Improved study of a possible Θ^+ production in the $pp \to pK^0\Sigma^+$ reaction with the COSY-TOF spectrometer

The COSY-TOF Collaboration

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Abstract

The $pp \to pK^0\Sigma^+$ reaction was investigated with the TOF spectrometer at COSY at 3.059 GeV/c incident beam momentum. The main objective was to clarify whether or not a narrow exotic $S = +1$ resonance, the Θ^+ pentaquark, is populated at 1.53 GeV/c^2 in the pK^0 subsystem with a data sample of much higher statistical significance compared to the previously reported data in this channel. An analysis of these data does not confirm the existence of the Θ^+ pentaquark. This is expressed as an upper limit for the cross section $\sigma(pp \to \Sigma^+\Theta^+) < 0.15$ μb at the 95% confidence level.

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1 Introduction

The quark model introduced by Gell-Mann in 1964 [1] successfully explains strongly interacting particles, observable as being colorless systems of either a quark-antiquark pair for mesons or of three quarks for baryons. However, QCD does not exclude the existence of other color singlet objects containing additional quark-antiquark pairs or gluons as constituents. Within a chiral soliton model Diakonov, Petrov, and

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Polyakov [2] predicted the existence of an anti-decuplet of baryonic states with $J^p = 1/2^+$ consisting of four quarks and one anti-quark. Three members of this anti-decuplet are manifestly exotic, having combinations of strangeness and isospin not allowed for three-quark systems. The lightest of these exotic states is the Θ^+ pentaquark with a quark content of $uudd\bar{s}$ and thus strangeness $S = +1$, a predicted mass of about 1.53 GeV/c^2 [2], and rather narrow width of less than 15 MeV [3].

The first experimental evidence for a narrow $S = +1$ baryonic resonance in the predicted mass region came from the LEPS collaboration at SPring8 [4] who observed a peak in the K^+n invariant system at 1.54 GeV/c^2 in the $\gamma n \rightarrow K^+K^-n$ reaction on ^{12}C. Shortly after, the DIANA collaboration found evidence in the K^0p system in a re-analysis of bubble chamber data of the reaction $K^+\mathrm{Xe} \rightarrow K^0pX$ [5]. Soon after these first observations positive signals indicating the existence of a narrow resonance in this mass region were also reported by CLAS [6, 7], SAPHIR [8], HERMES [9], ZEUS [10], COSY-TOF [11], SVD-2 [12], by Asratyan *et al.* [13], and by Aslanyan *et al.* [14] in a large variety of reactions including even neutrino-induced processes [13].

Evidence from these experiments was claimed for the existence of a narrow state in the systems K^0p and K^+n in the mass region between 1.522 and 1.555 GeV/c^2. In each of these cases the signal is based on at most 50 events. Thus, none of these experiments has the statistical accuracy required to establish the existence of the Θ^+. Moreover, several experiments particularly at high energies including BES [15], BABAR [16], Belle [17], HERA-B [18], SPHINX [19], HyperCP [20], CDF [21], and FOCUS [22] did not confirm the state and set upper limits on the production cross section. Although the production mechanism of the Θ^+ pentaquark in the high energy reactions studied may differ strongly from that for conventional baryonic states, the null results cast additional doubt on the existence of the Θ^+.

In the meantime a series of improved experiments and analyses were carried out by the groups who had reported a positive signal in their first experiments in order to obtain data with higher statistical accuracy. Recently, the results of dedicated experiments at CLAS were published. These yielded negative results both on hydrogen [23] and deuterium targets [24]. The high statistics null result on the hydrogen target is in clear contradiction to the SAPHIR result [8]. The negative result on the deuterium target does not agree with the earlier positive result of CLAS in the channel $\gamma d \rightarrow pK^-\Theta^+$ and sets an upper limit to the Θ^+ production cross section. In contrast, SVD-2 [25] and DIANA [26] analyzed additional data which were not included in the first publications with optimized analysis methods. Both groups confirmed their previous positive results with increased significance. Furthermore, DIANA estimated the Θ^+ width to be only 0.4 MeV. A recent measurement at KEK [27] of the channel $\pi^-p \rightarrow K^-X$ revealed a bump at 1.530 GeV/c^2 in the K^- missing mass spectrum with a significance of 2.5 σ. A recent dedicated experiment of the LEPS Collaboration shows a peak around 1.530 GeV/c^2 in the channel $\gamma d \rightarrow pK^-\Theta^+$ [28], for which CLAS did not confirm its previous positive result. However, the detector acceptance regions covered by these experiments are different.

