Search for the pentaquark candidate $\Theta(1540)^+$ in the hyperon beam experiment WA89

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We report on a high-statistics search for the $\Theta(1540)^+$ resonance in Σ^--nucleus collisions at 340 GeV/c. No evidence for this resonance was found in our data sample which contains 13 million $K_s^0 \rightarrow \pi^+\pi^-$ decays above background. For the decay channel $\Theta^+ \rightarrow K_s^0 p$ and the kinematic range $x_F > 0.05$, we find the production cross section to be $\mathrm{BR}(\Theta^+ \rightarrow K_s^0 p)\,\sigma_0 < 1.8\ \mu$b per nucleon at 99% C.L.

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During the last few years, 12 experimental groups have reported evidence for a narrow baryonic resonance in the KN channel at a mass of about 1540 MeV/c^2 [1–12]. Figure 1 shows a collection of the first nine published results that gave evidence for the existence of the so-called $\Theta(1540)^+$. While the number of positive observations seems to be quite convincing, when plotting the data points with error bars but without background curves to guide the eye it becomes obvious that having limited statistics is a common drawback of the individual observations. It is remarkable that the event statistics are nearly independent of the experimental situation, and it is disturbing that the peak positions differ significantly in the various experiments. On the other hand, at least 11 experiments reported negative search results [13–23]. It was argued that this discrepancy may be due to very different production cross sections in the various reaction processes (see, e.g., Refs. [24–29]). Faced with this situation, further high-statistics searches for this resonance under different experimental conditions—e.g., different beam particles—are highly desirable.

The hyperon beam experiment WA89 at CERN ran from 1990 to 1994 in the West Hall. Its primary goal was the study of charmed particles and their decays. At the same time, it collected a high-statistics data sample of hyperon resonances and K_s^0 decays. We have already published the negative result of a search for the pentaquark candidate $\Phi(1860)$, alternatively called $\Xi(1860)^{--}$ [30]. Here we report a search for the pentaquark candidate $\Theta(1540)^+$ in the $K_s^0 p$ decay channel,

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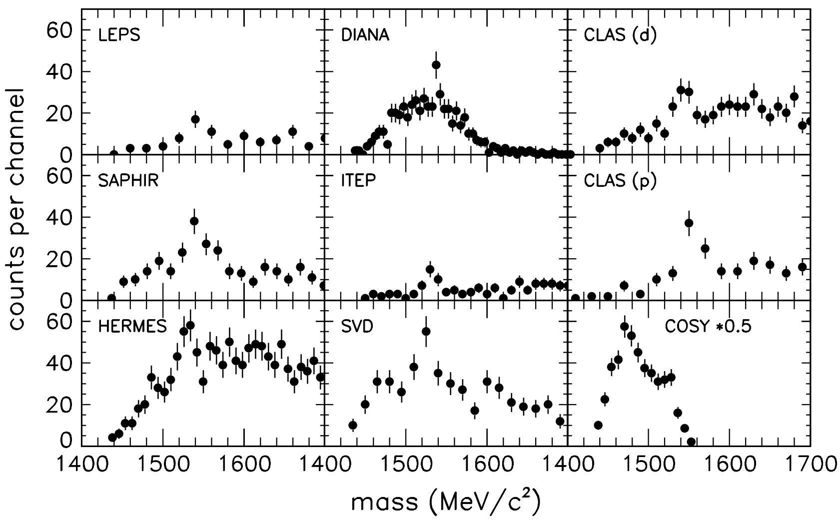

FIG. 1. Summary of the first nine published observations of the $\Theta(1540)^+$ resonance [1–9].

produced inclusively in Σ^--nucleus reactions. The results are based on the data collected in 1993 and 1994.

