COSY Proposal and Beam Request

For Lab. use	
Exp. No.:	Session No.
171	32

Title of Experiment

Study of the energy dependence of the pp→K⁺nΣ⁺ reaction close to threshold

Collaborators: ANKE Collaboration

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No support from the LSF program of the EC was requested

Date: 02.10.2006

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Total number of particles and type of beam (p,d,polarization)	Momentum range (GeV/c)	Intensity or internal reaction rate (particles per second)	
		minimum needed	maximum useful
Protons	2.6-2.8	$2 \cdot 10^{10}$	
Type of target	Safety aspects (if any)	Earliest date of installation	Total beam time (2weeks)
ANKE cluster-jet target (H_2)	-	Second half 2007	2 weeks

What equipment, floorspace etc. is expected from Forschungszentrum Jülich/IKP?

Summary of experiment:

It is proposed to investigate the production of positively charged Σ^+-hyperons in proton-proton collisions at five beam energies T_p between threshold (T_p=1.79 GeV) and ~2 GeV, using the ANKE spectrometer. The $pp \rightarrow K^+n\Sigma^+$ reaction channel will be tagged by detecting the K^+ in coincidence with the π^+originating from the Σ^+-decay. Due to strangeness conservation, there is no other source of such correlated pairs below the $K^+n\Lambda\pi^+$ threshold (T_p=1.98 GeV).
Two weeks of beam time will provide a knowledge of the energy dependence of the total cross section to complement the information available for the other hyperons.

Proposal/Beam-time request:

Study of the energy dependence of the $pp \to K^+n\Sigma^+$ reaction close to threshold.

Yu. Valdau (*Spokesperson*), V. Koptev, M. Nekipelov, H. Ströher,

C. Wilkin, and the ANKE collaboration

November 22, 2006

Abstract

It is proposed to investigate the production of positively charged Σ^+–hyperons in proton–proton collisions at five beam energies T_p between threshold ($T_p = 1.79\,\mathrm{GeV}$) and $\approx 2\,\mathrm{GeV}$, using the ANKE spectrometer. The $pp \to K^+n\Sigma^+$ reaction channel will be tagged by detecting the K^+ in coincidence with the π^+ originating from the Σ^+-decay. Due to strangeness conservation, there is no other source of such correlated pairs below the $K^+n\Lambda\pi^+$ threshold ($T_p = 1.98\,\mathrm{GeV}$).

Two weeks of beam time will provide a knowledge of the energy dependence of the total cross section to complement the information available for the other hyperons.

1 Introduction and motivation

Hyperon production in proton–proton collisions in the close-to-threshold region has been extensively studied at different experimental facilities. The energy dependence of the total cross sections for $pp{\to}K^+p\Lambda$ and $pp{\to}K^+p\Sigma^0$ follow phase-space, though modified in the former case by the Λp final-state interaction (FSI) [1], as illustrated in Fig. 1. However, new data on the $pp{\to}K^+n\Sigma^+$ channel, published recently by the COSY-11 collaboration at excess energies of $\varepsilon = 13\,\mathrm{MeV}$ and $60\,\mathrm{MeV}$, show surprisingly high production rates [2]. The ratio $R(\Sigma^+/\Sigma^0) = \sigma(pp{\to}K^+n\Sigma^+)/\sigma(pp{\to}K^+p\Sigma^0)$ of the total cross sections measured at these two excess energies was found to be 230±70 and 90±40, respectively [3]. As was shown in Ref. [2], these experimental results are in striking contradiction to available model calculations [5]. A model–independent estimate might be obtained from the isospin relation linking the different Σ production channels, the amplitudes for which are related by

$$f(pp \to K^+n\Sigma^+) + f(pp \to K^0p\Sigma^+) + \sqrt{2}\,f(pp \to K^+p\Sigma^0) = 0\,. \qquad (1)$$

