Investigation of the reaction $pp \to pK^0\pi^+\Lambda$ in search of the pentaquark

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Abstract. The reaction $pp \to pK^0\pi^+\Lambda$ has been studied with the ANKE spectrometer at COSY-Jülich at a beam momentum of $3.65\,\mathrm{GeV/c}$ in order to search for a possible signal of the pentaquark $\Theta^+(1540)$, decaying into the pK^0 system. By detecting four charged particles in the final state (π^+, π^- and two protons), the K^0 and the Λ have been reconstructed to tag strangeness production. It has been found that the $\pi^+\Lambda$ missing-mass spectrum displays no significant signal expected from the $\Theta^+(1540)$ excitation. The total cross section for the reaction $pp \to pK^0\pi^+\Lambda$ has been deduced, as well as an upper limit for the Θ^+ production cross section. The intermediate $\Delta^{++}K^0\Lambda$ state seems to provide a significant contribution to the reaction.

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1. Introduction

The reactions $pp{\to}NK\pi\Lambda$ have been intensively used for hadron spectroscopy at beam momenta above $5\,\mathrm{GeV/c}$, since they offer an excellent opportunity to search for baryon and hyperon resonances by studying πN and $\pi\Lambda$ final states, respectively [1–9]. It also allows one to investigate the KN system, which attracted a lot of attention due to its putative coupling to the pentaquark baryon $\Theta^+(1540)$ [10]. Despite a number of experimental indications for the existence of such a state, recent negative results, mostly obtained at higher energies (see e.g. [11] and references therein), have cast serious doubt on the existence of the pentaquark Θ^+. Its current status is reviewed in [12]. There is no theoretical investigation that reconciles both the positive and the negative observations, although it has been shown in [13] that the production of Θ^+ should be strongly suppressed at higher energies. Hadronic experiments at low energies are believed to be crucial to clarify the situation.

The main features of the available data for $pp{\to}pK^0\pi^+\Lambda$ [1–9] are as follows: a) Structures in the $\pi^+\Lambda$ and π^+p systems have been clearly identified as $\Sigma^+(1385)$ and $\Delta^{++}(1232)$ resonances, respectively, providing the dominant contributions to the reaction cross section. In the π^+K system the $K^*(892)$ resonance has been detected, although its contribution is rather small. b) An enhancement in the $K\Lambda$ invariant mass spectrum at $1.7\,\mathrm{GeV}$, which is expected because of the excitation of the $P_{11}(1710)$ and $P_{13}(1720)$ baryon resonances [12], has been observed [3,4]. In [1] it has been argued that this enhancement results from a kinematical reflection due to $\Sigma^+(1385)$ production. c) The KN and ΛN invariant mass spectra have not been investigated yet. All published data suffer from rather limited statistics and a moderate energy resolution.

It is thus important to re-examine this reaction with new measurements with improved statistical accuracy and high mass resolution. Such a dedicated experiment has been performed with the magnetic spectrometer ANKE [14] at the COoler SYnchrotron COSY [15] at the Research Centre Jülich.