Recent theoretical studies by Sibirtsev *et al.* [29][30], by Roberts [31], and by Diakonov [32] obtain small values of about 1 MeV as upper limit for the Θ^+ width. Ref. [32] reviews the present experimental status and concludes that for a width below 1 MeV as estimated by DIANA [26] the existence of the Θ^+ is not ruled out by the recent negative results including those of CLAS [23][24]. In this situation further measurements with improved accuracy using different reactions were needed to clarify the Θ^+ puzzle.

In this letter we report on the results of an experiment studying the $pp \rightarrow pK^0\Sigma^+$ reaction with the COSY-TOF spectrometer with substantially improved statistical accuracy and extended detection capability. COSY-TOF is the only experiment involved in Θ^+ studies which provides an exclusive measurement of the final state in pp collisions, and it is unique in its almost complete coverage of the three-body phase space. Moreover the exclusive measurement selects the strangeness in the K^0p system to be $S = +1$, which is a unique feature for experiments searching for the Θ^+ in the K^0p system.

In the following the improved experimental setup will be described and the results obtained by three independent analyses will be presented.

2 Experiment

The experiment was performed at the cooler synchrotron COSY with the COSY-TOF spectrometer [33]. The preceeding measurement [11] was carried out at a beam momentum of 2.95 GeV/c, a slightly higher momentum of 3.059 GeV/c was chosen for the new measurement. At this higher momentum the upper bound of the K^0p invariant mass is 1.597 GeV/c^2 and therefore a possible structure at 1.530 GeV/c^2 is further removed from the upper mass limit.

The reaction $pp \rightarrow pK^0\Sigma^+$ is induced by focusing the proton beam on a spot of about 1 mm in diameter on a liquid hydrogen target (length 4 mm, diameter 6 mm). The start detector system, which was upgraded for the experiment described here, is mounted 2 cm downstream of the target. A schematic view is shown in Fig. 1 together with the event topology of the studied reaction. The first detector is a thin scintillation counter with a diameter of 15 cm, consisting of two segmented layers of 1 mm thickness. Each layer is subdivided into 12 wedge shaped scintillators. This detector provides the multiplicity of the charged particles close to the target as well as the start signal for the time-of-flight measurement. It is followed by a double-sided silicon microstrip detector with a diameter of about 6 cm, the front and rear sides of which consist of 100 rings and 128 sectors, respectively, giving a precise track point close to the target. At a distance of about 10 cm and 20 cm two scintillating fiber hodoscopes are installed to obtain two further track points. These detectors are required to identify the tracks from the delayed decay of K^0_S mesons into $\pi^+\pi^-$ pairs. The track of the K^0- meson is defined by the vertex of its decay and the primary vertex. For the measurement described here the first hodoscope was replaced by an upgraded version. It consists of two crossed planes and a stereo plane at 45^0, all built of squared fibers (2 mm $\times$ 2 mm), forming an inner part of about 20 cm $\times$ 20 cm with three layers and an outer part of about twice the size with two layers. The second hodoscope with a size of about 40 cm$\times$ 40 cm consists of two crossed layers. The inner detector system covers the full phase-space of the primary particles (Σ^+-hyperon, K^0-meson, and proton) apart from tiny holes with a diameter of about 2 mm for the beam.