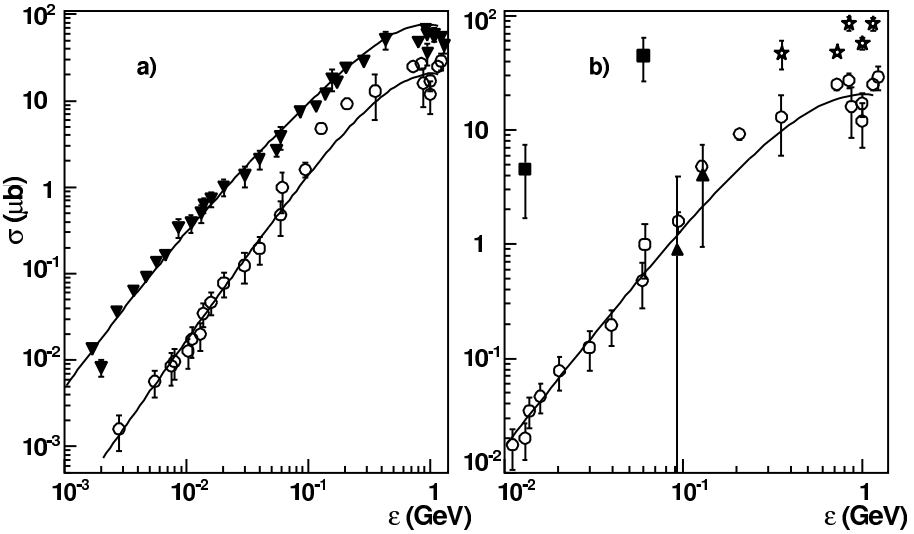

Figure 1: a) Total cross sections for the reactions $pp \to K^+ p\Lambda$ (inverted triangles) and $pp \to K^+ p\Sigma^0$ (circles) as functions of the excess energy. The lines show the normalized three–body phase space dependence $\propto \varepsilon^2$ with FSI effects in the Λ case, as described in Ref. [1], where details of the experimental data set are to be found. b) Total cross sections for the reactions $pp \to K^+ p\Sigma^0$ (circles) and $pp \to K^+ n\Sigma^+$ (squares [2], and stars [4]) as functions of the excess energy. The results of the present analysis for the $pp \to K^+ n\Sigma^+$ channel are shown by triangles. The solid line reflects the parameterization of the total cross section for the $pp \to K^+ p\Sigma^0$ channel.

This leads therefore to a triangle inequality between the total cross sections:

$$\sigma(pp \to K^+ n\Sigma^+) \leq \left[\sqrt{\sigma(pp \to K^0 p\Sigma^+)} + \sqrt{2\sigma(pp \to K^+ p\Sigma^0)}\right]^2 . \qquad (2)$$

There is evidence that $\sigma(pp \to K^0 p\Sigma^+) \approx \sigma(pp \to K^+ p\Sigma^0)$ at $\varepsilon \approx 128\,\mathrm{MeV}$ [6] and, if this is so, the inequality of Eq. (2) predicts that $R(\Sigma^+/\Sigma^0) < 6$ at this excess energy. The COSY-11 results exceed this limit by more than an order of magnitude but they were obtained closer to threshold, where no other $K^0 p\Sigma^+$ data have been published[1]. Since one cannot exclude an anomalous threshold behavior associated with the $I{=}\frac{1}{2}$ $K^+ n$ (and $K^0 p$) system, further experimental studies of the $pp \to K^+ n\Sigma^+$ reaction are necessary in order to clarify the situation.

The authors of Ref. [8] analyzed published data on inclusive K^+ momentum spectra measured in pp collisions at different angles and different beam energies, with the aim of isolating the $K^+ n\Sigma^+$ channel. For K^+ missing masses below the $p\Lambda\pi^0$ threshold, only contributions from the $K^+ p\Lambda$, $K^+ p\Sigma^0$, and $K^+ n\Sigma^+$ channels are relevant. It was assumed that the first two reactions could be described by three-body phase-space, possibly with corrections due to FSI. After subtracting these known contributions from the inclusive spectra, the cross section for

[1]There are, however, some unpublished data for different hyperon production channels taken by the COSY-TOF collaboration [7].

$pp \to K^+ n\Sigma^+$ could be deduced. However, the available data were restricted to relatively high excess energies, $\varepsilon > 170\,\mathrm{MeV}$, and had therefore no direct bearing on the COSY-11 results.

Following the method suggested in Ref. [8], we have analysed inclusive K^+ momentum spectra that had been measured at energies of 2.06 and 2.16 GeV at ANKE. These correspond respectively to excess energies of 93 and 128 MeV in the $K^+ n\Sigma^+$ system. The details of this are to be found in Appendix A.

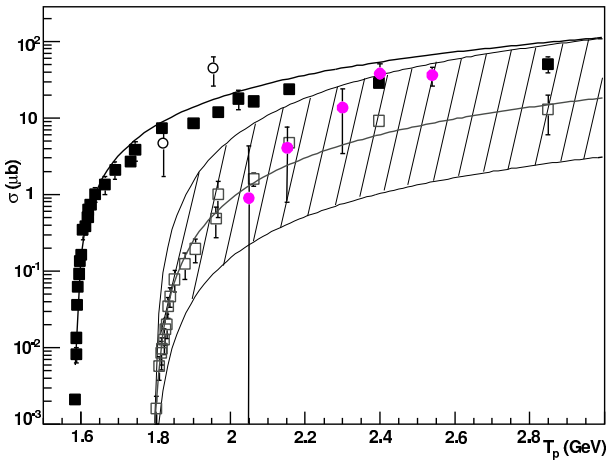

Figure 2: Total cross sections for the reactions $pp \to K^+ p\Lambda$ (solid squares) and $pp \to K^+ p\Sigma^0$ (open squares) as functions of the proton beam energy. The lines show the normalized three–body phase space dependence with FSI effects in the Λ case, as described in Ref. [1], where the details of the experimental data set are to be found. The $pp \to K^+ n\Sigma^+$ total cross sections measured at COSY11 are shown by the open circles [2]; the solid circles are estimates of the total cross section using inclusive K^+ data from Ref. [8] and Appendix A. The hatched area shows the limitations on the Σ^+ production total cross section coming from the triangle inequality.

In Fig. 2 measurements and estimates for Σ^+ total cross section are shown and compared with data on Λ and Σ^0 production in the COSY energy range. Even after our analysis of the 2.06 and 2.16 GeV inclusive data, the information available on Σ^+ production rates does not completely exclude the possibility of some kind of threshold anomaly. Additional measurements are therefore needed in the 1.8–2.0 GeV energy range to provide information about the energy dependence of the total cross section comparable to that found for the other hyperon channels.