2. The experiment

COSY provided a circulating proton beam of $p_\mathrm{p} = 3.65\,\mathrm{GeV/c}$ with an intensity of approximately 4×10^{10} protons per spill interacting with a hydrogen cluster jet target [17] with a thickness of about $5 \times 10^{14}\,\mathrm{cm^{-2}}$. The detection systems of ANKE, capable of detecting charged particles with angles $\theta < 12°$, were triggered by a three-fold coincidence of two positively charged particles and a π^- (from Λ decay). The reaction has been identified by the off-line selection of four particles, namely a π^+ and π^- meson and two protons. Detection and identification of all the charged particles was performed by a combination of scintillation counters and multi-wire proportional chambers (MWPC). While the first allowed one to exploit the time-of-flight technique, the MWPCs supplied full tracking and momentum information, and permitted the selection of particles originating from the target *via* analysis of their vertical angle (for
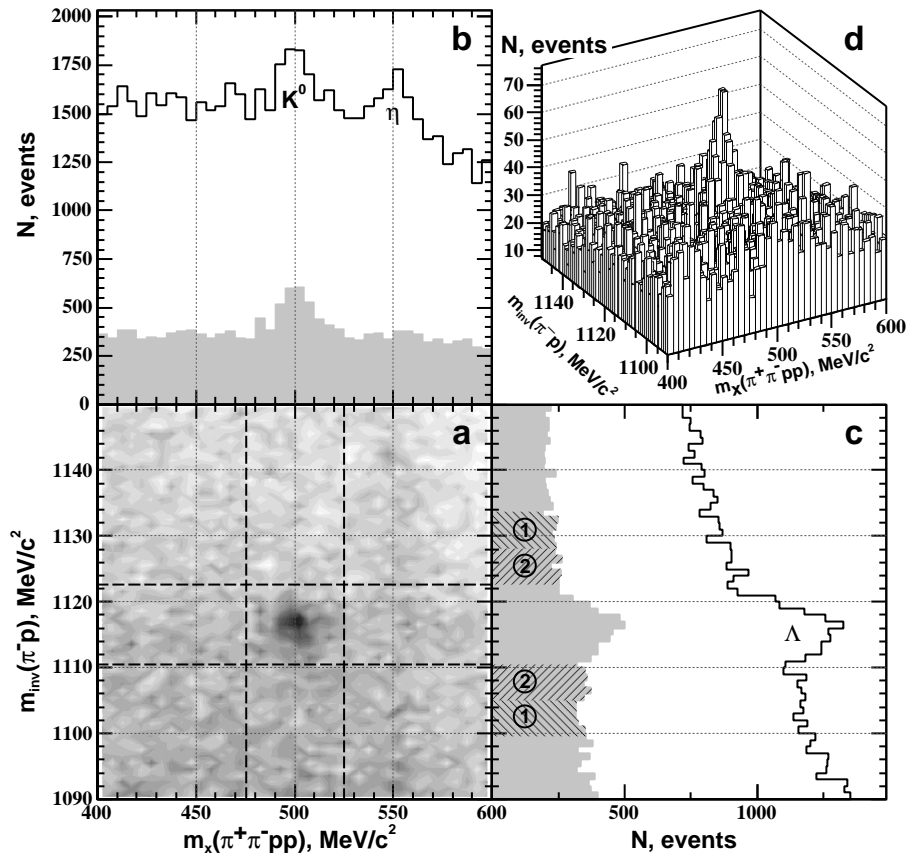
Figure 1. a) Mass contour plot: invariant mass of $\pi^- p$ versus missing mass of $\pi^+\pi^- pp$. An enhancement corresponding to the masses of K^0 (497.7 MeV/c²) and Λ (1115.7 MeV/c²) is seen. Corresponding projections are presented in figures b and c. A lego plot is given in figure d. Shaded areas in the projection plots onto the axes $m_{\text{inv}}(\pi^- p)$ (c) and $m_{\text{x}}(\pi^+\pi^- pp)$ (b) correspond to the independent cuts on masses of K^0 and Λ, respectively. The dashed lines indicate these cuts. The hatched areas, marked as 1 and 2 in the $m_{\text{inv}}(\pi^- p)$ plot (c) denote the regions used for the background subtraction (see text).

details see [14,16]). A coincidence measurement of four particles reduced the accidental background to a negligible level. The amount of misidentified particles was also small, due to the analysis of time-of-flight differences between detected particles. Therefore, the remaining background was almost entirely of physical origin.

The reaction $pp \to pK^0\pi^+\Lambda$ has been reconstructed by identifying the Λ hyperon in the $\pi^- p$ invariant mass and the K^0 meson in the missing mass of the $\pi^+\pi^- pp$ system. The K^0 signal thus includes both contributions from K_S^0 and K_L^0. The corresponding invariant mass *versus* missing-mass scatter plot is shown in figure 1a. An enhancement of $K^0\Lambda$ coincidences is clearly visible on top of a sizeable background, remaining after cuts on masses are made (see shaded areas in figures 1b and c). This background was removed by the side-band subtraction method. For the subtraction, events in the regions besides the Λ peak are selected, assuming that the background behaviour is smooth. The latter assumption was checked by choosing two different background regions (hatched
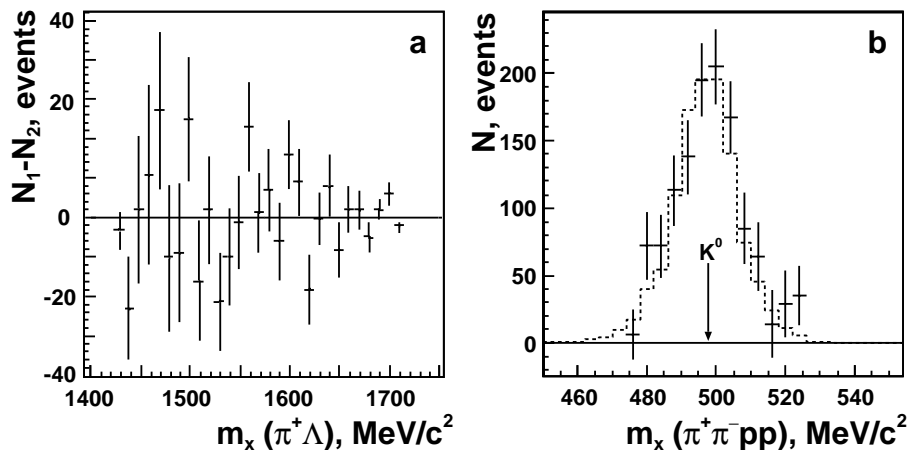
Figure 2. Side band subtraction technique. a) The difference of two missing mass spectra is plotted, in which different background regions were selected for the subtraction. b) K^0 signal after background subtraction has been applied. The dashed line shows the result of Monte Carlo simulations assuming a $pK^0\pi^+\Lambda$ phase space behaviour.

