. The quality of the channel identification is shown in Figure 1 where the K_S^0 and the missing neutron peaks are seen above a small background. Reactions involving decay of hyperons, contribute to the same final state. The most sizable are: $\gamma p \rightarrow K^+ \Lambda^*(1520) \rightarrow K^+ \bar{K}^0 n$, $\gamma p \rightarrow \pi^- K^+ \Sigma^+$, and $\gamma p \rightarrow \pi^+ K^+ \Sigma^-$. Figure 2 shows the background hyperon peaks: $\Lambda^*(1520)$ in the K^+ missing mass spectrum and the Σ^+ , Σ^- peaks in the $n\pi^+$ and $n\pi^-$ invariant mass spectra respectively. The mass region of each of these hyperon peaks was excluded from the final data set, as shown from the shaded regions in the same figure. While they represent a background to the pentaquark search, but easily removable in our analysis with a cut around their masses, they can be used as a check of the entire procedure, e.g. by extracting their production cross sections and comparing to the world data. After all cuts, the data sample contains 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 distribution 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 a possible resonance signal not visible in the integrated distribution, we selected different 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 ($\theta_{K^0}^{CM} < 30^\circ$). No structures were found in the distribution when specific angular ranges were selected.

Since no signal was found, an upper limit for the Θ^+ production cross section in this reaction channel was extracted. The nK^+ mass distribution was fit using the maximum likelihood procedure to the sum of a narrow Gaussian function and a 5^{th} -order polynomial that parameterizes, respectively, the Θ^+ contribution and a smooth background. The resonance position was varied from 1520 to 1600 MeV in 5 MeV steps while the width was fixed at 2.5 MeV, a value derived by Monte Carlo simulation for a long-lived resonance and following the same analysis chain used to process the data. The measured yields were then used to evaluate an upper limit on the Θ^+ yield using the Feldman and Cousins approach [28]. The upper limit on the number of Θ^+ events at the 95% confidence level was compared with the number of observed $\Lambda^*(1520)$'s shown in the upper panel of Fig. 2, which was estimated using a Breit-Wigner resonance shape fit. The ratio between the two yields is $\sim 220/100k = 0.22\%$. 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 Θ^+ branching ratio to nK^+ of 50%, and several models for the production mechanism. The upper panel in Fig. 4 shows the upper limit on the total cross section as a function of the Θ^+ mass obtained in the most conservative scenario (forward peaked center-of-mass production). An upper limit of 0.8 nb was found for $M=1540$ MeV including a systematic uncertainty of 20% estimated by comparing different analysis procedures. The process to extract the yield described above was repeated for each angular bin to derive the 95% CL upper limit on the $\Theta^+(1540)$ differential cross section. 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.

Our upper limit on the cross section is in clear disagreement with the findings of Ref.[6] which reported a Θ^+ signal of 55 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 $\bar{K}^0$ ($\theta_{CM}^{\bar{K}^0} > 60^\circ$) were used and the hyperons were not cut. The resulting mass distribution is shown in the inset of Fig. 2: it remains smooth and structureless.

CONCLUSIONS

Spurred by an initial report by the LEPS Collaboration in 2003, many experimental collaborations reported possible evidence for a pentaquark state. The observed signals

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

suffered from low statistics and were challenged by null results reported last year by many other experiments in different kinematic regions and reactions. Our analysis of a dedicated high-statistics and high-resolution measurement conducted under similar kinematic conditions and with more than ten times the statistics of a previously reported positive result found that there is no evidence for a Θ^+ pentaquark in $\bar{K}_0 K^+ n$ reaction channel setting an upper limit of less than 1nb on the production cross section. Analysis of other reaction channels on the new JLab data are still underway and expected to release results in a short time.

REFERENCES

1. D. Diakonov, V. Petrov and M. Polyakov, Z. Phys. A **359**, 305 (1997).
2. T. Nakano *et al.* (LEPS Collaboration), Phys. Rev. Lett. **91**, 012002 (2003).
3. S. Stepanyan *et al.* (CLAS Collaboration), Phys. Rev. Lett. **91**, 252001 (2003).
4. V. Kubarovsky *et al.* (CLAS Collaboration), Phys. Rev. Lett. **92**, 032001 (2004).
5. V. V. Barmin *et al.* (DIANA Collaboration), Phys. Atom. Nucl. **66**, 1715 (2003).
6. J. Barth *et al.* (SAPHIR Collaboration), Phys. Lett. B **572**, 127 (2003).
7. A.E. Asratyan, A.G. Dolgolenko, and M.A. Kubantsev, Phys. Atom. Nucl. **67**, 682 (2004).

8. A. Airapetian *et al.* (HERMES Collaboration), Phys. Lett. B **585**, 213 (2004).
9. M. Abdel-Bary *et al.* (COSY-TOF Collaboration), Phys. Lett. B **595**, 127 (2004).
10. S. Chekanov *et al.* (ZEUS Collaboration), Phys. Lett. B **591**, 7 (2004).
11. A. Aleev *et al.* (SVD Collaboration), Phys. At. Nucl. **68**, 974 (2005) and hep-ex/0509033.
12. A. Aktas *et al.* (H1 Collaboration), Phys. Lett. B **588**, 17 (2004).
13. S. Schael *et al.* (ALEPH Collaboration), Phys. Lett. B **599**, 1 (2004).
14. B. Aubert *et al.* (BABAR Collaboration), arXiv:hep-ex/0408064.
15. K. Abe *et al.* (Belle Collaboration), arXiv:hep-ex/0411005.
16. J. Z. Bai *et al.* (BES Collaboration), Phys. Rev. D **70**, 012004 (2004).
17. I. V. Gorelov (CDF Collaboration), arXiv:hep-ex/0408025; D. O. Litvintsev (CDF Collaboration), Nucl. Phys. Proc. Suppl. **142**, 374 (2005).
18. K. Stenson (FOCUS Collaboration), arXiv:hep-ex/0412021.
19. I. Abt *et al.* (HERA-B Collaboration), Phys. Rev. Lett. **93**, 212003 (2004); K. T. Knopfle, M. Zavertyaev and T. Zivko (HERA-B Collaboration), J. Phys. G **30**, S1363 (2004).
20. M. J. Longo *et al.* (HyperCP Collaboration), Phys. Rev. D **70**, 111101 (2004).
21. J. Napolitano, J. Cummings and M. Witkowski, arXiv:hep-ex/0412031.
22. S. R. Armstrong, Nucl. Phys. Proc. Suppl. **142**, 364 (2005).
23. C. Pinkenburg (PHENIX Collaboration), J. Phys. G **30**, S1201 (2004).
24. Y. M. Antipov *et al.* (SPHINX Collaboration), Eur. Phys. J. A **21**, 455 (2004).
25. M. I. Adamovich *et al.* (WA89 Collaboration), arXiv:hep-ex/0405042.
26. M. Ostrick, Prog. Part. Nucl. Phys. **55**, 337 (2005).
27. B. Mecking *et al.*, *Nucl. Instrum. and Meth.* **A503**, 513 (2003).
28. G. J. Feldman and R. D. Cousins, Phys. Rev. D **57** 3873 (1998).