2 Experimental techniques

In order to observe the $pp \to K^+ n\Sigma^+$ reaction, one can detect the K^+ in coincidence with the neutron and identify the production channel *via* the missing mass technique [2]. There is, however, an alternative that does not rely on detecting neutrons. Below the $K^+ n\Lambda\pi^+$ threshold at $T_p = 1.98\,\mathrm{GeV}$, the production channel may be isolated by measuring the K^+ in coincidence with a π^+ from the Σ^+

decay. Due to strangeness and charge conservation, there are no other sources of such correlated pairs in this energy interval. Furthermore, up to $T_p = 2.02\,\mathrm{GeV}$ one can distinguish the π^+ produced in a $K^+n\Sigma^+$ final state from that in the $K^+n\Lambda\pi^+$ reaction channel by using simple kinematical constraints. For the same beam energy, the excess energy in the second production channel is approximately 50 MeV lower than the first. The π^+ from the Σ^+ decay will therefore have a higher momentum and this can be unambiguously identified in the momentum spectra. It is this $K^+\pi^+$ approach that is proposed for the ANKE measurements.

ANKE is well equipped to detect pions and kaons of either charge [9]; this has been shown repeatedly [11] and will not be further discussed here in detail. In the proposed measurements, the K^+ and π^+ will be detected in coincidence in the momentum range of 200–1000 MeV/c using the positive side detector system. A dedicated proton–proton elastic trigger will be used for the normalisation. A separate so–called delayed–veto trigger will allow us to measure the double–differential inclusive K^+ production cross sections at all the energies. This will allow the possibility of a further cross–check on the extracted total cross section by using the method described in Appendix A.

3 Beam-time request

In order to provide a data sample for Σ^+ hyperon channel with a similar number of data points to that available for the Λ and Σ^0, we propose to measure at five excess energies between threshold and about 100 MeV, for which a measurement time of 10 days will be sufficient.

Energy (GeV)	ε (MeV)	σ (μb)	Rate (ev/day)	Beam time (days)
1.826	13	0.015	24	3
1.873	30	0.098	96	1.5
1.920	47	0.238	169	1.5
1.958	60	0.385	230	1
2.020	82	0.680	328	1

Table 1: Expected number of events per day for the reaction $pp{\to}K^+n\Sigma^+$ reaction channel detected at ANKE. For the count rate estimates, a luminosity of $5 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ has been assumed.

Table 1 shows the expected number of events for the $pp{\to}K^+n\Sigma^+$ reaction assuming a luminosity $\sim 5 \times 10^{30}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The $\Sigma^+ \to n\pi^+$ branching ratio of 48% [12] has been included. These estimates have been made in the case where $\sigma(K^+n\Sigma^+) \approx \sigma(K^+p\Sigma^0)$. In addition to the beam time requested for the measurements, two days are necessary for the calibration of the K^+ detectors and optimisation of the degraders, as well as four days for machine development.

In summary, we ask for **10 days of measurement time** with a hydrogen cluster-jet target as well as **4 days of machine–development time.** This

should allow us to obtain data on the energy dependence of the $pp \to K^+ n\Sigma^+$ total cross section near threshold that are comparable in quality to those available for the other hyperon production channels. The beam time should be scheduled in the **second half of 2007**.

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A Preliminary analysis of the experimental data measured at 2.06 and 2.16 GeV at ANKE

The $pp \to K^+X$ double–differential cross sections measured at 2.06 GeV and 2.16 GeV and averaged over the intervals 0–4°, 4–8° and 8–12° in K^+ laboratory angles are presented on a logarithmic scale in Fig. 3. At these energies the inclusive K^+ spectra correspond not only to reactions with just $p\Lambda$, $n\Sigma^+$ and $p\Sigma^0$ in the final state but might also involve the production of an additional pion. For this reason the data are plotted in terms of the K^+ missing mass so that intervals free of pion contamination can be readily identified. Thus the regions of the Jacobean peaks at large missing masses were not used in any fits. The thresholds for $N\Lambda$, $N\Sigma$ and $N\Lambda\pi$ production are shown in the Fig. 3 by arrows. For simplicity, we have neglected the difference between the Σ^+ and Σ^0 masses and that between the proton and neutron.

		Total cross section(μb)	
Reaction	T_p =	2.06 GeV	2.16 GeV
$pp \to K^+p\Lambda$		19.1 (16.5 ± 1.7 [13])	23.8 (23.9 ± 1.2 [15])
$pp \to K^+p\Sigma^0$		1.6 (1.6 ± 0.3 [14])	4.9 (4.8 ± 0.4 [15])
$pp \to K^+N\Sigma\,(\Sigma^+{+}\Sigma^0)$		2.5 ± 2.3	9.0 ± 3.5
$pp \to K^+n\Sigma^+$		0.9 ± 2.3	4.1 ± 3.5

Table 2: Total cross sections for the $pp{\to}K^+p\Lambda$ and $pp{\to}K^+p\Sigma^0$ reaction channels at 2.06 GeV and 2.16 GeV used in the analysis [1]. These are compared with experimental results published at fixed energies [13–15]. The summed $pp{\to}K^+N\Sigma$ total cross section extracted from the data of the present work are shown together with errors which are the result of both statistical and systematic uncertainties. After the subtraction of the $K^+p\Sigma^0$ contribution, estimates for the $pp \to K^+n\Sigma^+$ total cross sections are obtained.

