DESY 04-148

Limits for the central production of Θ^+ and Ξ^{--} pentaquarks in 920 GeV pA collisions

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We have searched for $\Theta^+(1540)$ and $\Xi^{--}(1862)$ pentaquark candidates in proton-induced reactions on C, Ti and W targets at mid-rapidity and $\sqrt{s} = 41.6$ GeV. In $2 \cdot 10^8$ inelastic events we find no evidence for narrow ($\sigma \approx 5\,\mathrm{MeV}/c^2$) signals in the $\Theta^+ \to \mathrm{pK}^0_S$ and $\Xi^{--} \to \Xi^-\pi^-$ channels; our 95% CL upper limits (UL) for the inclusive production cross section times branching fraction $\mathcal{B}{\cdot}\mathrm{d}\sigma/\mathrm{dy}|_{y\approx 0}$ are 3.7 and 2.5 μb/N. The UL of the yield ratio of $\Theta^+ / \Lambda(1520) < 2.7\,\%$ is significantly lower than model predictions. Our UL of $\mathcal{B}{\cdot}\Xi^{--} / \Xi(1530)^0 < 4\%$ is at variance with the results that have provided first evidence for the Ξ^{--} signal.

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Recent experimental evidence suggests not only that pentaquarks (PQs), i.e. baryons with at least five constituent quarks, exist but that their production in high energy collisions is common. After the possible discovery of the Θ^+ PQ ($uudd\bar{s}$) at 1540 MeV/c^2 in the $\gamma\mathrm{n} \to \mathrm{K}^-\mathrm{K}^+\mathrm{n}$ process on carbon [1], more than 10 experiments using incident beams of photons, electrons, kaons, protons or (anti)-neutrinos have observed resonances within ± 20 MeV/c^2 of this mass in either the nK^+ [2] or the pK^0_S [3, 4, 5] decay channels; the measured widths have all been consistent with the experimental resolutions ranging from 20 MeV/c^2 to 2 MeV/c^2 [5]. The Θ^+ interpretation is based on a prediction [6] of the chiral soliton model (CSM) according to which the Θ^+ is expected to have a mass of 1530 MeV/c^2, a width of less than 15 MeV/c^2, and to decay into the KN channel. In both the CSM and the correlated quark model [7], the Θ^+ is a member of an antidecuplet with two further exotic isospin 3/2 states of $S = -2$, the Ξ^{--} ($ddss\bar{u}$) and the $\Xi^+_{3/2}$ ($uuss\bar{d}$). In pp collisions at $\sqrt{s} \approx 18$ GeV, narrow candidate resonances for both the Ξ^{--} and its neutral isospin partner have been found in the $\Xi^-\pi^-$ and $\Xi^-\pi^+$ final states at the mass of 1862 MeV/c^2 [8]. Theoretically, PQs are not restricted to the strange sector, and experimental evidence for an anti-charmed PQ, Θ^0_c ($uudd\bar{c}$), with a mass of 3.1 GeV/c^2 has recently been reported [9]. In this context also earlier already 'forgotten' $\mathrm{c\bar{c}}$ PQ candidates [10] have been recalled [11].

On the other hand, criticism addressed to some of the reported PQ signals includes the problem of kinematic reflections [12], of spurious states [13], and of low statistics [14]. Other puzzles include the surprisingly narrow width of the Θ^+ [15], the large and systematic [16] spread of measured Θ^+ masses, and the non-observation of the Θ^0_c in an equivalent experiment [17]. Hence, for establishing the existence and character of the new resonances, high statistics mass spectra are needed as well as measurements of spin, parity, width and cross sections. In addition, considering the results of high statistics studies which have found neither the Θ^+ signal in $\psi(2S)$ and J/ψ hadronic decays [18] nor the Ξ^{--} signal in Σ^--induced reactions on nuclear targets [19], the need for a thorough understanding of the PQ production mechanism has been emphasized [20]. Benchmarks for PQ production exist based on statistical hadronization models; they typically predict particle ratios such as $\Theta^+/\Lambda(1520)$ in heavy ion [21, 22, 23] and pp [23, 24, 25] collisions. Taking advantage of a large data sample with good mass resolution (see Table I) HERA-B can contribute significantly to many of these topics. The simultaneous study of $\Theta^+ \to \mathrm{pK}^0_S \to \mathrm{p}\pi^-\pi^+$ and $\Xi^{--} \to \Xi^-\pi^- \to \Lambda\pi^-\pi^-$ decays in proton-nucleus collisions at $\sqrt{s}$=41.6 GeV allows a test of these theoretical predictions and a comparison with earlier experimental results including the possible first confirmation of the Ξ^{--} signal.

