

SEARCH FOR PENTAQUARKS WITH HERA-B*

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A large data set of proton-nucleus collisions at $\sqrt{s} = 41.6$ GeV has been searched for Θ^+ and $\Xi(1862)$ pentaquark candidates. In 2×10^8 inelastic events we find no evidence for narrow signals ($\sigma \approx 5$ MeV/ c^2) in the $\Theta^+ \rightarrow pK_s^0$ and $\Xi(1862) \rightarrow \Xi\pi$ channels. Upper limits on production cross sections at mid-rapidity and on ratios of production cross sections to those of well established resonances are presented.

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1. Introduction

The possible discovery of an exotic baryon with at least five constituent quarks in γn reactions at low energies [1] has initiated a very active search for these so-called pentaquark states. Up to now, twelve experiments [1–12] have reported evidence for a narrow resonance Θ^+ with a mass near to 1540 MeV/ c^2 decaying into pK_s^0 or nK^+ final states. In contrast to this, the higher mass states $\Xi^{--}(1862) \rightarrow \Xi^-\pi^-$ [13] and $\Theta_c^0 \rightarrow D^*p$ [14] were each observed by only one experiment.

However, despite all these experimental data, this subject remains controversial because an increasing amount of experiments report negative results on searches for these states [15–27]. Furthermore, the masses of the Θ^+ candidates show a large and systematic spread. For recent reviews of the experimental situation see [28–30] and references therein.

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2. Data sample

HERA-B is a fixed-target experiment which studies collisions of protons with the nuclei of atoms in target wires positioned in the halo of HERA's 920 GeV proton beam. The large acceptance of the HERA-B spectrometer coupled with high-granularity particle-identification devices and a precision vertex detector allow for detailed studies of complex multi-particle final states. Fig. 1 shows a plan view of the detector in the configuration of the 2002–2003 data run.

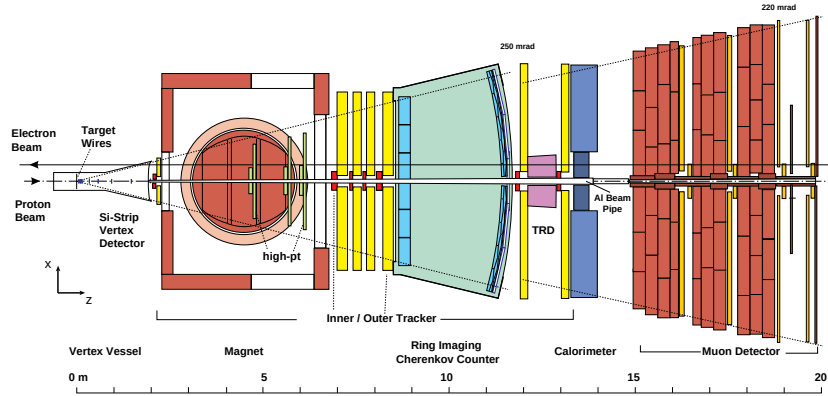


Fig. 1. Plan view of the HERA-B detector.

For this analysis [31] the information from the silicon vertex detector, the main tracking system, the ring-imaging Cherenkov counter and the electromagnetic calorimeter was used. A data sample of 2×10^8 minimum bias events was recorded at $\sqrt{s} = 41.6$ GeV using target wires of different materials (carbon, titanium and tungsten).

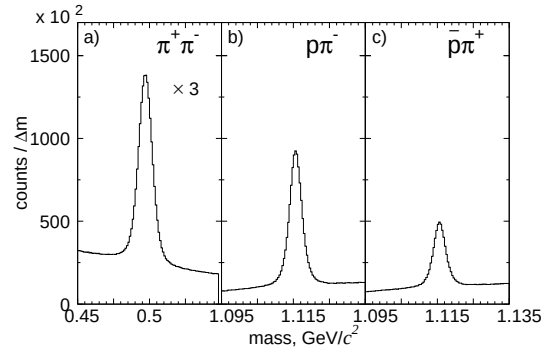


Fig. 2. Signals obtained with the C target from decays of (a) $K_s^0 \rightarrow \pi^+ \pi^-$, (b) $\Lambda \rightarrow p \pi^-$ and (c) $\bar{\Lambda} \rightarrow \bar{p} \pi^+$.