areas marked as (1) and (2) in figure 1c), and building the bin-by-bin difference between them. The side-band subtraction method can be applied, if such a difference spectrum does not exhibit any distinctive structures. For our case the result of this investigation is presented in figure 2a for the missing mass distribution $m(\pi^+\Lambda)$, indicating that no signal shape distortion should occur because of background subtraction. The resulting K^0 missing mass spectrum after background subtraction is shown in figure 2b. The dashed line shows the result of Monte Carlo simulations assuming a $pK^0\pi^+\Lambda$ phase space behaviour, which reproduces the experimental spectrum.

Differential distributions of the individual particles, such as momenta and scattering angles, are also well described by Monte Carlo simulations with the total reaction cross section as a free parameter and assuming four-body phase space distributions in the final state. The missing mass distribution $m(\pi^+\Lambda)$, shown in figure 3, is the one where the signal from the pentaquark would be expected to appear. However, no obvious peak at $1.54\,\mathrm{GeV/c^2}$ is visible. The total number of collected $pK^0\pi^+\Lambda$ events is 1041, which corresponds to a rate of 82 events/day for a total integrated luminosity of $36\,\mathrm{pb^{-1}}$. Together with the experimental data, results from the simulations are plotted as the solid line in figure 3. As one can see, only a moderate agreement ($\chi^2_{ndf} = 1.41$) between experimental data and simulations based on four-body phase space is achieved. While for the high mass part of the spectrum the agreement is reasonable, an obvious excess of experimental events is observed around $1.47\,\mathrm{GeV/c^2}$. Such an enhancement may be connected with the excitation of some intermediate resonances.

Indeed, at higher energies the reaction $pp \to pK^0\pi^+\Lambda$ proceeds mainly through the production of intermediate resonances $\Delta^{++}(1232)$ and $\Sigma^+(1385)$ [2, 4]. It has also been argued that $N^*(1650)$ or $N^*(1710)$, as well as an excitation of $K^*(892)$, might be important [4].
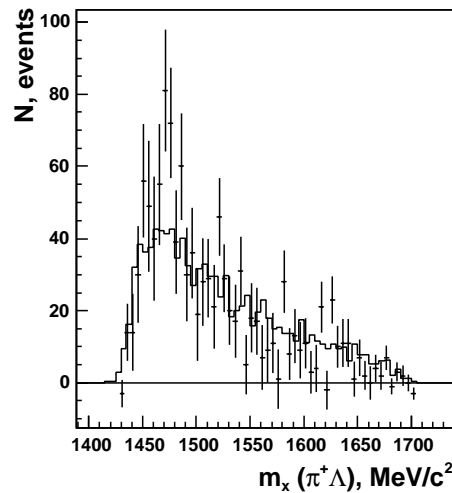
Figure 3. Missing mass spectrum of $\pi^+\Lambda$ system. The solid line shows the result of Monte Carlo simulations assuming $pK^0\pi^+\Lambda$ phase space behaviour.