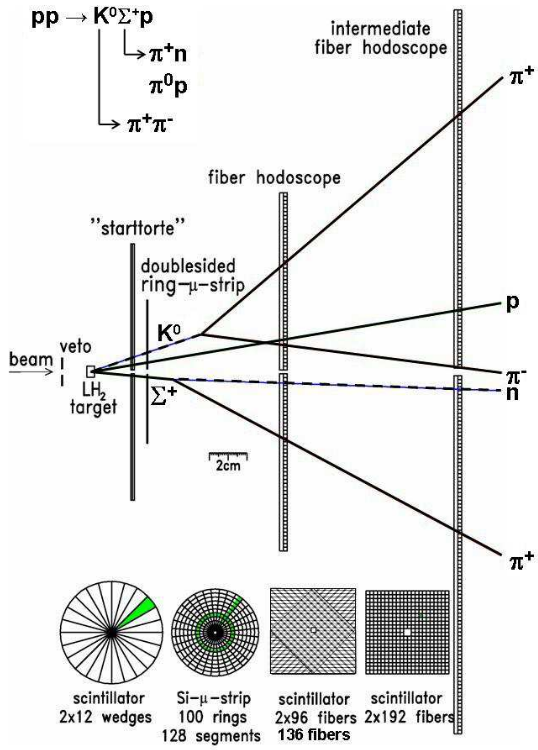

Figure 1: Schematic view of the start region with the track pattern of a $pp \to pK^0\Sigma^+$ event

This also holds for the outer detector system, which consists of 96 scintillating bars arranged as a barrel with radius of 1.5 m and length of 2.8 m, and a forward wall at 3.3 m distance from the target [34][35]. The outer detector provides the stop signal for the time-of-flight measurement as well as additional track points.

The trigger condition is based on the increase in charged-particle multiplicity between the start scintillator and the outer detector system, which results from the $K^0_S \to \pi^+\pi^-$ decay (see Fig. 1). The used trigger reduces the event rate by a factor of about 10^4.

The TOF spectrometer supplies very good position information due to its high granularity allowing track reconstruction. Together with time-of-flight information this is exploited in the three analyses of the data in various ways, as described in the following section.

3 Data Analysis

The analysis was carried out with three independent analysis programs (A, B, C), which differ in algorithms and event selection methods, but are based on a common calibration of all detector components. In order to cross-check each analysis the complete data sample was divided into two independent parts (events recorded with either even or odd number). The analysis procedures were developed using even events only and the odd events were analyzed only after the analysis procedures were frozen.

A $pK^0\Sigma^+$ event is identified according to Figure 1 by its topology, that is a prompt track emerging from the target (proton), a delayed decay (K^0) and optionally a kink in a charged track (Σ^+).

A prompt track emerging from the target is assigned to a proton. The χ^2 of a straight line fit and the number of detector elements with hits on this track are used as quality criteria, which serve for the track selection. The selection parameters are different in the three analyses. The momentum is calculated from the time-of-flight and the proton mass. The K^0_S is reconstructed from the invariant mass of the decay particles $\pi^+\pi^-$. The secondary vertex is reconstructed from the fitted pion tracks and restricted to the region between the microstrip detector and the first fiber hodoscope. The plane defined by these tracks must contain the primary vertex. In order to discriminate against the $\Lambda \to p\pi^-$ decay the different analyses place different selections on the angles of the decay particles with respect to the K^0_S direction and on their velocities. The Σ^+ is identified by a kink in a charged particle track. The direction of the Σ^+ is measured with the silicon micro strip detector.

The main aspects in which the analyses differ, are the following: AnalysisA: The Σ^+ is reconstructed from the missing mass of the pK^0system, the value of the missing mass is used as the final selection criterion. As the Σ^+ signal in the microstrip detector is not required, no constraint on the Σ^+ decay vertex is imposed. Analysis B: The detection of a kink due to the Σ^+ decay is required. The direction of the Σ^+ is calculated from the microstrip detector pixel and the primary vertex. For the two subsystems $\pi^+\pi^-$ and $p\Sigma^+$ the invariant and missing mass are calculated, respectively. Both calculations require the direction of K^0 in addition. If there is more than one candidate topology for a $pK^0\Sigma^+$ event, the topology with the minimum difference of both calculated masses to the K^0 mass is chosen. A 3C-kinematic fit is applied to the final event. Event selection is based on the subsystem masses and on the χ^2 of the kinematic fit. Analysis C: The Σ^+ is identified as in analysis B. A 3C-kinematic fit is applied for all possible topologies of one event, that with the lowest χ^2 is selected, if the χ^2 is lower than a given limit.

In all analyses an instrumental background from incorrectly reconstructed events in the data sample was investigated by various methods. These include side band investigations and variations of the maximum χ^2. The background was found to be smooth in the pK^0, $p\Sigma^+$ and $K^0\Sigma^+$ invariant mass distributions. The background is determined to be 21% (A), 25% (B), 28% (C).