Applying soft vertex cuts, signals from $K_s^0 \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ are identified above a small background, as can be seen in Fig. 2. K_s^0/Λ ambiguities are rejected. Selecting Λ 's by an invariant mass cut of 3σ around the peak value and requesting the $\Lambda\pi^-$ vertex to be at least 2.5 cm downstream of the target, we obtain clean signals of $\Xi^- \rightarrow \Lambda\pi^-$ and charge conjugated (c.c.) decays (see Fig. 3(a)). The statistics of these signals together with their mass resolutions is given in Table I.

TABLE I

Statistics and experimental resolutions σ of the relevant signals.

Signal	C target	all targets	σ / (MeV/ c^2)
K_s^0	2.2M	4.9M	4.9
Λ [c.c.]	440k [210k]	1.1M [520k]	1.6
$\Lambda(1520)$ [c.c.]	1.3k [760]	3.5k [2.1k]	2.3
Ξ^- [c.c.]	4.7k [3.4k]	12k [8.2k]	2.6
$\Xi(1530)^0$ [c.c.]	610 [380]	1.4k [940]	2.9

3. Search for $\Theta^+ \rightarrow pK_s^0$

Protons are identified by requesting that the proton likelihood, which is provided by the RICH, be above 0.95. This cut allows to reduce the misidentification probability to less than 1% in the selected momentum range from 22 to 55 GeV/c. As a reference state we reconstruct the $\Lambda(1520)$ by its decay into pK^- . A prominent $\Lambda(1520) + \text{c.c}$ signal can be seen in Fig. 3(b).

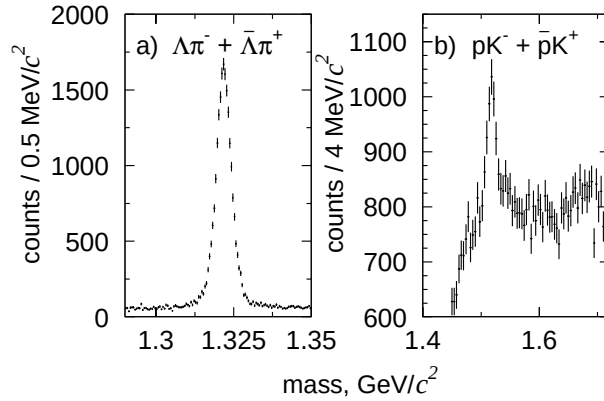


Fig. 3. Signals obtained with the C target from decays of (a) $\Xi^- \rightarrow \Lambda\pi^-$ and $\Xi^+ \rightarrow \bar{\Lambda}\pi^+$, and (b) $\Lambda(1520) \rightarrow pK^-$ and $\bar{\Lambda}(1520) \rightarrow \bar{p}K^+$.

For the search for $\Theta^+ \rightarrow pK_s^0$ decays, we combine these well identified protons with K_s^0 candidates. The invariant mass distribution is shown in Fig. 4(a) for the carbon sample. The spectrum exhibits a smooth shape which is well described by the background estimate obtained from event mixing. In order to determine an upper limit on the production cross section at mid-rapidity, we fit the spectrum with a Gaussian plus a background of fixed shape. Due to the uncertainty in the Θ^+ mass, the mean of the Gaussian is varied in steps of $1 \text{ MeV}/c^2$. The resolution increases from 2.6 to $6.1 \text{ MeV}/c^2$ over the considered mass range. The resolution is $3.9 \text{ MeV}/c^2$ at $1530 \text{ MeV}/c^2$ which is approximately the mean of the reported Θ^+ masses in the pK_s^0 channel. Using the prescription of Feldman and Cousins [32], we arrive at the upper limit (95%) curve for $\mathcal{B} \times d\sigma/dy$ per carbon nucleus shown as solid line in Fig. 4(b). The rapidity interval selected is $y_{\text{cm}} = \pm 0.3$. The dashed line indicates the experimental sensitivity. The range of reported mass values of Θ^+ candidates is indicated by arrows in Fig. 4(b).