Unfortunately, the present data set does not contain a region where the $K^+p\Lambda$ production channel could be unambiguously isolated in the missing–mass distribution and the rise at the Σ threshold observed. We therefore have to rely on the absolute normalisation of both our inclusive spectra and other measurements of exclusive Λ production. The analysis of the available data performed in Refs. [1,8] shows that the $K^+p\Lambda$ reaction channel can be very well described by phase space modified by the Λp FSI, whereas no FSI was needed for Σ^0 production. Within the framework of this model, the double–differential cross sections for $pp{\to}K^+p\Lambda$ and for the sum of $pp{\to}K^+p\Sigma^0$ and $pp{\to}K^+n\Sigma^+$ were calculated. The total cross sections for the Λ production were fixed by fits to the published data shown in Fig. 1a [1] and the total cross section for the summed Σ production used as the single free parameter. The best fit of this calculated spectrum to the experimental data shown Fig. 2 allowed us to obtain the value of the Σ production total cross section given in Table 2.

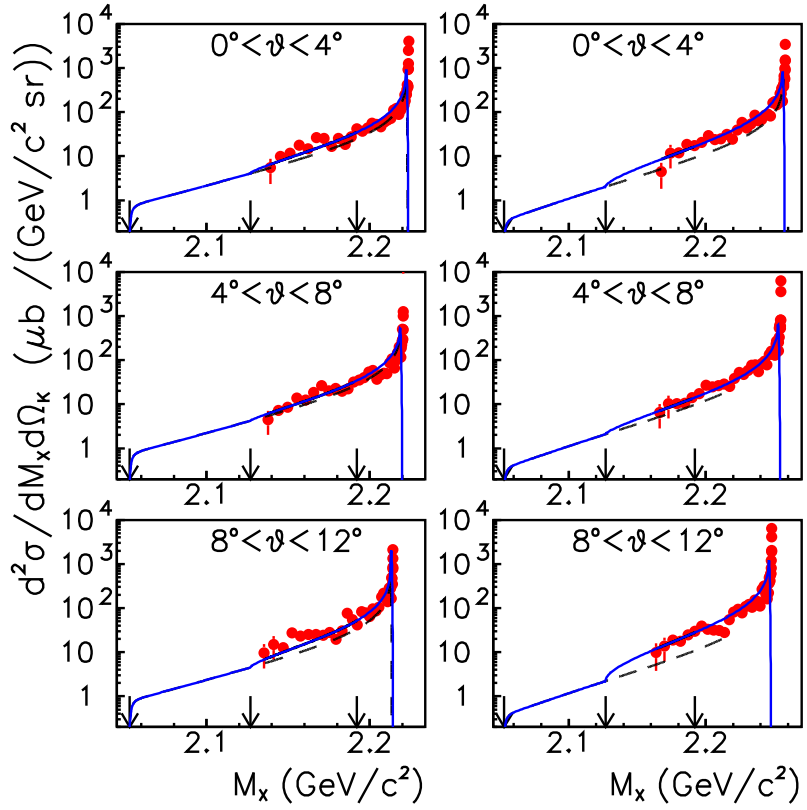

Figure 3: Double–differential cross sections for $pp \rightarrow K^+X$ production at 2.06 GeV and 2.16 GeV (left and right panels), integrated over different angular ranges compared with model calculations. The arrows indicate the thresholds for $N\Lambda$, $N\Sigma$, and $N\Lambda\pi$ production. The dashed lines show the contribution from the $pp \rightarrow K^+p\Lambda$ channel, while the solid lines are our fit as described in the text.

The summed $K^+N\Sigma$ total cross sections extracted from the data sets measured in three different angular ranges agree within errors. The difference between the values obtained with and without correcting for the Λp FSI is one way to estimate the systematic uncertainty inherent in the procedure. This was found to be 20% and 12% for the lower and higher excess energy, respectively. The $K^+N\Sigma$ results are shown in Table 2, where they are compared with the available data on Λ and Σ^0 production. Subtraction of the Σ^0 contribution then yields the $pp \rightarrow K^+n\Sigma^+$ total cross section at $\varepsilon = 93$ MeV and 128 MeV. Though our analysis at the lower energy provides little more than an upper bound, the results are consistent with Σ^+ and Σ^0 production having similar strength and behaviour and we have based our counting–rate estimates upon this assumption. It should be noted that our ε=128 MeV result satisfies the triangle inequality presented in Eq. (2).