The corrections for detector acceptance and for the efficiencies of the analyses are deduced from Monte Carlo simulations that use an equal population of 3-body phase space as input. The efficiencies of the analyses (including all branching ratios) are $(2.0 \pm 0.1) \cdot 10^{-3}$ (B,C) and $(4.2 \pm 0.2) \cdot 10^{-3}$ (A). The latter one is larger since there is no restriction on the location of the Σ^+-decay vertex. The resolution in the invariant mass distribution of the pK^0 subsystem is $\sigma = 6$ MeV/c^2 for analyses A,C and 5 MeV/c^2 for analysis B as deduced from Monte Carlo.

Elastically scattered events were recorded in parallel in order to determine the luminosity. In total $1.3 \cdot 10^{10}$ events were recorded with an integrated luminosity of (214 ± 20) nb^{-1}. Approximately 4000 $pK^0\Sigma^+$ events in analysis B,C, and 7900 events in analysis A, are reconstructed. Due to the different strategies of the analysis about 300 events are found both in B and C. For each combination A,B and A,C about 600 events are shared. Therefore, in total more than 12.000 independent $pK^0\Sigma^+$ events were reconstructed.

4 Evaluation of results

The total cross section, obtained by the different analyses, is given in Table 1. Only statistical errors are quoted. The systematic error of the total cross section is estimated to be ± 1 μb. It is mainly caused by uncertainties in the determination of both the luminosity and the detection and reconstruction efficiencies.

analysis	cross section
A	6.9 μb $\pm$ 0.2 μb
B	7.0 μb $\pm$ 0.3 μb
C	7.0 μb $\pm$ 0.3 μb

Table 1: Total cross section of $pp \to pK^0\Sigma^+$

The invariant mass spectra of the subsystems pK^0, $p\Sigma^+$, and $K^0\Sigma^+$ as extracted from the three analyses are shown in Fig. 2 after background subtraction and acceptance correction.

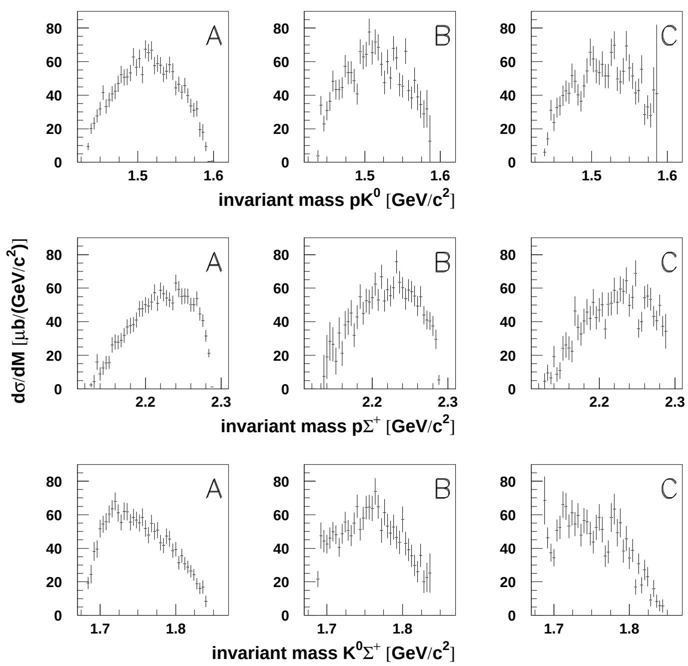

Figure 2: The invariant masses for the three subsystems in the $pK^0\Sigma^+$ final state. The first column shows the results of analysis A, the second one that of analysis B, the third one that of analysis C.

All results agree within statistical uncertainties. No significant differences of spectra obtained from even and odd events were found. The invariant mass spectra do not follow an equal population of phase space. However this is without implication for the search for the Θ^+.