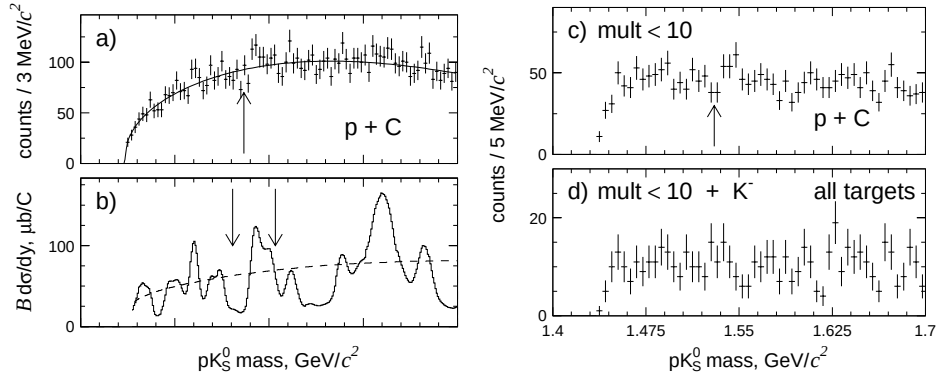


Fig. 4. The pK_s^0 invariant mass distributions: (a) data from pC collisions and background estimate (line); (b) upper limit at 95% CL on $\mathcal{B} \times d\sigma/dy$ per carbon nucleus; the dashed line shows our 95% CL sensitivity; (c), (d) same as (a) but requiring (c) a charged track multiplicity of < 10 , and (d) in addition a strange particle in the event. The arrows mark the masses of 1521, 1530 and 1555 MeV/c^2 .

Further search strategies are tried including (i) a cut on the charged track multiplicity of < 10 (Fig. 4(c)), or (ii) the additional request of a strange tagging particle such as Λ , Σ or K^- (Fig. 4(d)). No statistically significant structure can be observed.

Searching the carbon sample within the mass interval indicated in Fig. 4(b), the largest positive fluctuation of 54 ± 23 events can be found at a mass of $1541 \text{ MeV}/c^2$ (see Fig. 5(a)). For the Ti sample (Fig. 5(b)) we find 13 ± 22 at a mass of $1521 \text{ MeV}/c^2$ and for the W sample (Fig. 5(c)) 68 ± 34

at a mass of $1518 \text{ MeV}/c^2$, respectively. All these peaks are consistent with statistical fluctuations. Assuming an atomic mass dependence of $A^{0.7}$ for the production cross section, the UL(95%) of $\mathcal{B} \times d\sigma/dy$ varies from 3 to $22 \text{ } \mu\text{b}/\text{nucleon}$ for a Θ^+ mass between 1521 and $1555 \text{ MeV}/c^2$. The upper limits derived from the full data sample are in agreement with the carbon results (see Table II).

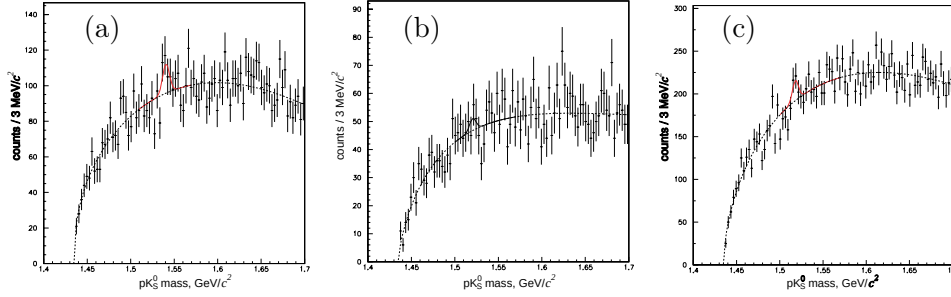


Fig. 5. The pK_s^0 invariant mass distributions for the (a) carbon, (b) titanium and (c) tungsten data sets. The full line indicates a fit with a Gaussian and fixed background in the region with the highest upper limit.