In order to check these hypotheses a simultaneous fit of the two mass distributions, namely $m_{\mathrm{x}}(\pi^+\Lambda)$ on one hand and $m_{\mathrm{inv}}(\pi^+p)$ (for $\Delta^{++}(1232)$), or $m_{\mathrm{inv}}(\pi^+\Lambda)$ (for $\Sigma^+(1385)$), or $m_{\mathrm{x}}(\pi^+p)$ (for $N^*(1710)$) on the other, has been performed. Since the beam momentum is close to the $K^*(892)$ production threshold the relevant mass region is not populated, and therefore this resonance does not contribute significantly. By introducing the $N^*(1710)$ resonance into the simulations the agreement with experimental data significantly decreases, thus unfavouring this channel. No significant difference is found
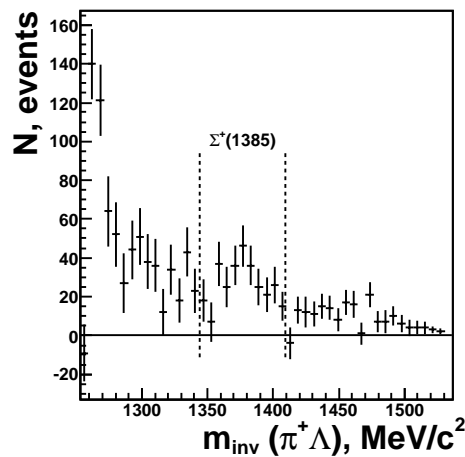

Figure 4. a) Invariant mass spectrum of $\pi^+\Lambda$ system. The dashed lines restrict the area where a signal of $\Sigma(1385)$ is expected.

in the quality of the fit including both the non-resonant channel and the one with an intermediate $\Sigma^+(1385)$, although a small amount of events can be attributed to the production of $\Sigma^+(1385)$ (see figure 4). The fit results in a $\Sigma^+(1385)$ peak area, which is compatible with being a statistical fluctuation of the background. Therefore, only an upper limit for the possible $\Sigma^+(1385)$ production can be deduced. Our estimates are

based on the method of calculating the upper limit for the peak area as given in [18]. This method assumes that the maximum peak area depends on the background and the total counts in the peak region. The upper limit is then obtained for a given significance level, taking into account that the background is not exactly known and has a certain error. As a result we extract $N_\Sigma < 69$ events at the 95% confidence level, from which an upper limit for the cross section is deduced, given further below.

The contribution from the formation of an intermediate $\Delta^{++}(1232)$ becomes obvious in the mass distribution of the π^+p system shown in figure 5a. Here the dotted region originates from the $pK^0\pi^+\Lambda$ phase space, while the solid line depicts the sum of the latter and contributions from $\Delta^{++}(1232)$ and Θ^+. The overall agreement between experimental data and simulations improves ($\chi^2_{ndf} = 1.24$), as shown in figure 5b. The inset in figure 5b presents the individual contributions from non-resonant production and from intermediate $\Delta^{++}(1232)$ excitation. Since the shapes of the distributions above $1.47\,\mathrm{GeV/c^2}$ are very similar, any conclusion about the possible Θ^+ production does not depend on the assumption made for "non-exotic" mechanisms.
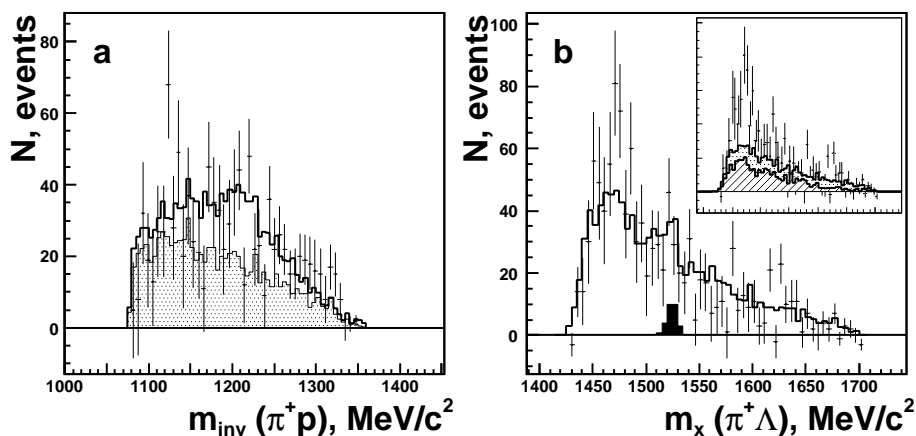

Figure 5. a) Invariant mass of π^+p system. The dotted area is obtained from the simulations assuming phase space without intermediate resonances, and the solid line is the sum of all the contributions. b) Missing mass spectrum of $\pi^+\Lambda$ system. The solid line denotes the sum of all the contributions. The inset shows individual contributions from non-resonant production (dotted) and from intermediate $\Delta^{++}(1232)$ (hatched). The black region corresponds to the maximum permissible $\Theta^+(1540)$ signal.