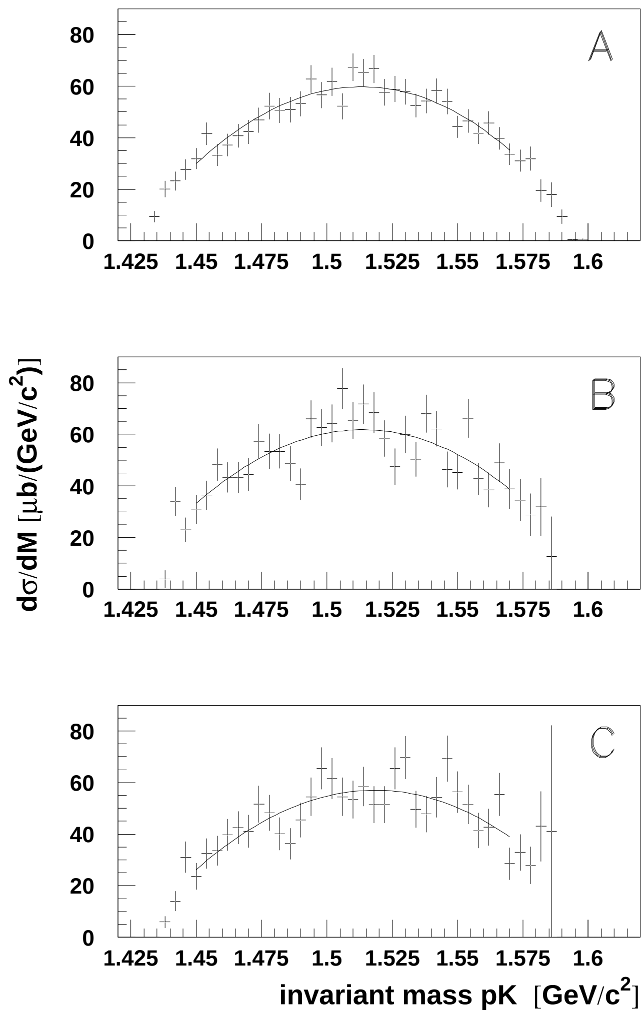

Figure 3: The invariant masses of the pK^0 system for the three analyses together with a 3^{rd} order polynomial parameterization.

The pK^0 mass spectra are presented again in Fig. 3 together with a 3^{rd} order polynomial parameterization in the mass region of 1.45 GeV/c^2 $<$ M_{pK^0} $<$ 1.57 GeV/c^2. They were analyzed in order to determine the statistical significance with which a narrow structure might be present. A narrow structure was added to the polynomial described above. The shape of this narrow structure has been taken from Monte Carlo simulations of a resonance with a width negligible compared to the detector resolution. The width of the added structure therefore corresponds to the experimental resolution of the invariant pK^0 mass of $\sigma = 6\, MeV/c^2$ for analyses A,C and $\sigma = 5\, MeV/c^2$ for analysis B (see chapter 'data analysis') The mass of the resonance was varied in 1 MeV/c^2 steps over the M_{pK^0} range from 1.50 GeV/c^2 - 1.55 GeV/c^2. The strength of the structure for each setting was varied between $-1\ \mu\mathrm{b} < \sigma_{\mathrm{tot,X}} < +1\ \mu\mathrm{b}$. The negative values here correspond to a drop of the M_{pK^0} differential cross section below the expectation based on the polynomial parameterization. For each combination of M_{pK^0} and $\sigma_{tot,X}$ the value of χ^2 of the fit to the data was determined. These results are summarized in Figure 4.

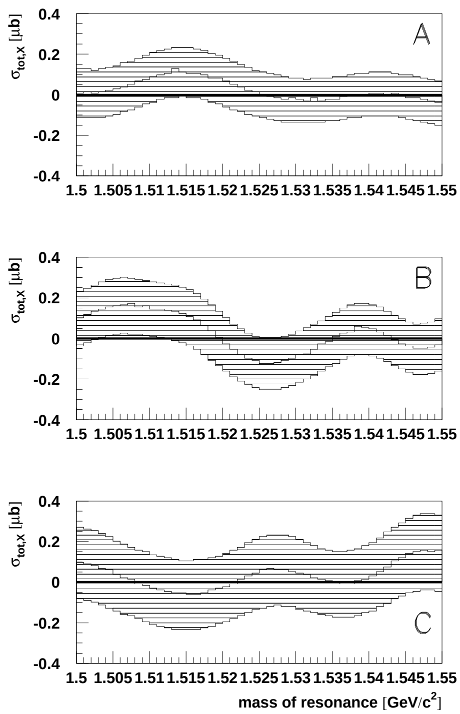

Figure 4: 95% confidence range for the cross section of a narrow resonance as a function of M_{pK^0} for the A, B, C analyses in the top, center, and lower frames, respectively. The central lines of each band present the contribution of a hypothetical narrow resonance with the lowest χ^2 value.