TABLE II

Upper limits (95%) of $\mathcal{B} \times d\sigma/dy$ per nucleon for Θ^+ pentaquarks in $\mu\text{b}/N$.

Mass (MeV/c^2)	1530		1521–1555	
Signal	C target	all targets	C target	all targets
$\Theta^+ \rightarrow pK_s^0$	3.7	4.8	3–22	4–16

In addition, we have evaluated the upper limit on the ratios of Θ^+ to Λ and $\Lambda(1520)$, allowing for a direct comparison with other experiments. Assuming $\mathcal{B}(\Theta^+ \rightarrow pK_s^0) = 0.25$, we obtain the following upper limits at 95% CL: $\Theta^+/\Lambda = 0.92\%$ and $\Theta^+/\Lambda(1520) = 2.7\%$ at a mass of $1530 \text{ MeV}/c^2$, using the full data sample. For a Θ^+ mass of $1540 \text{ MeV}/c^2$, the quoted values must be multiplied by ≈ 4 . Assuming similar production mechanisms, our limits are at variance with the findings of HERMES [7] and ZEUS [11, 33] experiments (see Table III).

TABLE III

Relative yields of Θ^+ assuming $\mathcal{B}(\Theta^+ \rightarrow pK_s^0) = 0.25$ for a mass value of $1530 \text{ MeV}/c^2$. The HERA-B results refer to the full data sample.

Reaction	$\sqrt{s}$ (GeV)	source	Θ^+/Λ	$\Theta^+/\Lambda(1520)$
$pA, y \approx 0$	41.6	HERA-B	< 0.0092	< 0.027
ed	27.6	HERMES		1.6–3.5
ep	320	ZEUS	0.05	

4. Search for $\Xi(1862) \rightarrow \Xi\pi$

We search for neutral and doubly-charged pentaquark candidates in the $\Xi\pi$ channels. The pion tracks are requested to come from the primary vertex. In addition, soft particle identification cuts are applied. The invariant mass spectra of all four $\Xi\pi$ combinations from our carbon sample are plotted in Fig. 6(a). The background estimates obtained from event mixing normalized to the data are indicated as smooth lines. The $\Xi^0(1530)$ hyperons show up as a prominent signal (see Table I) in both neutral charge combinations. However, none of these mass spectra shows evidence for the narrow pentaquark candidates at $1862 \text{ MeV}/c^2$ reported by the NA49 collaboration [13].

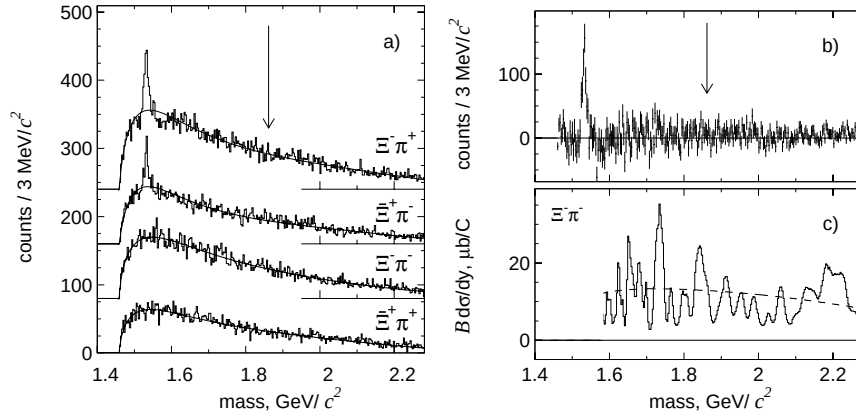


Fig. 6. The $\Xi\pi$ invariant mass distributions: (a) data from pC collisions and background estimate (line) in all four charge combinations; (b) sum of all four $\Xi\pi$ spectra with the background subtracted; (c) upper limit (95%) for the pC production cross section at mid-rapidity; the dashed line shows our 95% CL sensitivity. The arrow marks the mass of $1862 \text{ MeV}/c^2$.

