The energy dependence of the $pp \to K^+ n \Sigma^+$ reaction

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Abstract. The energy dependence of the total cross section for the $pp \to K^+ n \Sigma^+$ reaction has been investigated at the magnetic spectrometer COSY-ANKE. Signals from the production of the Σ^+ hyperon were searched for in three simultaneously measured spectra. The values obtained for the total production cross section $\sigma(\Sigma^+)$ are slightly below those of $\sigma(\Sigma^0)$ at the same excess energies. They follow a phase space dependence and do not show any evidence for strong threshold effects or a significant $n\Sigma^+$ final state interaction.

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Light hyperon production in proton-proton collisions is an important part of the experimental program carried out at the COoler-SYnchrotron Jülich. The energy dependence of the total cross sections for Λ and Σ^0 production has been well investigated in the COSY range of excess energies ($\varepsilon < 1$ GeV) [1]. The ratio of the total cross sections for these two productions, $R(\Lambda/\Sigma^0) = \sigma_\Lambda/\sigma_{\Sigma^0}$, falls from a factor of 27 close to threshold down to 3 at high ε [2, 3]. At the moment, there is no agreed theoretical explanation for such a behavior. Calculations within the Jülich meson exchange model [4] suggest that the suppression of near-threshold Σ^0 production with respect to the Λ could be associated with differences between the production mechanisms and a destructive interference between K and π exchanges.

A recently published analysis [5] of the measured angular distributions for $pp \to K^+ p\Lambda$ and $pp \to K^+ p\Sigma^0$ reactions suggests that N^* resonances play a major role in Λ production whereas in the case of the Σ^0 no indication for such an effect has been observed. It is also concluded that kaon exchange is significant for Σ^0 production while it is less important for Λ [5]. However, these data were collected at relatively high excess energies, where the many partial waves and final-state interactions make the interpretation of the experimental data difficult.

The third light hyperon production channel, $pp \to K^+ n\Sigma^+$, has not been so well investigated. The primary reason for this is the presence of the neutron in the final state, which make any identification of the reaction complicated. On the other hand, this reaction channel is an isospin-$3/2$ filter for nucleon isobars [6]. Thus, the N^* resonances, which are believed to be important for Λ production [7], cannot contribute in the Σ^+ case.

Experimental data on $pp \to K^+ n\Sigma^+$ reaction close to threshold are scarce. Pioneering measurements, performed close to the reaction threshold at $\varepsilon = 13$ and 60 MeV using a neutron detector, reported surprisingly high values of the total cross sections [8]. These data could only be understood if the production mechanism and the final state interaction for the Σ^+ hyperon were completely different from those of other light hyperons.

The cross sections for the different Σ hyperon production channels can be linked together using a triangle inequality [9]. At high ε there is evidence that $\sigma(pp \to K^+ p\Sigma^0) \approx \sigma(pp \to K^0 p\Sigma^0)$ [10] and, assuming this, the inequality can be written as $1/6 < \sigma(pp \to K^+ p\Sigma^+)/\sigma(pp \to K^+ p\Sigma^0) < 6$ [11]. The ratio of total cross sections $R(\Sigma^+/\Sigma^0)$ obtained using the data from Ref. [8] is 127 and 60 at $\varepsilon = 13$ and 60 MeV, respectively. Thus, the values of Σ^+ total cross section would violate isospin invariance by a large factor unless there were a very striking threshold anomaly.

This unexpected result led to a series of investigations of the $pp \to K^+ n\Sigma^+$ reaction at COSY [11, 12]. These were based on a three-prong approach where the signal from the Σ^+ hyperon production was searched for in three simultaneously measured spectra. The measurements were done at the magnetic spectrometer ANKE, which is placed at an internal target station of the COSY-Jülich accelerator. The ANKE spectrometer consists of three dipole magnets. Two of them, $D1$ and $D3$, are used to deflect the circulating proton beam onto and away from the target, while the third one, $D2$, is the analyzing magnet. Positively charged particles from a reaction are deflected into the positive (Pd) and forward (Fd) detectors, while negatively charged particles can be registered in the so-called negative detector (not used in the analysis).