The hyperon beamline selected negatively charged particles with a mean momentum of 340 GeV/c and a momentum spread of $\sigma(p)/p = 9\%$. At the experimental target, the π^- to Σ^- ratio of the beam was about 2.3. The beam pions were strongly suppressed at the trigger level by a set of transition radiation detectors resulting in a remaining pion contamination of about 12%. In addition, the beam contained small admixtures of K^- and Ξ^-. The experimental target itself consisted of one copper slab with a thickness of 0.025 λ_I in the beam direction, followed by three carbon (diamond powder) slabs of 0.008 λ_I each. The trajectories of incoming and outgoing particles were measured in silicon microstrip detectors upstream and downstream of the targets. Only events with a reconstructed interaction vertex in the targets and the surrounding counters were retained in the analysis.

The momenta of charged particles were measured in a magnetic spectrometer equipped with multiwire proportional counters and drift chambers. The spectrometer magnet was placed with its center 13.6 m downstream of the target, thus providing a field-free decay zone about 10 m long for hyperons and K_s^0 emerging from the target.

A ring-imaging Cherenkov counter (RICH) [31] placed downstream of the spectrometer magnet provided particle identification. It was followed by a lead-glass electromagnetic calorimeter and an iron/scintillator hadron calorimeter, which were not used in this analysis.

K_s^0 were reconstructed in the decay $K_s^0 \to \pi^+\pi^-$, using all pairs of positive and negative particles that formed a decay vertex in the decay zone. $\Lambda \to p\pi^-$ decays with decay particle momenta corresponding to $K_s^0 \to \pi^+\pi^-$ decays can produce a spurious mass peak at 1540 MeV/c^2 if a mirror image of the decay proton is used in the search for $K_s^0 p$ decays [14,32]. To avoid this, we excluded K_s^0 candidates with a reconstructed $p\pi^-$ mass within $\pm 2\sigma_m(\Lambda)$ of the Λ mass. [$\sigma_m(\Lambda)$ was 1.8 MeV/c^2 at low momenta and 2.8 MeV/c^2 at 200 GeV/c.] This requirement reduced the K_s^0 sample by 3% and the background by 1/3.

The reconstructed $\pi^+\pi^-$ mass distribution of the remaining K_s^0 candidates is shown in Fig. 2. The peak from K_s^0 decays contains about 13 million events, their momentum spectrum extends from 10 to about 200 GeV/c. Above this momentum, very few K_s^0 are left, and they do not contribute to $K_s^0 p$ effective masses below 1570 MeV/c^2. The mass resolution is $\sigma_m(K_s^0) = 4$ MeV/c^2 at low momenta and increases to 7 MeV/c^2 at 200 GeV/c. Candidates with a reconstructed $\pi^+\pi^-$ mass within $\pm 2\sigma_m$ of the K_s^0 mass were retained for further analysis.

All positive particles with a reconstructed track extending from the microstrip counters downstream of the target to the wire chambers beyond the spectrometer were considered as proton candidates, excluding of course the π^+ from the K_s^0 decay. Requiring track reconstruction in the microstrip counters rejected most of the protons from Λ decays. The track had to be inside the acceptance of the RICH counter, which implies a momentum threshold at around 12 GeV/c.

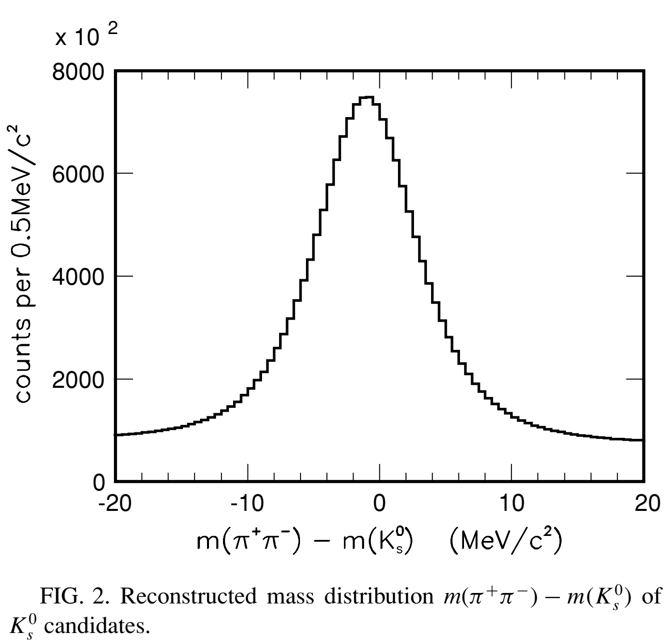

FIG. 2. Reconstructed mass distribution $m(\pi^+\pi^-) - m(K_s^0)$ of K_s^0 candidates.

