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 $\Sigma^-$-nucleus collisions at 340 GeV/c . No evidence for this resonance was found in our data sample which contains 13 millions $K^0\rightarrow \pi^+\pi^-$ decays above background. For the decay channel $\Theta^+\rightarrow K_s^0p$ and the kinematic range $x_F > 0.05$ we find the production cross section to be $BR(\Theta^+\rightarrow K_s^0p) \cdot \sigma_0 < 1.8 \mu$b per nucleon at 99% CL.

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During the last years twelve experimental groups have reported evidence for a narrow baryonic resonance in the KN channel at a mass of about 1540 MeV/c\(^2\). 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 the limited statistics is a common drawback of the individual observations. It is remarkable that the event statistics is 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 have reported negative search results. Figure 1 shows a collection of the first nine published results which gave evidence for the existence of the so-called $\Theta(1540)^+$. The results include evidence for a narrow baryonic resonance in the KN channel at a mass of about 1540 MeV/c\(^2\). 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 the limited statistics is a common drawback of the individual observations. It is remarkable that the event statistics is 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 have reported negative search results.
argued that this discrepancy may be due to very different production cross sections in the various reaction processes (see e.g. Refs. [23, 24, 25, 26, 27, 28, 29]). Facing such a 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 hyperons and hyperon resonances, among these Λ decays, and also Υ(1540) decays, and also Φ(1860), alternatively called Ξ(1860) candidates. The results are based on the data collected in the years 1993 and 1994.

The hyperon beamline selected negatively charged particles with a mean momentum of 340 GeV/c and a momentum spread of σ(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 λ1 in beam direction, followed by three carbon (diamond powder) slabs of 0.008 λ1 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 MWPCs 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 of about 10 m length for hyperons and K0s emerging from the target.

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

K0s were reconstructed in the decay K0s → π+π−, using all pairs of positive and negative particles which formed a decay vertex in the decay zone. Λ → pπ− decays with decay particle momenta corresponding to K0s → π+π− decays can produce a spurious mass peak at 1540 MeV/c², if a mirror image of the decay proton is used in the search for K0s decays [14, 31]. To avoid this, we excluded K0s candidates with a reconstructed pπ− mass within ±2σm(Λ) of the Λ mass (σm(Λ) was 1.8 MeV/c² at low momenta and 2.8 MeV/c² at 200 GeV/c). This requirement reduced the K0s sample by 3% and the background by 1/3.

The reconstructed π+π− mass distribution of the remaining K0s candidates is shown in fig. 2. The peak from K0s decays contains about 13 million events, their momentum spectrum extends from 10 GeV/c to about 200 GeV/c. Above this momentum, very few K0s are left, and they do not contribute to K0s effective masses below 1570 MeV/c². The mass resolution is σm(K0s) = 4 MeV/c² at low momenta and increases to σm(K0s) = 7 MeV/c² at 200 GeV/c. Candidates with a reconstructed π+π− mass within ±2σm of the K0s 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 K0s decay. Requiring track reconstruction in the microstrip counters rejected most of the p-candidates.

FIG. 1: Summary of the first nine published observations of the Θ(1540)+ resonance.

FIG. 2: Reconstructed mass distribution m(π+π−) - m(K0s) of K0s candidates.
tons from Λ decays. The track had to be inside the acceptance of the RICH counter, which implies a momentum threshold of around 12 GeV/c. Since the proton threshold of the RICH was at 38 GeV/c we did not require proton identification, but rejected clearly identified \( π^+ \) and \( K^+ \) (thresholds at 5.5 and 20 GeV/c, resp.). From a study of reconstructed Λ decays, we determined that this requirement rejected 4% or less of genuine protons at all momenta, while the \( K^0_s \) candidate sample was reduced by a factor of 3.

The final \( K^0_s p \) sample contained 5.2 million \( K^0_s p \) candidates. Fig. 3 shows the \( K^0_s p \) mass distribution of all candidates up to 2 GeV. No narrow signal is visible in this plot, neither did we see narrow signals around an invariant mass of 1540 MeV in subsamples of \( x_F \) or transverse momentum \( p_t \). We define \( x_F \) as \( x_F = 2p_L^*/\sqrt{s} \), where \( p_L^* \) is the \( K^0_s p \) momentum component in beam direction in the beam-nucleon CMS 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. 3 for the \( K^0_s p \) 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 col. 1 of Table II. We used four mass windows of 20 MeV/\( c^2 \) width, centered at 1520, 1530, 1540 and 1550 MeV/\( c^2 \), resp., for \( i = 1, 2, 3, 4 \), thus covering the full range of reported values for the \( Θ^+ \) mass. The width was chosen taking into account our mass resolution, \( σ_m(K^0_s p) = 4 \) MeV/\( c^2 \), and the reported values for the intrinsic width of the \( Θ^+ \). The observed number of \( K^0_s p \) combinations in each mass window is \( n_i \). From a fit to the observed \( K^0_s p \) mass spectrum between 1460 and 1700 MeV/\( c^2 \) we calculated the expected non-resonant backgrounds \( b_i \). Upper limits \( n_{max} \) on the number of \( Θ^+ \rightarrow K^0_s p \) decays were then obtained by the formula \( n_{max} = max_i(n_{max}(0, n_i - b_i) + 3\sqrt{b_i}) \) and are listed in columns 2 and 5 of Tab. II. These limits have a confidence level of 99% and scale approximately with the square root of the width of the search window.