Finally, the black area in (figure 5b) corresponds to the possible signal expected from the Θ^+ production. It has been found that the maximum permissible number of pentaquark events weakly depends both on the width and the position of the resonance. The width was varied from 1 up to $15\,\mathrm{MeV/c^2}$, with the latter value comparable to the missing mass resolution (FWHM) of the apparatus, while the Θ^+ mass ranged between $1.52\,\mathrm{GeV/c^2}$ and $1.54\,\mathrm{GeV/c^2}$. The maximum number of pentaquark events found under these various assumptions is given by the best fit to the experimental data and equals to 28 ± 20. It is obvious, that even with the best fit the signal is compatible with zero within errors, and therefore cannot be used for the cross section estimates. Thus, as in

the $\Sigma^+(1385)$ case, only an upper limit for the cross section will be given below. For the evaluation of the upper limit of the Θ^+ yield at the 95% confidence level the approach from [18] has again been used. This resulted in 44 Θ^+ events, used for calculation of an upper limit of the cross section (see below).

For normalisation of the data, the reaction $pp \rightarrow pK^+\Lambda$ has been used. This reaction was measured simultaneously during the experiment. Again all four particles in the final state have been detected, including the proton and π^- from Λ decay. Contrary to the $pp \rightarrow pK^0\pi^+\Lambda$ reaction there are no background channels in the case of the production of $pK^+\Lambda$ (see figure 6). Such a normalisation procedure, where a reaction with known cross section [19, 20] and nearly the same final state is measured, allows one to avoid most of the systematic uncertainties connected with particle identification and detector efficiencies, although adding a contribution due to the uncertainty in the acceptances of both measured channels.
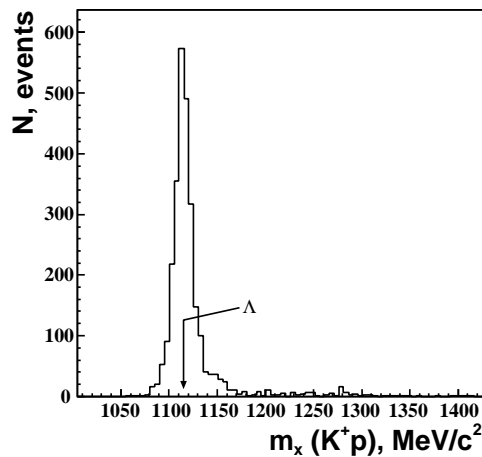

Figure 6. Missing mass spectrum of K^+p system in the reaction $pp \rightarrow pK^+\Lambda$. A background-free final-state identification has been achieved.

3. Results and discussion

Since the acceptances of both four-body phase-space production and production with an intermediate $\Delta^{++}(1232)$ are very similar, a total cross section for the $pK^0\pi^+\Lambda$ final state can be calculated largely independent of the decomposition into separate channels. After the normalisation and efficiency corrections, the following total cross section for the $pK^0\pi^+\Lambda$ final state has been deduced:

$$\sigma_{\text{tot}} = 1.41 \pm 0.05 \pm 0.33 \, \mu\text{b},$$

where the first error is statistical, while the second is systematic. The systematic uncertainty is mostly coming from the error of $\sigma_{pK^+\Lambda}$ [19].

The total cross sections for the non-resonant channel and the channel with the $\Delta^{++}(1232)$ excitation have also been evaluated:

$$\sigma_{pK^0\pi^+\Lambda}^{\text{non-resonant}} = 0.92 \pm 0.16 \pm 0.21 \, \mu\text{b},$$

$$\sigma_{\Delta^{++}K^0\Lambda} = 0.49 \pm 0.14 \pm 0.11 \, \mu\mathrm{b}.$$

Unlike with the total cross section, where the calculation relies on the number of experimental events, the results for the individual channels include an additional error from the decomposition. The measured cross section for the $pp \to \Delta^{++}K^0\Lambda$ reaction is significantly lower than a model prediction, $\sigma \approx 6 \, \mu\mathrm{b}$ [20]. However, this model overestimates as well the data available at high energies.

Table 1. Contributions of different channels to the cross section for $pp \to pK^0\pi^+\Lambda$ in per cent of the total cross section σ_{tot} (see also figure 7). NR denotes non-resonant production.