B Extended analysis of the correlation experimental data measured at 2.16 GeV at ANKE

Since the submission of the proposal, considerable effort has been expended to extract the maximum information from the data taken at 2.16 GeV. These measurements were carried out in parallel with the experiment on ω production in the $pp \to pp\omega$ reaction. Only about twelve hours of beam time were taken for this test and the luminosity was about six or seven times lower than that which we plan to use for the current proposal. The most crucial feature of ANKE for

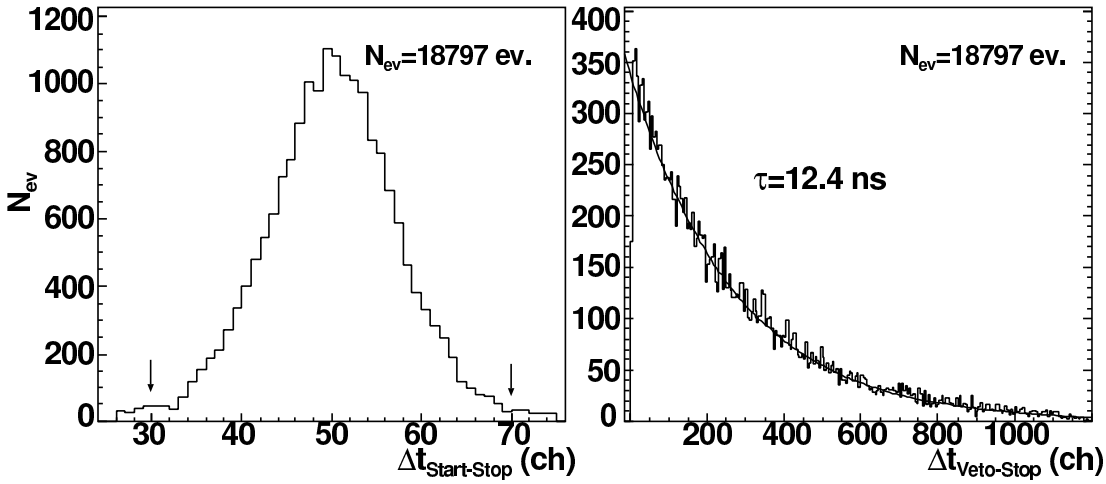

Figure 4: Time of flight between start and stop counters for inclusive K^+ production in pp collisions at 2.16 GeV (left). Time difference between the detection of K^+ meson in a stop counter and a decay π^+ or μ^+ in the corresponding veto counter of the same telescope (right). The characteristic 12.4 ns lifetime of the K^+ is clearly seen in the data.

this experiment is that, by detecting the μ^+ and π^+ from positive kaons stopped in the telescopes, we can select cleanly K^+ mesons with a background of less than 5%. The quality of the apparatus for this purpose is illustrated in Fig. 4.

The inclusive spectra shown in the main body of the proposal represent the sum of K^+ contributions from the four reactions $pp \to K^+ p\Lambda$, $pp \to K^+ p\Sigma^0$, $pp \to K^+ n\Sigma^+$ and $pp \to K^+ n\Lambda\pi^+$. Our energies are close to the threshold for $\pi^+\Lambda$ production and, as will be seen later, this channel gives $\leq 3\%$ of the total count rate. On the basis of the simulations, it is expected that more than $\frac{2}{3}$ of the K^+–spectrum results from the $pp \to K^+ p\Lambda$ channel. Since the ANKE acceptance for the K^+ from $pp \to K^+ p\Lambda$ is very small ($\leq 1\%$) then, in addition to the experimental uncertainties (about 10%), there are ambiguities arising from the use of a theoretical model to describe the inclusive spectra, as illustrated in Fig. 5 by the curves evaluated with and without the FSI. Furthermore, there might be deviations from the isotropy assumed for the kaon angular distribution in centre–of–mass system.

The K^+ distribution coming from the $pp \to K^+ n\Sigma^+$ and $pp \to K^+ p\Sigma^0$ reactions

must lie on top of the Λ curve shown in Fig. 5. After taking into account the normalisation uncertainties and the existing knowledge of the $pp{\to}K^+p\Sigma^0$ total cross section, it would be fair to say that one can realistically only obtain estimates on the production rates of the Σ, and in particular the Σ^+, with rather large error bars. The Σ curves shown in the figure were evaluated with total cross sections $\sigma(pp \to K^+\Sigma^0 p) = 2.3\,\mu$b, and $\sigma(pp \to K^+\Sigma^+ n) = 2.8\,\mu$b, which follow from analyses of the correlation spectra discussed later in this Appendix. It was the simple estimate of the Σ^+ cross section from the inclusive spectrum, rather than the much higher values obtained on the basis of COSY11 data [2], that was used to evaluate the count rates that are found in the proposal.

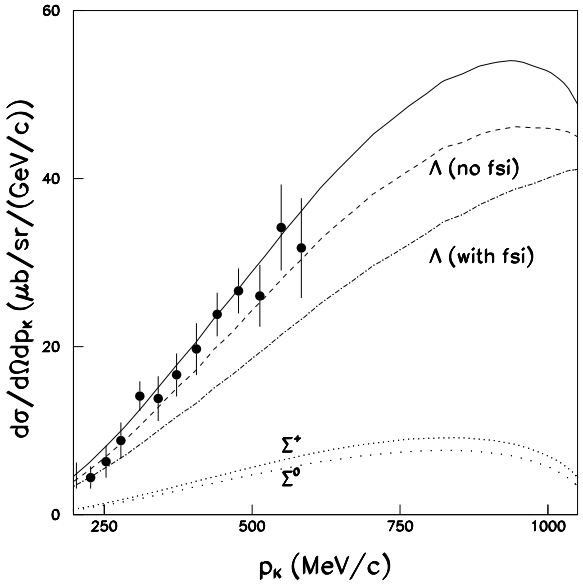

Figure 5: Inclusive K^+ momentum spectrum for $\theta_K^{\rm lab} < 12^\circ$ from pp collisions at 2.16 GeV. The phase–space simulations have been evaluated with $\sigma(pp \to K^+\Lambda p) = 23.9\,\mu$b, $\sigma(pp \to K^+\Sigma^0 p) = 2.3\,\mu$b, and $\sigma(pp \to K^+\Sigma^+ n) = 2.8\,\mu$b. In the Λ case the simulation is shown with and without the effect of the Λp final state interaction (fsi). The sum of the result with the fsi plus the two Σ contributions is shown by the solid line.