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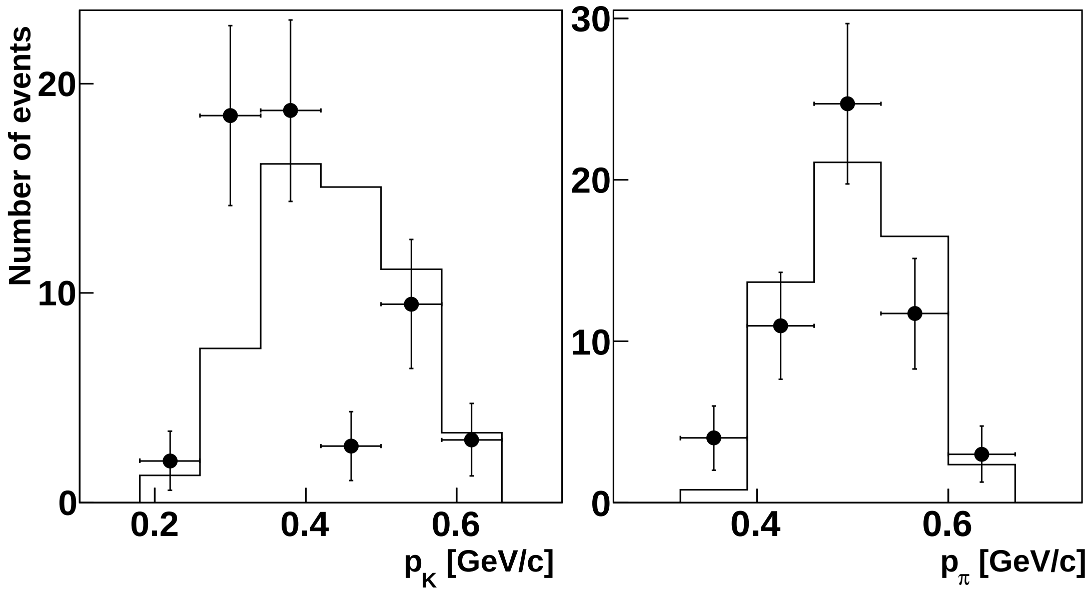

FIGURE 1. The K^+ and π^+ momentum spectra measured at $T_p = 1.958$ GeV in comparison to phase space simulations for the $pp \to K^+ n\Sigma^+$ reaction.

The Fd consists of a hodoscope of scintillator counters, two multi-wire proportional and one drift chamber. This was used for the identification of the high momentum protons from pp elastic scattering, used for normalization, and protons from the reactions of interest. In the analysis, the positive side detector allowed the π^+ and K^+ identification.

The Pd detector is made up of start counters, placed close to the exit window of the $D2$ vacuum chamber, two multi-wire proportional chambers, and stop counters. The first fifteen stop counters are part of the range telescopes used for K^+ identification on the basis of the delayed-veto technique. Each of the range telescopes consists of a stop counter, scintillator counter for measurements of the energy loss of the particles, a so-called veto counter for measurements of time, and two passive degraders. The thickness of the first degrader is chosen such that a K^+ deposits the maximum energy in the energy-loss counter and stops either at the edge of it or in the second degrader. The time signal from the K^+ decay products is then registered in the veto counter, allowing one to identify K^+ mesons against a 10^6 times higher background. The details of the ANKE detector analysis can be found in Ref. [13].

In contrast to the Λ and Σ^0 hyperons, the Σ^+ hyperon has a decay mode leading to a π^+ in the final state and this has a branching ratio of 50%. Thus, below the threshold of the $pp \to K^+ n\Lambda\pi^+$ reaction, the $pp \to K^+ n\Sigma^+$ reaction is the only source of $K^+\pi^+$ coincidences. Even at higher energies, the total cross section for $\Lambda\pi^+$ production is factor of seven smaller than the total cross section for Σ^+ production [9]. The identification of $K^+\pi^+$ coincidences therefore allows one to identify unambiguously Σ^+ production and to estimate the total cross section. The correlated K^+ and π^+ momentum spectra measured at 1.958 GeV are compared to phase-space simulations, corrected according to the ANKE acceptance, and presented in Fig. 1.