TABLE I: Statistics and experimental resolutions σ of the relevant signals (charge-conjugate modes indicated by c.c.).

Signal	C target	all targets	$\sigma/(\mathrm{MeV}/c^2)$
K^0_S	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

HERA-B is a fixed target experiment at the 920 GeV proton storage ring of DESY. It is a forward magnetic spectrometer with a large acceptance centered at mid-rapidity ($\mathrm{y}_{cm} \approx 0$), featuring a high-resolution vertexing and tracking system and excellent particle identification [26]. The present study is based on a sample of $2 \cdot 10^8$ minimum bias events which were recorded at $\sqrt{s} = 41.6$ GeV using carbon (C), titanium (Ti) and tungsten (W) wire targets during the 2002/03 run pe-

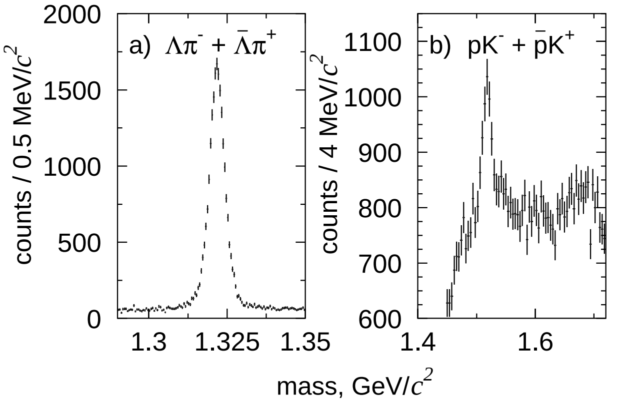

FIG. 1: Signals obtained with the C target from decays of a) $\Xi^- \to \Lambda\pi^-$ and $\bar{\Xi}^+ \to \bar{\Lambda}\pi^+$, and b) $\Lambda(1520) \to pK^-$ and $\bar{\Lambda}(1520) \to \bar{p}K^+$.

riod. For this analysis the information from the silicon vertex detector, the main tracking system, the ring-imaging Cherenkov counter (RICH), and the electromagnetic calorimeter (ECAL) was used.

With standard techniques described in [26], signals from $K^0_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ decays are identified above a small background without particle identification (PID) requirements. Similar clean signals from $\Xi^- \to \Lambda\pi^-$ and c.c. decays (Fig. 1a) are obtained by requesting the $\Lambda\pi^-$ vertex to be at least 2.5 cm downstream of the target and the event to exhibit a cascade topology: a further downstream Λ vertex and the Ξ^- pointing back to the target wire (impact parameter $b < 1$ mm). Table I summarizes the statistics of these signals, together with their measured mass resolutions σ. These resolutions are about 20% larger than those of the Monte Carlo (MC) simulation, while all mass values agree within $<1\,\mathrm{MeV}/c^2$ with the nominal masses. For all particle selections, invariant masses are required to be within $\pm 3\sigma$ of the respective nominal mass.

For the search for $\Theta^+ \to pK^0_S$ decays, events with at least one reconstructed primary vertex were selected. The proton PID was provided by the RICH. The cut in proton likelihood of > 0.95 implies a misidentification probability of less than 1% in the selected momentum range from 22 to 55 GeV/c [27]. The Λ and $\bar{\Lambda}$ contaminations [13] were removed [26] in the K^0_S sample. The invariant mass spectrum of the pK^0_S pairs is shown in Fig. 2a) for the p+C data. The solid line represents the background determined from event mixing after normalization to the data. The spectrum exhibits a smooth shape in the mass region from 1.45 to 1.7 GeV/c^2. Using the prescription of ref. [28], we have calculated from these data upper limits at 95% confidence level, UL(95%), for the inclusive production cross section of a narrow resonance at mid-rapidity, $\mathcal{B}{\cdot}\mathrm{d}\sigma/\mathrm{dy}|_{y\approx 0}$, (Fig. 2b); the y_{cm}-