In order to avoid the large subtractions involved in the inclusive approach, it is preferable to study $K^+\pi^+$ correlation data, which can only arise from the $pp{\to}K^+n\,(\Sigma^+{\to}\pi^+n)$ (BR 48.3%) reaction. Such data were taken at 2.06 and 2.16 GeV, and we here will present information derived from analysing the higher energy results. ANKE has a very small acceptance for this reaction ($\approx 4\times10^{-4}$ at 2.16 GeV) and so we need a model in order to try to construct total cross sections. As these data were taken not too far from threshold, one might expect the S–waves to be dominant and that the simple phase–space approach could be used. As shown in Ref. [1], this model was successfully used to describe the $pp{\to}K^+p\Sigma^0$ reaction without introducing any $p\Sigma^0$ final–state interaction.

To check the methodology within the framework of our acceptance, from the same set of runs we have obtained K^+p correlations arising primarily from the $pp{\rightarrow}K^+p\Lambda$ and $pp{\rightarrow}K^+p\Sigma^0$ reactions. The resulting missing–mass spectra are presented in Fig. 6. Two peaks corresponding to the Λ and Σ^0 are very prominent. In addition there is a continuum which results from the $\Lambda \rightarrow \pi^- p$ and $\Sigma^0 \rightarrow \gamma\Lambda \rightarrow \gamma p\pi^-$ decays, as well as a contribution from the $\Sigma^+ \rightarrow p\pi^0$ (BR 51.6%) decay. This continuum is described rather well by our simulations.

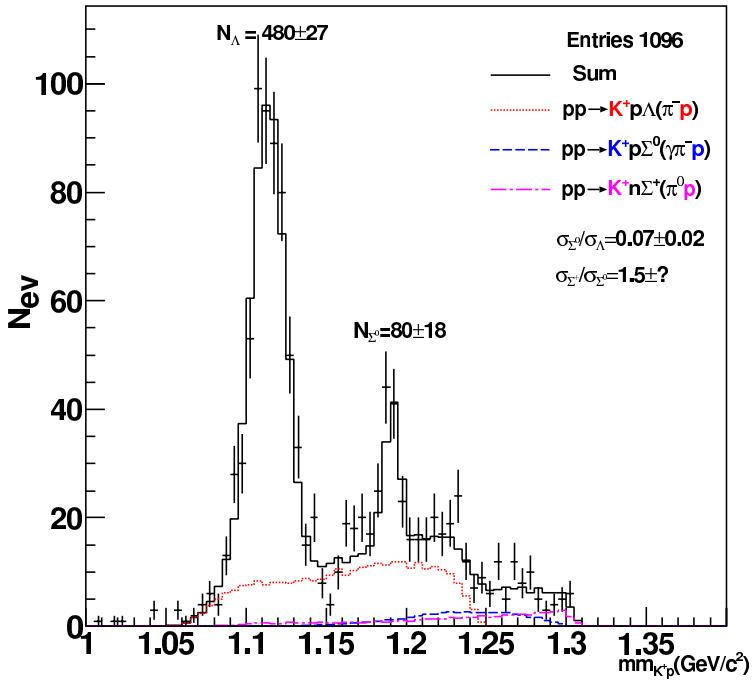

Figure 6: Missing mass of K^+p pairs produced in pp collisions at 2.16 GeV. In addition to the two peaks corresponding to direct protons from the $pp \rightarrow K^+p\Lambda/\Sigma^0$ reactions, there are secondary protons arising from the $pp \rightarrow K^+p(\Lambda \rightarrow \pi^- p)$ (dotted line), $pp \rightarrow K^+p(\Sigma^0 \rightarrow \gamma\Lambda \rightarrow \gamma\pi^- p)$ (dashed line), and $pp \rightarrow K^+n(\Sigma^+ \rightarrow \pi^0 p)$ (chain curve). These have been simulated in the Monte Carlo with the results indicated. The total with the two direct peaks is shown by the solid histogram.