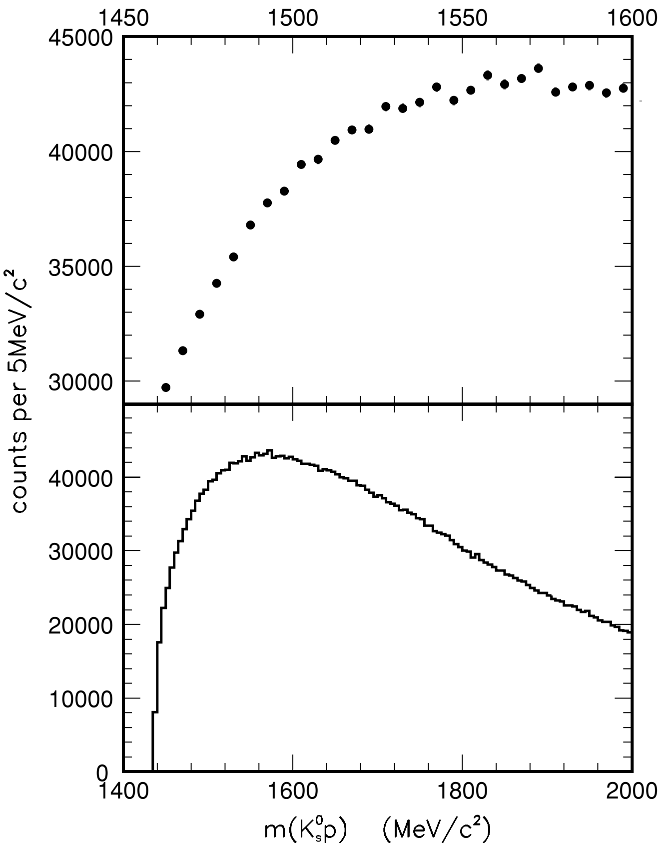

FIG. 3. Invariant mass spectrum of all observed $K_s^0 p$ candidates. Upper plot shows an extended view of the region around 1540 MeV/c^2. Statistical errors are approximately the size of the dots.

Since the proton threshold of the RICH was at 38 GeV/c, we did not require proton identification, but we rejected the clearly identified π^+ and K^+ (thresholds at 5.5 and 20 GeV/c, respectively.). From a study of reconstructed Λ decays, we determined that this requirement rejected 4% or less of the genuine protons at all momenta, while the $K_s^0 p$ candidate sample was reduced by a factor of 3.

The final $K_s^0 p$ sample contained 5.2 million $K_s^0 p$ candidates. Figure 3 shows the $K_s^0 p$ mass distribution of all candidates up to 2 GeV. No narrow signal is visible in this plot, nor did we see narrow signals around an invariant mass of 1540 MeV/c^2 in subsamples of x_F or transverse momentum p_t [33]. We define x_F as $x_F = 2p_L^*/\sqrt{s}$, where p_L^* is the $K_s^0 p$ momentum component in the beam direction in the beam-nucleon c.m.s and $\sqrt{s}$ is the invariant mass of the beam-nucleon system. In our case, $\sqrt{s} = 25.2$ GeV. The x_F distribution is shown in Fig. 4 for the $K_s^0 p$ mass region between 1500 and 1560 MeV/c^2; it starts at $x_F = 0.05$ and thus covers part of the central production region.