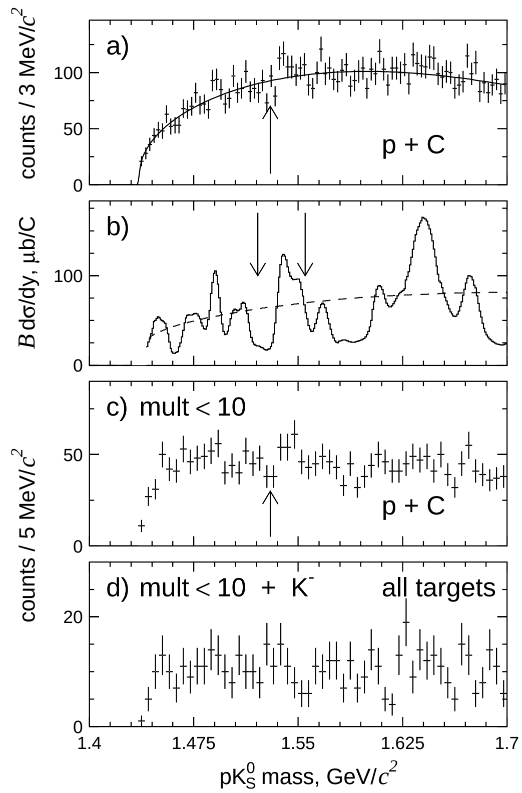

FIG. 2: The pK^0_S invariant mass distributions: a) data from the p+C collisions and the background estimate (continuous line); b) deduced UL(95%) for the p+C inclusive cross section at mid-rapidity; the dashed line shows our 95% CL sensitivity; c,d) same as a) but requiring c) a track multiplicity of <10, and d) in addition a K^- particle in the event. The arrows mark the masses of 1521, 1530 and 1555 MeV/c^2.

interval is ± 0.3. The data have been fitted with a Gaussian plus a background of fixed shape. The mean of the Gaussian was varied in steps of 1 MeV/c^2 but fixed in the fit; its width was fixed to the MC prediction multiplied by 1.2 and increased from 2.6 to 6.1 MeV/c^2 over the considered range. At the Θ^+ mass, the width was 3.9 MeV/c^2. The reconstruction efficiencies have been determined by MC simulations assuming a flat rapidity distribution and a p_t^2 distribution proportional to $\exp(-B \cdot p_t^2)$ with $B = 2.1\,(\mathrm{GeV}/c)^{-2}$ [26]. Assuming an atomic mass dependence of $A^{0.7}$ for the production cross section, the UL(95%) of $\mathcal{B}{\cdot}\mathrm{d}\sigma/\mathrm{dy}$ varies from 3 to 22 μb/nucleon (N) for a Θ^+ mass between 1521 and 1555 MeV/c^2. A systematic error of 14% was taken into account. For the Θ^+ mass of 1530 MeV/c^2(about the average of the mass values observed in the pK^0_S final state [16]), our limit is $\mathcal{B}{\cdot}\mathrm{d}\sigma/\mathrm{dy} <$ 3.7 μb/N. The ULs from all target data are within $\pm 30\%$ of these values.

Further search strategies were tried including i) a cut on the track multiplicity of the event (Fig. 2c) which would otherwise peak at ≈ 13, ii) the request of a tagging particle such as a Λ, Σ or K^- in the event, or iii) both conditions (Fig. 2d). None yielded a statistically significant structure in Θ^+ mass region. Also, the effect of lowering the cut on the RICH proton likelihood and the corresponding increase of the proton momentum acceptance has been systematically studied without yielding a Θ^+ signal. On the other hand, as shown in Fig. 1b, when the same proton PID requirement used to produce Fig. 2 is applied to pK^- candidates, a strong $\Lambda(1520)$ signal results, further demonstrating the capabilities of the RICH. The cut in the K^- likelihood of > 0.95 implies a selection of kaon momenta from 12 to 55 GeV/c. With the same cut on the K^0_S momenta, and assuming a branching ratio of $\mathcal{B}(\Theta^+ \to pK^0_S) = 0.25$, the UL(95%) of the particle ratio $\Theta^+(1530)/\Lambda(1520)$ at $y_{cm} \approx 0$ is 2.7%.