Ref.	p_{p} GeV/c	σ_{tot} μb	NR %	Δ^{++} %	Σ^{*+} %	K^* %	N^* %
This work	3.65	1.41	65	35	*seen*	–	–
[3]	6.70	64	36	36	18	10	*seen*
[4]	7.87	72.4	5.7	34.2	29.1	15.5	15.6

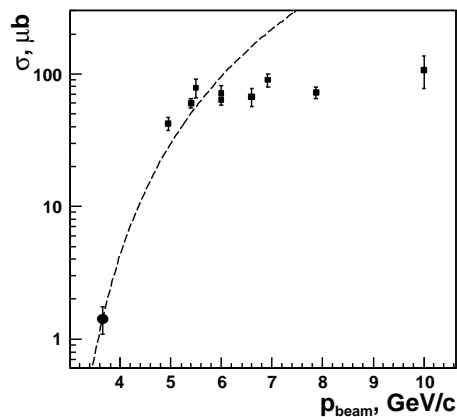**Figure 7.** Total cross sections for the reaction $pp \to pK^0\pi^+\Lambda$ as a function of the beam momentum. The ANKE data point is denoted by a circle, while the other cross sections (see [1–9]) are given by squares. The dashed line corresponds to four-body phase space normalised to the ANKE data point.

The energy dependence of the total cross section of the reaction $pp \to pK^0\pi^+\Lambda$ is shown in figure 7. The data point from the current work is denoted by the full circle, while cross sections from other experiments are shown as squares. A nearly constant cross section above $p_{\mathrm{p}} \approx 6 \, \mathrm{GeV/c}$ can be understood if the reaction proceeds via intermediate resonances. Otherwise, a steep rise of the total cross section due to four-body phase space should be expected, as is shown by the dashed line in figure 7. Such a resonance dominance has been observed at higher beam energies [2, 4], where $\Delta^{++}(1232)$ and $\Sigma^+(1385)$ provide the dominant contribution to the yield. Nevertheless, below $p_{\mathrm{p}} \approx 6 \, \mathrm{GeV/c}$, where the energy available for the production of the resonances is

limited, non-resonant production is still competitive, and its relative contribution should decrease with increasing energy. The opposite behaviour is expected for resonance channels. Their contribution should increase with the beam momentum as illustrated in table 1.

Taking into account the estimated maximum number of 44 events for the Θ^+ from the discussion above, we have evaluated an upper limit for the cross section of Θ^+-production in $pp \to \Theta^+\pi^+\Lambda$ at $p_{\mathrm{p}} = 3.65\,\mathrm{GeV/c}$:

$$\sigma_{\Theta^+\pi^+\Lambda} < 0.058\,\mu\mathrm{b} \qquad (95\%\,CL).$$

It is not possible to directly compare this result with the cross section for $pp \to pK^0\Sigma^+$ measured at $p_{\mathrm{p}} = 2.95\,\mathrm{GeV/c}$ by the COSY-TOF collaboration [21], indicating a Θ^+-signal. The exit channels are distinct and even the number of particles in the final state differs. As a crude estimate, one may assume that production of an additional pion leads to the reduction of the cross section by an order of magnitude. However, a similar factor can be regained due to the production of a Λ instead of a Σ. But a difference in beam momentum of $700\,\mathrm{MeV/c}$ makes such a comparison very rather simplistic and questionable.

The upper limit for the $\Sigma^+(1385)$ production cross section is also provided by our data:

$$\sigma_{\Sigma^+(1385)K^0p} < 0.15\,\mu\mathrm{b} \qquad (95\%\,CL).$$

As has already been mentioned above, the estimates of these cross sections do not depend on how the corresponding mass distributions are decomposed, since the shapes of the separate contributions are very similar in regions where the peaks from Θ^+ and $\Sigma^+(1385)$ are expected.

In summary, we have presented measurements of the reaction $pp \to pK^0\pi^+\Lambda$ for $p_{\mathrm{p}} = 3.65\,\mathrm{GeV/c}$. While at higher beam momenta the formation of this final state is dominated by the production of intermediate resonances, non-resonant production seems to prevail at COSY energies, although the intermediate $(\Delta^{++}K^0\Lambda)$–state provides an important contribution to the yield. Unlike at higher energies, the contribution of $\Sigma^+(1385)$ is small. We have found no obvious signal indicative of the $\Theta^+(1540)$. Its cross section in $pp \to \Theta^+\pi^+\Lambda$ reaction is limited to be less than $58\,\mathrm{nb}$.

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