Upper limits on the product of \( BR \), the \( Θ(1540)^+ \rightarrow K^0_s p \) decay branching ratio, and the differential production cross sections \( dσ_A/dx_F \) per nucleus are given in columns 3 and 6 of Tab. II. Assuming the dependence of the cross section on the mass number to be \( σ_A \propto σ_0 \cdot A^{2/3} \), where \( σ_0 \) is the cross section per nucleon, we finally obtained the limits on \( BR \cdot dσ_0/dx_F \) in columns 4 and 7 of the table.

Limits on the integrated production cross sections \( σ \) were calculated by summing quadratically the contributions \( (dσ/dx_F) \cdot Δx_F \) in the nine individual \( x_F \) bins. The results are \( BR \cdot σ_A(x_F > 0.05) < 38 \) and \( < 15 \mu b \) per nucleus for the copper and carbon target, respectively. An extrapolation to the cross sections per nucleon yields the two values \( BR \cdot σ_0(x_F > 0.05) < 2.4 \) and \( < 2.9 \mu b \) per nucleon. Since these are statistically independent upper limits, we can combine them to obtain \( BR \cdot σ_0 < 1.8 \mu b \) per nucleon for \( Θ(1540)^+ \) production by \( Σ^- \) of 340 GeV/c in the region \( x_F > 0.05 \).
TABLE I: Upper limits on yields and cross sections. BR denotes the $\Theta(1540)^+ \rightarrow K^0\Lambda$ decay branching ratio. $\sigma_A$ and $\sigma_0$ denote cross sections per nucleus and per nucleon, respectively.

| $x_F$ | copper target | carbon target | copper target | carbon target |
|-------|---------------|---------------|---------------|---------------|
|       | $BR \cdot \sigma_A / d\sigma / dx_F [\mu b]$ | $BR \cdot \sigma_A / d\sigma / dx_F [\mu b]$ | $BR \cdot \sigma_0 / d\sigma / dx_F [\mu b]$ | $BR \cdot \sigma_0 / d\sigma / dx_F [\mu b]$ |
| 0.15 - 0.25 | 520 | 230 | 14.5 | 550 | 105 | 20.0 |
| 0.25 - 0.35 | 340 | 140 | 8.8 | 350 | 55 | 10.5 |
| 0.35 - 0.45 | 390 | 140 | 8.8 | 390 | 40 | 7.6 |
| 0.45 - 0.55 | 290 | 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 |
|         | 38 | 2.4 | BR $\cdot \sigma_A$ | BR $\cdot \sigma_0$ | BR $\cdot \sigma_A$ | BR $\cdot \sigma_0$ |

For a comparison of our result to observations of searches for the $\Theta(1540)^+$ we concentrate on hadronic reactions. It is interesting to note that all these experiments investigated the $K^0\Lambda$ decay channel, but only the SPHINX experiment searched in the $K^+\Sigma^+$ decay channel as well. Four experiments have reported observations of the $\Theta(1540)^+ \rightarrow K^0\Lambda$ decay branching ratio. $\sigma_A$ and $\sigma_0$ denote cross sections per nucleus and per nucleon, respectively.

Out of these 6 experiments studied hadronic induced interactions $[13, 14, 15, 17, 18, 20, 21, 22, 28]$. Usually these collaborations have compared their $\Theta^+$ production limits with their $\Lambda(1520)$ observations, and have obtained limits below 3% on the event or production ratio of $\Theta(1540)^+ \rightarrow \Lambda(1520)$. This we cannot do, although we do observe $\Lambda(1520)$ decays, because in our experiment two-body decay channels were suppressed in the trigger. We have, however, compare our result to the HERA-B result of $BR \cdot d\sigma / dy < 4 \times 16 \mu b$ per nucleon at 95% CL for the $\Theta^+$ masses between 1521 and 1555 MeV/c^2, at rapidity $y_{cm} \approx 0$. This value corresponds to $BR \cdot d\sigma / dx_F < 30 - 120 \mu b$ per nucleon, to be compared to our result $BR \cdot d\sigma / dx_F < 12 \mu b$ at 99% CL and for 0.05 $< x_F < 0.15$ (this limit was obtained by combining the statistically independent carbon and copper target results).

If the $\Theta(1540)^+$ exists, as many experiments suggest, then the cross sections for $\Theta^+$ 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 the $\Theta(1540)^+$.
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[32] At large $xF > 0.8$ 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 $\Sigma^*$ resonances. A detailed analysis of this structure will be presented in a future paper.