Upper limits on the Θ^+ production cross sections were calculated separately for the copper and carbon targets in bins of x_F as listed in column 1 of Table I. We used four mass windows of 20 MeV/c^2 width, centered at 1520, 1530, 1540, and 1550 MeV/c^2, respectively, for $i = 1, 2, 3, 4$, thus covering the full range of reported values for the Θ^+ mass. The width was chosen by taking into account our mass resolution, $\sigma_m(K_s^0 p) = 4$ MeV/c^2, and the reported values for the intrinsic width of the Θ^+. The observed number of $K_s^0 p$ combinations in each mass window is n_i. From a fit to the observed $K_s^0 p$ mass spectrum between 1460 and 1700 MeV/c^2, we calculated the expected nonresonant backgrounds b_i. Upper limits $n_{\max}$ on the number of $\Theta^+ \to K_s^0 p$ decays were then obtained by the formula $n_{\max} = \max_i\{\max(0, n_i - b_i) + 3\sqrt{b_i}\}$ and are listed in columns 2 and 5 of Table. I. These limits have a confidence level of 99% and scale approximately with the square root of the width of the search window.

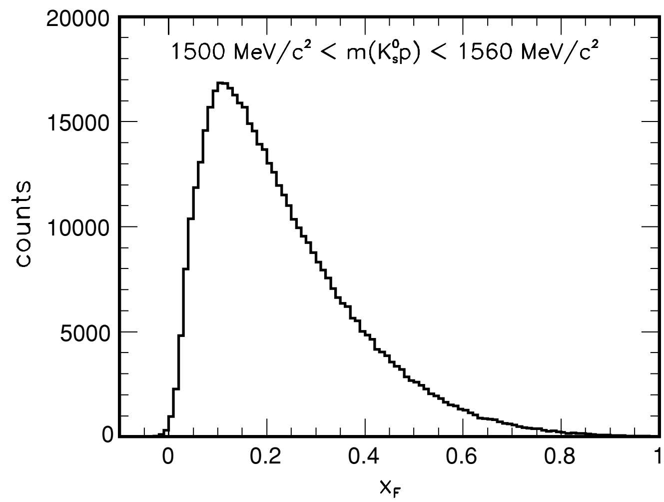

FIG. 4. x_F distribution for $K_s^0 p$ pairs in the mass range $1500 < m(K_s^0 p) < 1560$ MeV/c^2.

Upper limits on the product of the $\Theta(1540)^+ \to K_s^0 p$ decay branching ratio BR and the differential production cross sections $d\sigma_A/dx_F$ *per nucleus* are given in columns 3 and 6 of Table I. Assuming the dependence of the cross section on the mass number to be $\sigma_A \propto \sigma_0 A^{2/3}$, where σ_0 is the cross section *per nucleon*, we finally obtained the limits on BR $d\sigma_0/dx_F$ in columns 4 and 7 of the table.

Limits on the integrated production cross sections σ were calculated by summing quadratically the contributions $(d\sigma/dx_F)\,\Delta x_F$ in the nine individual x_F bins. The results are BR $\sigma_A(x_F > 0.05) < 38$ and <15 μb per nucleus for the copper and carbon target, respectively. An extrapolation to the cross sections per nucleon yields the two values BR $\sigma_0(x_F > 0.05) < 2.4$ and < 2.9 μb per nucleon. Since these are statistically independent upper limits, we can combine them to obtain BR $\sigma_0 < 1.8$ μb per nucleon for $\Theta(1540)^+$ production by Σ^- of 340 GeV/c in the region $x_F > 0.05$.