All three light hyperons, Λ, Σ^0 and Σ^+, have decay modes where there is a proton in the final state. The $pp \to K^+ p\Lambda/\Sigma^0$ reactions can be identified from the peaks in the experimental K^+p missing-mass spectra. These sit on physical backgrounds arising from hyperon decay. The total cross sections for Λ and Σ^0 production can be determined from the numbers of events in these peaks. However, since we have clean K^+ identification, the other events in the K^+p missing-mass spectra can also be analyzed and information about the total cross section for Σ^+ production extracted [12].

The K^+p missing-mass spectra measured at 2.062 and 2.157 GeV are compared to simulations in Fig. 2. Individual contributions from $\Lambda \to p\pi^-$, $\Sigma^0 \to \Lambda\gamma \to p\pi^-\gamma$ and $\Sigma^+ \to p\pi^0$ are shown by colored histograms. Despite the limited statistical precision in the spectra, it is already clear by eye that $R(\Sigma^+/\Sigma^0)$ is less than a factor of five. In fact, if one makes the drastic assumption that all the events above the kinematic limit for the Λ are to be associated with Σ^+ production, upper limits on $R(\Sigma^+/\Sigma^0)$ of 1 and 2 are obtained at 2.062 and 2.157 GeV, respectively. The data at 2.062 GeV were collected with a relatively low field in the spectrometer magnet $D2$, which means that the acceptance

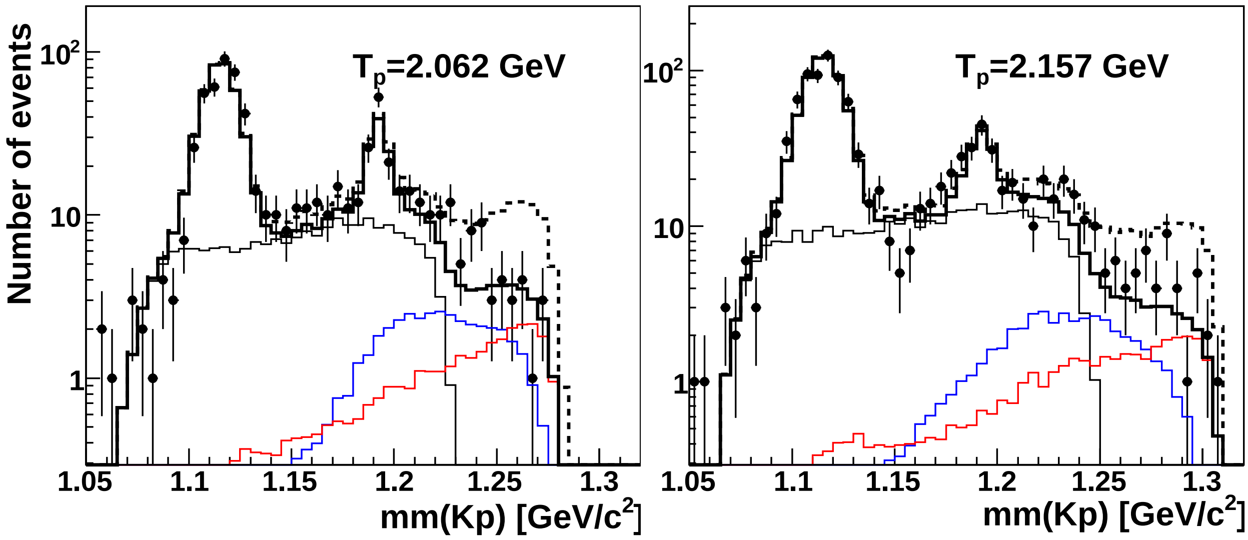

FIGURE 2. The K^+p missing-mass spectra measured at $T_p = 2.062$ and 2.157 GeV compared to simulations. Simulations for the Λ, Σ^0 and Σ^+ decay protons are shown by black, blue and red lines, respectively. Predictions for the complete spectra assuming $R(\Sigma^0/\Sigma^+) = 1$ and 5 are shown by solid and dashed lines, respectively. The numbers of events in the physical backgrounds are determined by the contents of the Λ and Σ^0 peaks.