Both doubly-charged and neutral $\Xi_{3/2}$ PQ candidates as well as their anti-particles have been searched for in the $\Xi\,\pi$ channels. The pion candidates were required to originate from the primary vertex. The background was further reduced by weak cuts on the PIDs from the ECAL and RICH which eliminated all the tracks with a positive electron, proton, or kaon PID. The histograms of Fig. 3a) show the resulting $\Xi\,\pi$ invariant mass spectra obtained from the C target data. The smooth lines are the background estimates from event-mixing normalized to the data. In the neutral channels the $\Xi(1530)^0$ resonance shows up as a prominent signal of $\approx 10^3$ events (see Table I). The observed width ($\approx$9.5 MeV/c^2) of the $\Xi(1530)^0$ agrees with MC simulations which imply an experimental resolution of 2.9 MeV/c^2. None of these mass spectra shows evidence for the narrow, less than 18 MeV/c^2 (FWHM) wide PQ candidates at 1862 MeV/c^2 reported by the NA49 collaboration [8] nor for any other narrow state at masses between 1.6 and 2.3 GeV/c^2. Fig. 3b) shows the sum of the four spectra of Fig. 3a) after background subtraction and can be compared directly to Fig. 3 of ref. [8]. The corresponding ULs(95%) of the production cross sections $\mathcal{B}\cdot d\sigma/dy|_{y\approx 0}$ per carbon nucleus at mid-rapidity (Fig. 3c) have been obtained in the same way as described above for the pK^0_S channel; here the y_{cm}-interval is ± 0.7, the experimental resolution increases from 2.9 to 10.6 MeV/c^2 in the considered mass range, and is 6.6 MeV/c^2 at 1862 MeV/c^2. At this $\Xi^-\pi^-$ mass, the UL(95%) of $\mathcal{B}\cdot d\sigma/dy$ is 2.5 μb/N; the corresponding limits in the $\Xi^-\pi^+$, $\bar{\Xi}^+\pi^+$, and $\bar{\Xi}^+\pi^-$channels are 2.3, 0.85, and 3.1 μb/N. With an $A^{0.7}$ dependence, the ULs from all targets are 2.7, 3.2, 0.94, and 3.1 μb/N, respectively.

Table II lists our ULs(95%) of various relative yields for the Θ^+ and Ξ^{--}. Reference states for the Θ^+ are the Λ and the $\Lambda(1520)$, and for the Ξ^{--}, the Ξ^- and the $\Xi(1530)^0$. The Θ^+ and Ξ^{--} widths are assumed to be equal to our experimental mass resolution and their momentum distributions are assumed to be the same as those of the reference states. Table II lists also predictions of various statistical hadronization models for the respective ratios. We note that these ratios show no significant variation between $17 < \sqrt{s} < 40$ GeV, nor is there a significant difference between predictions for pp and AA collisions. We find our UL for $\Theta^+/\Lambda(1520)$<2.7% to be more than one order of magnitude lower than the model predictions. Also, the UL of Θ^+/Λ< 0.92% is lower than all predictions including the model which uses the Gribov-Regge approach for describing the Θ^+ production and its $\sqrt{s}$ dependence in pp collisions [25]. Our UL of the Ξ^{--}/Ξ^- yield ratio is