The ratio of the Σ^0/Λ count rates, N_{Σ^0}/N_Λ, is practically independent of the conditions of the experiment (luminosity, telescope efficiencies), but dependent on the acceptances and the total cross section in the combination:

$$(N_{\Sigma^0}/N_\Lambda) \times \left(\mathrm{acc}_{K^+p(\Lambda)}/\mathrm{acc}_{K^+p(\Sigma^0)}\right) = \sigma_{\mathrm{tot}}(\Sigma^0)/\sigma_{\mathrm{tot}}(\Lambda). \qquad (3)$$

The ratio of the acceptances was calculated using the phase–space model with a Λp FSI for $pp{\rightarrow}K^+p\Lambda$ reaction but without any $p\Sigma^0$ FSI for the $pp{\rightarrow}K^+p\Sigma^0$ reaction and this leads to the following estimates: $\mathrm{acc}_{K^+p(\Lambda)} = 1.6 \times 10^{-4}$ and $\mathrm{acc}_{K^+p(\Sigma^0)} = 4.6 \times 10^{-4}$. Thus

$$\sigma_{\mathrm{tot}}(\Sigma^0)/\sigma_{\mathrm{tot}}(\Lambda) = \frac{(80 \pm 18)}{(480 \pm 27)} \times \frac{1.8 \times 10^{-4}}{4.6 \times 10^{-4}} = \frac{1}{(15 \pm 4)}\,. \qquad (4)$$

Using the known value of the total cross section for Λ production of $\sigma_{\rm tot}(\Lambda) = (23.9 \pm 1.2)\,\mu$b, the ratio leads to $\sigma_{\rm tot}(\Sigma^0) = (1.7 \pm 0.4)\,\mu$b at $T_p = 2.16$ GeV. This value is consistent with the interpolatory curve shown on the total cross section picture of Fig. 8, though it is much smaller than the $\sigma_{\rm tot}(\Sigma^0) = (4.8 \pm 0.4)\,\mu$b quoted in the TOF thesis [15].

Despite the small ANKE acceptance, the results achieved from the K^+p correlation studies give us some confidence in the application of the phase–space model to describe other K^+–hyperon production data. Encouraged by this, we have applied the same model to the more complex four–body final state arising from the $pp{\to}K^+n(\Sigma^+ \to \pi^+ n)$ reaction. It is important to note that these data were also taken in the same experimental runs. The K^+ acceptance for this reaction is, therefore, identical to that for the K^+p correlation data from the $pp{\to}K^+p\Sigma^0$ reaction. Furthermore, the π^+ acceptance is known and is nearly the same as that of the prompt protons. The momentum distributions of the K^+ and π^+ detected in coincidence at 2.16 GeV are presented in Fig. 7. Simulations carried out within the framework of the phase–space model show reasonable agreement with the experimental data. From the ratio

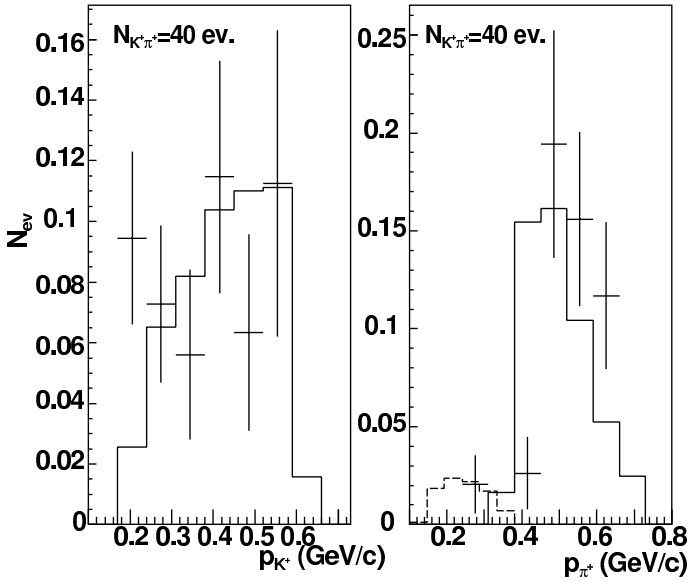

Figure 7: Momentum distributions of K^+ and π^+ from the $pp \to K^+\pi^+X$ reaction at 2.16 GeV. The solid lines correspond to the simulation of the $pp \to K^+n(\Sigma^+ \to \pi^+n)$ reaction in the phase–space model. The possible contribution of the $pp \to K^+\pi^+\Lambda n$ reaction is indicated by the dashed line.

$$\mathrm{BR}_{\Sigma^+\to\pi^+n} \times \frac{\sigma_{\rm tot}(\Sigma^+)}{\sigma_{\rm tot}(\Sigma^0)} = \frac{N_{K^+\pi^+(\Sigma^+)}}{N_{K^+p(\Sigma^0)}} \times \frac{\mathrm{acc}_{K^+p(\Sigma^0)}}{\mathrm{acc}_{K^+\pi^+(\Sigma^+)}} \tag{5}$$

we obtain the following values of the ratio of Σ^+/Σ^0 total production cross section:

$$\frac{\sigma_{\rm tot}(\Sigma^+)}{\sigma_{\rm tot}(\Sigma^0)} = \frac{(40 \pm 7)}{(80 \pm 18)} \times \frac{4.6 \times 10^{-4}}{3.8 \times 10^{-4}} \times \frac{1}{0.48} = 1.3 \pm 0.4\,. \tag{6}$$

Evaluating the total cross section directly from the knowledge of our acceptances and efficiencies, we find rather

$$\sigma_{\rm tot}(\Sigma^+) = (2.8 \pm 0.4_{\rm stat} \pm 0.6_{\rm syst})\ \mu{\rm b}, \tag{7}$$

where both statistical and systematic uncertainties are indicated. This gives a slightly different value from that obtained using the ratio in Eq. (6), but the results are consistent within the systematic error bars.