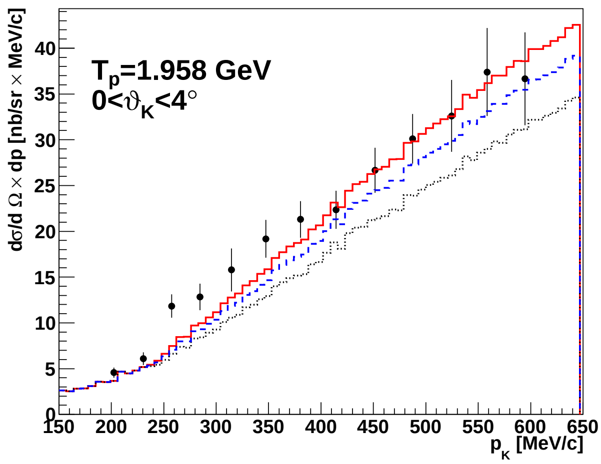

FIGURE 3. Inclusive K^+ momentum spectra for $\vartheta_{K^+} < 4^\circ$ resulting from pp collisions at $T_p = 1.958$ GeV. The simulation of the $pp \to K^+p\Lambda$ reaction is shown by the black histogram. The addition of contributions from $pp \to K^+p\Sigma^0$ and $pp \to K^+n\Sigma^+$ are shown by blue and red histograms, respectively. The total cross sections for all reaction channels are taken from Ref. [12].

for the data accumulated at this energy significantly differs from the others.

Only very limited information about total cross section can be extracted from the K^+ inclusive spectra. Inclusive K^+ differential cross sections measured at $T_p = 1.958$ GeV and integrated over $\vartheta_{K^+} < 4^\circ$ are presented in Fig. 3 in comparison to simulations. Individual contributions from different hyperon production channels, normalized to the corresponding total cross sections, are also shown.

A method to extract the Σ^+ total production cross section from a detailed analysis of K^+ inclusive spectra has, however, been proposed [14]. This was applied to new zero-degrees data in a recent paper by the HIRES collaboration and a value of $R(\Sigma^+/\Sigma^0) = 5$ at $T_p = 2.08$ GeV reported [15]. This high Σ^+ total production cross section follows the general trend of values extracted from measured K^+ inclusive spectra using this method [14].

The experimental data on the K^+p correlations, measured with ANKE spectrometer at very close energy 2.06 GeV, presented in Fig. 2, indicate a very modest value of $R(\Sigma^+/\Sigma^0)$, far below the factor of five claimed [15]. Possible uncertainties in the analysis of inclusive K^+ data, in particular in the assumptions regarding the behavior of the $pp \to K^+p\Lambda$ forward cross section, are discussed in detail in Ref. [16]. The new COSY-TOF data on differential observables for the Λ and Σ^0 reaction channels [5] support their conclusion that K^+ inclusive spectra can only lead to conservative upper limits on $\sigma(\Sigma^+)$ [16].

The energy dependence of the $pp \to K^+n\Sigma^+$ reaction has been investigated over a wide energy range at the magnetic spectrometer COSY-ANKE. The values of $\sigma(\Sigma^+)$, extracted from $K^+\pi^+$ correlations, are cross checked using the K^+p missing-mass and K^+ inclusive spectra. The values of $\sigma(\Sigma^+)$ thus obtained are consistent with a phase-space energy variation without any obvious sign of a strong $n\Sigma^+$ final state interaction or significant threshold anomaly.

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