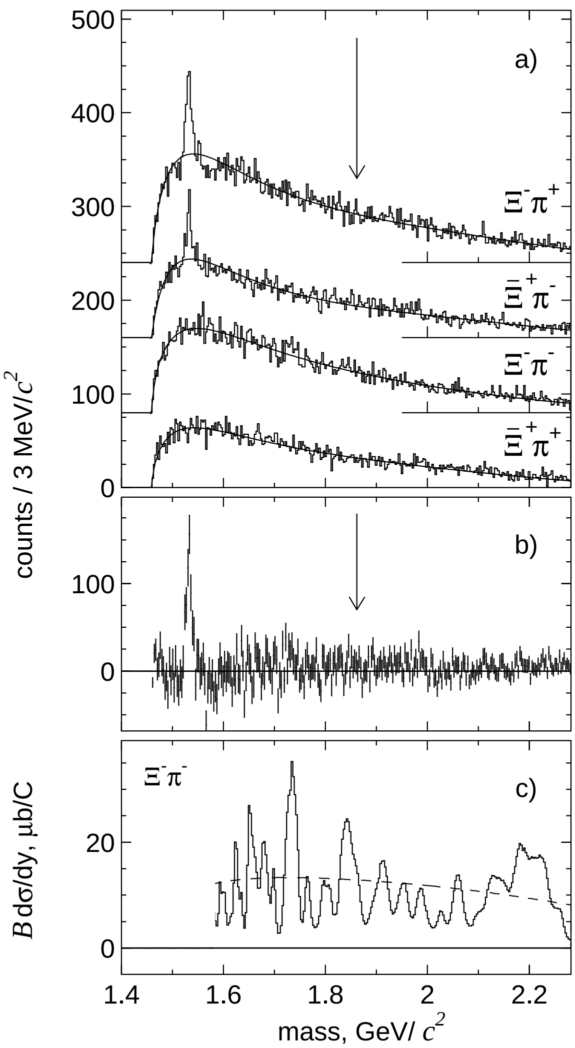

FIG. 3: The $\Xi\pi$ invariant mass distributions: a) data from the p+C collisions in indicated neutral and doubly-charged channels and the background estimates (continuous lines); b) sum of all four $\Xi\pi$ spectra with the background subtracted, and c) deduced UL(95%) for the p+C inclusive cross section at mid-rapidity. The dashed line shows our 95% CL sensitivity. The arrows mark the mass of 1862 MeV/c^2.

TABLE II: Our 95% CL upper limits on the relative yields of $\Theta^+(1530)$ and $\Xi^{--}(1862)$ PQs at $y_{cm} \approx 0$ and predictions for pp and AA collisions. For a Θ^+ mass of 1540 MeV/c^2, the quoted values have to be multiplied by ≈4.

Reaction	$\sqrt{s_{NN}}$ [GeV]	$\frac{\Theta^+}{\Lambda}$ [%]	$\frac{\Theta^+}{\Lambda(1520)}$ [%]	$\frac{\Xi^{--}}{\Xi^-}$ [%]	$\frac{\Xi^{--}}{\Xi(1530)^0}$ [%]	Ref.
pA, y≈ 0	42	< 0.92	< 2.7	< 3/$\mathcal{B}$	<4/$\mathcal{B}$	
pp, y=0	18	2.3				[25]
pp	20/40	6.3/5.0		2.5/3.6		[24]
pp	17	4.7	57			[23]
AA	20	3-10	50-200	0.4-1		[22]
	40	3-7	44-140	0.4-1		[22]

compatible with the model predictions. No theoretical value is yet available for the $\Xi^{--}/\Xi(1530)^0$ ratio, but our UL of <4%/$\mathcal{B}$ should be compared with the value from the NA49 experiment which, however, is not explicitly quoted in the original paper [8] which reports only the number of 38 Ξ^{--} events. According to ref. [14], the number of $\Xi(1530)^0$ events is about 150 leading to a yield ratio [29] in contradiction to our UL unless the relative efficiencies for $\Xi(1530)^0$ and Ξ^{--} of NA49 (unpublished) differ markedly from those of HERA-B.

In conclusion, having found no evidence for narrow Θ^+ and Ξ^{--} signals, we have set UL(95%) for the central production cross sections of resonances in the pK^0_S and $\Xi^-\pi^-$ final states with widths less than our experimental resolution of $\approx 5\,\mathrm{MeV}/c^2$. For the $\Theta^+(1530)$ and the $\Xi^{--}(1862)$ the respective ULs of $\mathcal{B}\cdot d\sigma/dy|_{y\approx 0}$ are 3.7 and 2.5 μb/N. For the Θ^+ candidate observed in pA collisions at $\sqrt{s} = 11.5$ GeV, the total cross section for $x_F \geq 0$ was estimated to be 30 to 120 μb/N [4]. A decrease of the central Θ^+ production with increasing $\sqrt{s}$ could be understood if the Θ^+ is produced by disintegration of forward/backward peaked remnants [25]. On the other hand, our UL(95%) for $\Theta^+/\Lambda(1520)< 2.7\%$ is significantly lower than statistical hadronization predictions which yield a ratio of ≥0.5 in agreement with experiments in which the Θ^+ candidate and $\Lambda(1520)$ showed similar yields [31]. Our UL(95%) of $\mathcal{B}\cdot\Xi^{--}/\Xi^-<3\%$ is not low enough to contradict the theoretical predictions. It is, however, inconsistent with the previously-published [8] observation of the $\Xi^{--}(1862)$ at mid-rapidity which is based on a data sample of lower statistics (1.6k v. 12k Ξ^-) and comparable mass resolution (7.6 v. 6.6 MeV/c^2).

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