In this figure the value of $\sigma_{tot,X}$ corresponding to the minimal value of χ^2 is represented by the central line of the band as a function of M_{pK^0}. The 95% confidence interval for an enhancement or suppression of the measured M_{pK^0} differential cross section is indicated by the width of the band. The results presented in Figure 4 indicate that over the full M_{pK^0} range investigated here the parameterization assuming $\sigma_{tot,X}$ = 0 μb is consistent with the measured data within the 95% confidence level. In particular, this new, higher statistics data do not contain positive evidence for a narrow structure at M_{pK^0} =1.530 GeV/c^2. The fluctuation of the central value of the 95% confidence intervals are not correlated between the different analyses. Based upon the smallest upper limit of the three 95% confidence intervals the maximum cross section for a narrow resonance $\sigma_{tot,X} < 0.15$ μb has been deduced over the full mass range.

These results also have to be compared with the positive evidence for a Θ^+ resonance found in the data of the first measurement [11]. First of all the number of reconstructed events is much larger for the new measurement - about a factor of 4 for analyses B and C and about a factor of 8 for analysis A - which gives a strongly improved statistical accuracy. In addition, the three largely different analyses give a better understanding of systematic uncertainties. In the previous measurement the peak was located 32 MeV/c^2 below the upper kinematic limit of the populated pK^0 mass range and therefore resided on a continuum background with a steep negative slope. This caused uncertainties in the determination of the background. Therefore, in the present experiment a higher excess energy was chosen. Comparing the pK^0 spectra obtained in this work with the published one [11] a significant difference in the shape, which is more symmetric in the new measurement, is noticed. Since the pK^0 invariant mass distribution obtained in the new experiment is based on three independent analysis procedures including systematic studies of the instrumental background, we are confident in the symmetric shape of the pK^0 continuum. The data points of the three different analyses together with their uncertainties define a band, which represents the continuum shape of these analyses.

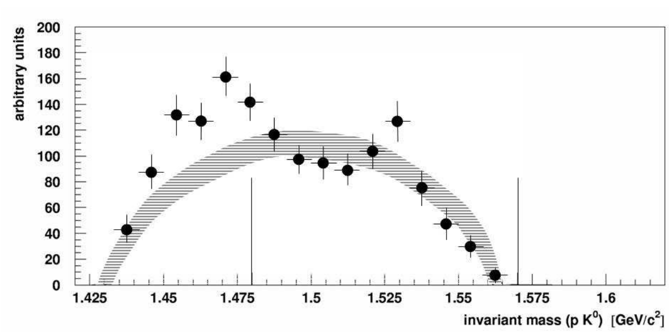

Figure 5: Invariant mass of the pK^0 spectrum of the previous measurement together with a band representing the shape of the new measurement. The height of the band is adjusted in the mass range indicated by the two vertical lines.

In order to compare it to the previous data, this band is scaled to the kinematically allowed range. Fitting its height within a mass region between 1.48 GeV/c^2 and 1.57 GeV/c^2, symmetric with respect to the peak observed at 1.53 GeV/c^2 [11], the significance of the peak decreases substantially if this shape is used as continuum for the previous data (see Figure 5).

5 Summary

The reaction $pp \to pK^0\Sigma^+$ was studied in an exclusive measurement at a beam momentum of 3.059 GeV/c with complete phase space coverage. The extracted pK^0 spectra do not show evidence for a narrow resonance in the mass region of 1.50 GeV/c^2 - 1.55 GeV/c^2 in any of the three independent analyses. The data are consistent with a cross section of $\sigma_{tot,X} = 0\,\mu$b and an upper limit of 0.15 μb is derived with a confidence level of 95%. The evidence for a Θ^+, which was found in a preceding measurement, is not confirmed.

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