To compare our results to observations of or searches for the $\Theta(1540)^+$, we concentrate on hadronic reactions. It is interesting to note that all these experiments investigated the $K_s^0 p$ decay channel, but only the SPHINX experiment searched in the $K^+ n$ decay channel as well. Four experiments reported observations of the $\Theta(1540)^+$ [2,8–10]. The COSY-TOF Collaboration, using a proton beam of 2.95 GeV/c and a liquid hydrogen target, measured a cross section $\sigma_0 = 0.4$ μb per nucleon for *exclusive* production in the reaction $pp \to \Sigma^+(K^0 p)$ [9]. This value is below our upper limit,

TABLE I. Upper limits on yields and cross sections. BR denotes the $\Theta(1540)^+ \rightarrow K_s^0 p$ decay branching ratio. σ_A and σ_0 denote cross sections per nucleus and per nucleon, respectively.

x_F	Copper target			Carbon target		
	$n_{\max}$	BR $d\sigma/dx_F$ [μb]		$n_{\max}$	BR $d\sigma/dx_F$ [μb]	
		$d\sigma_A$	$d\sigma_0$		$d\sigma_A$	$d\sigma_0$
0.05 – 0.15	520	230	14.5	550	105	20.0
0.15 – 0.25	500	205	13.0	480	80	15.3
0.25 – 0.35	340	140	8.8	350	55	10.5
0.35 – 0.45	390	140	8.8	290	40	7.6
0.45 – 0.55	250	65	4.1	240	25	4.8
0.55 – 0.65	190	53	3.3	160	16	3.0
0.65 – 0.75	115	33	2.1	130	13	2.5
0.75 – 0.85	70	21	1.3	55	6	1.1
>0.85	35	11	0.7	45	5	1.0
		BR σ_A	BR σ_0		BR σ_A	BR σ_0
		38	2.4		15	2.9

but an exclusive production cross section that close to the reaction threshold cannot be compared to inclusive production cross sections at energies of several hundred GeV. The JINR propane bubble chamber group, using a proton beam of 10 GeV/c, measured a total production cross section $\sigma_{\text{propane}} = 90\ \mu$b [10]. Again assuming a dependence of the cross section on the mass number as $\sigma_A \propto \sigma_0 A^{2/3}$, one obtains a production cross section $\sigma_0 = 3.8\ \mu$b per nucleon, which is larger by a factor of 2 than our limit. The SVD Collaboration, using a proton beam of 70 GeV/c and a combined carbon, silicon, and lead target, measured a production cross section $\sigma_0 = 30$–$120\ \mu$b per nucleon for $x_F > 0$ [8]. This is much higher than our upper limit in practically the same kinematic range. The DIANA Collaboration, using a K^+ beam of 0.85 GeV/c and a xenon bubble chamber, has not measured a cross section [2].

Negative search results were reported from at least 11 experiments [13–23]. Of these, six experiments studied hadronic-induced interactions [14–19]. Usually these collaborations compared their Θ^+ production limits with their $\Lambda(1520)$ observations and obtained limits below 3% on the event or production ratio of $\Theta(1540)^+$ with respect to $\Lambda(1520)$. This we cannot do, although we do observe $\Lambda(1520)$ decays, because in our experiment, two-body decay channels are suppressed in the trigger. We can, however, compare our result with the HERA-B result of BR $d\sigma/dy < 4$–$16\ \mu$b per nucleon at 95% C.L. for Θ^+ masses between 1521 and 1555 MeV/c^2, at rapidity $y_{\text{c.m.}} \approx 0$. This value corresponds to BR $d\sigma/dx_F < 30$–$120\ \mu$b per nucleon, which can be compared with our result BR$d\sigma/dx_F < 12\ \mu$b at 99% C.L. and for $0.05 < x_F < 0.15$ (this limit was obtained by combining the statistically independent carbon and copper target results).

If $\Theta(1540)^+$ exists, as many experiments suggest, then the cross sections for Θ^+ production in hadronic reactions at higher energies are surprisingly low compared to the production of hyperon resonances. This fact by itself could provide important information on the nature of $\Theta(1540)^+$.

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[33] At large $x_F > 0.8$, we do, however, observe a broad ($\Gamma \simeq 90$ Mev $/c^2$) resonance-like structure at a mass of $\simeq$1750 Mev$/c^2$ which is possibly related to known Σ^* resonances. A detailed analysis of this structure will be presented in a future paper.