The sum of the four spectra is plotted in Fig. 6(b) and can be compared directly to Fig. 3 of Ref. [13]. As described in the previous chapter, we obtain the upper limit (95%) curve for $\mathcal{B} \times d\sigma/dy$. For the carbon sample, the result for $\Xi^- \pi^-$ combinations is shown as a solid line in Fig. 6(c). The experimental mass resolution increases from 2.9 to 10.6 MeV/ c^2 in the mass range considered and is 6.6 MeV/ c^2 at 1862 MeV/ c^2 . The rapidity interval selected is $y_{cm} = \pm 0.7$. The dashed line indicates the experimental sensitivity. The upper limits are summarized in Table IV.

TABLE IV

Upper limits (95%) of $\mathcal{B} \times d\sigma/dy$ per nucleon for $\Xi(1862)$ pentaquarks in $\mu\text{b}/N$.

Signal	C target	all targets
$\Xi^{--}(1862) \rightarrow \Xi^- \pi^-$	2.5	2.7
$\Xi^0(1862) \rightarrow \Xi^- \pi^+$	2.3	3.2
$\Xi^{++}(1862) \rightarrow \Xi^+ \pi^+$	0.85	0.94
$\Xi^0(1862) \rightarrow \Xi^+ \pi^-$	3.1	3.1

The upper limits (95%) on the cross section ratios $\Xi^{--}/\Xi^0(1530)$ and Ξ^{--}/Ξ^- are collected in Table V together with limits measured by ZEUS [26] and CDF [18]. In order to compare our limit with the findings of NA49, we take the estimated number of $\Xi^{--}(1862)$ candidates from Ref. [13] and the estimated number (150) of $\Xi^0(1530)$ events from the same data set [34]. Assuming the relative efficiencies for $\Xi^{--}(1862)$ and $\Xi^0(1530)$ are similar for both HERA-B and NA49 detectors, we obtain a cross section ratio of $\Xi^{--}/\Xi^0(1530) \approx 0.18/\mathcal{B}$ for the NA49 signal which is in contradiction to our upper limit.

TABLE V

Relative yields of $\Xi(1862)$. The HERA-B results refer to the full data sample.

Reaction	$\sqrt{s}$ (GeV)	source	Ξ^{--}/Ξ^-	$\Xi^{--}/\Xi^0(1530)$
pA , $y \approx 0$	41.6	HERA-B	$< 0.03/\mathcal{B}$	$< 0.04/\mathcal{B}$
pp	17.0	NA49		$0.18/\mathcal{B}$
ep	320	ZEUS		$< 0.28/\mathcal{B}$
pp	1960	CDF		$< 0.04/\mathcal{B}$

5. Summary

In conclusion, HERA-B has found no evidence for narrow pentaquarks decaying into pK_s^0 or $\Xi\pi$ final states. We have set upper limits at 95% CL on the production cross sections $\mathcal{B} \times d\sigma/dy$ at mid-rapidity assuming the width of these states to be less than our experimental resolution of ≈ 5 MeV/ c^2 . Searching the full data sample for $\Theta^+ \rightarrow pK_s^0$ decays, the limit varies from 4 to 16 $\mu\text{b}/\text{nucleon}$ for a mass between 1521 and 1555 MeV/ c^2 . Assuming comparable production mechanisms, our limits of $\Theta^+/\Lambda < 0.92\%$ and $\Theta^+/\Lambda(1520) < 2.7\%$ contradict the results of ZEUS and HERMES experiments, respectively. Analyzing the $\Xi\pi$ channels, we determine upper limits $\mathcal{B} \times d\sigma/dy$ for $\Xi(1862)$ pentaquark candidates. Combining all three data samples, we obtain for a narrow resonance at a mass of 1862 MeV/ c^2 , 2.7, 3.2, 0.94 and 3.1 $\mu\text{b}/\text{nucleon}$ for $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\Xi^+\pi^+$ and $\Xi^+\pi^-$ final states, respectively. The upper limit (95%) on the cross section ratio $\Xi^{--}/\Xi^0(1530)$ of $0.04/\mathcal{B}$ is inconsistent with the evidence published by NA49 for such a resonance.

REFERENCES

- [1] T. Nakano *et al.* (LEPS Collaboration), *Phys. Rev. Lett.* **91**, 012002 (2003).
- [2] V.V. Barmin *et al.* (DIANA Collaboration), *Phys. Atom. Nucl.* **66**, 1715 (2003).
- [3] S. Stepanyan *et al.* (CLAS Collaboration), *Phys. Rev. Lett.* **91**, 252001 (2003).
- [4] J. Barth *et al.* (SAPHIR Collaboration), *Phys. Lett.* **B572**, 127 (2003).
- [5] A.E. Asratyan, A.G. Dolgolenko, M.A. Kubantsev, *Phys. Atom. Nucl.* **67**, 682 (2004).
- [6] V. Kubarovsky *et al.* (CLAS Collaboration), *Phys. Rev. Lett.* **92**, 032001 (2004), Erratum-ibid. **92**, 049902 (2004).
- [7] A. Airapetian *et al.* (HERMES Collaboration), *Phys. Lett.* **B585**, 213 (2004).
- [8] A. Aleev *et al.* (SVD Collaboration), [hep-ex/0401024](#).
- [9] M. Abdel-Bary *et al.* (COSY-TOF Collaboration), *Phys. Lett.* **B595**, 127 (2004).
- [10] P.Zh. Aslanyan, V.N. Emelyanenko, G.G. Rikhhkvitzkaya, [hep-ex/0403044](#).
- [11] S. Chekanov *et al.* (ZEUS Collaboration), *Phys. Lett.* **B591**, 7 (2004).
- [12] Yu.A. Troyan *et al.*, [hep-ex/0404003](#).
- [13] C. Alt *et al.* (NA49 Collaboration), *Phys. Rev. Lett.* **92**, 042003 (2004).
- [14] A. Aktas *et al.* (H1 Collaboration), *Phys. Lett.* **B588**, 17 (2004).
- [15] K.T. Knöpfle *et al.* (HERA-B Collaboration), *J. Phys. G* **30**, S1363 (2004).
- [16] M.I. Adamovich *et al.* (WA89 Collaboration), *Phys. Rev.* **C70**, 022201 (2004).

- [17] Yu.M. Antipov *et al.* (SPHINX Collaboration), *Eur. Phys. J.* **A21**, 455 (2004).
- [18] I.V. Gorelov (CDF Collaboration), [hep-ex/0408025](#).
- [19] B. Aubert *et al.* (BABAR Collaboration), [hep-ex/0408037](#).
- [20] S. Schael *et al.* (ALEPH Collaboration), *Phys. Lett.* **B599**, 1 (2004).
- [21] S. Chekanov *et al.* (ZEUS Collaboration), *Eur. Phys. J.* **C38**, 29 (2004).
- [22] M.J. Longo *et al.* (HyperCP Collaboration), *Phys. Rev.* **D70**, 111101 (2004).
- [23] X. Shen (BES Collaboration), [hep-ex/0410093](#).
- [24] K. Stenson, (FOCUS Collaboration), [hep-ex/0412021](#).
- [25] A. Airapetian *et al.* (HERMES Collaboration), *Phys. Rev.* **D71**, 032004 (2005).
- [26] S. Chekanov *et al.* (ZEUS Collaboration), *Phys. Lett.* **B610**, 212 (2005).
- [27] E.S. Ageev *et al.* (COMPASS Collaboration), [hep-ex/0503033](#).
- [28] A.R. Dzierba, C.A. Meyer, A.P. Szczepaniak, [hep-ex/0412077](#).
- [29] S. Kabana, [hep-ex/0503020](#).
- [30] K.H. Hicks, [hep-ex/0504027](#).
- [31] I. Abt *et al.* (HERA-B Collaboration), *Phys. Rev. Lett.* **93**, 212003 (2004).
- [32] G.J. Feldman, R.D. Cousins, *Phys. Rev.* **D57**, 3873 (1998).
- [33] R. Yoshida, *Acta Phys. Pol. B* **36**, (2005), these proceedings.
- [34] H.G. Fischer, S. Wenig, *Eur. Phys. J.* **C37**, 133 (2004).