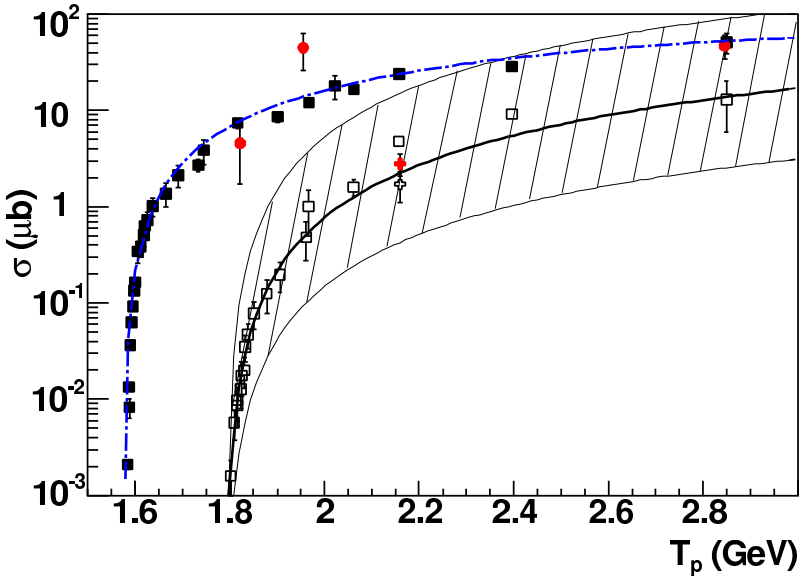

Figure 8: Total cross sections for the reactions $pp{\rightarrow}K^+p\Lambda$ (solid squares) and $pp{\rightarrow}K^+p\Sigma^0$ (open squares) as functions of the proton beam energy. The lines show the normalized three–body phase space dependence with FSI effects in the Λ case, as described in Ref. [1], where the details of the experimental data set are to be found. The $pp{\rightarrow}K^+n\Sigma^+$ total cross sections measured at COSY11 and a bubble-chamber experemint at large energy are shown by the closed circles [2,4]. Our estimates of the total cross sections for Σ^0 and Σ^+ production at 2.16 GeV are shown by open and closed Swiss crosses, respectively.

The results for the Σ^0 and Σ^+ total production cross sections, which are shown in Fig. 8, fall well within the boundaries fixed by isospin invariance. These cross sections are also used to estimate some of the continuum background in Fig. 6, where it is seen that the data at the high end of the missing–mass spectrum have some sensitivity to the sum of the Σ^0 and Σ^+ production rates. Though it is hard to draw definitive conclusions on the rates from these small background effects, the results are at least consistent with the other correlation data. On the other hand, it is very reassuring that the phase–space simulation of the inclusive K^+ spectra shown in Fig. 5 reproduces so well the experimental data. This means that the relationship between the inclusive and correlation data seems to be understood very well.

Despite the overall consistency of our analysis, the conclusions reached in this appendix on Σ^+ production could be modified somewhat if there were a very

strong $n\Sigma^+$ FSI. Note, however, that there is no evidence of any important $p\Sigma^0$ FSI from the energy dependence of $\sigma_T(pp{\rightarrow}K^+p\Sigma^0)$. This ambiguity can be resolved within our system by carrying out studies at lower energies, down towards the threshold. Under such conditions the ANKE acceptance for Σ production becomes much larger, and at the lowest proposed energy ANKE covers 100% of the allowed inclusive kaon angular ($\theta_{K^+} \leq 14^\circ$) and momentum ranges (see Fig. 9). In a case of the $K^+\pi^+$ correlation analysis, pions from the Σ^+ decay produce

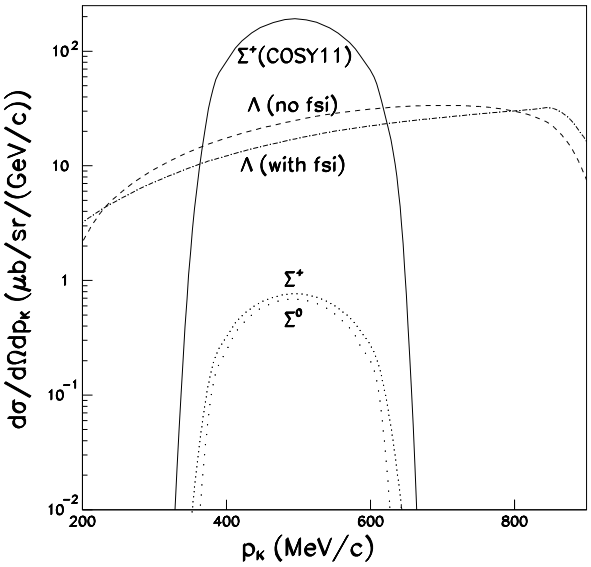

Figure 9: Predicted inclusive K^+ momentum spectrum for $\theta_K^{\rm lab} < 12^\circ$ from pp collisions at 1.826 GeV. The phase–space simulations have been evaluated with $\sigma(pp \rightarrow K^+\Lambda p) = 7\,\mu$b, $\sigma(pp \rightarrow K^+\Sigma^0 p) = 0.015\,\mu$b, and $\sigma(pp \rightarrow K^+\Sigma^+ n) = 0.018\,\mu$b. The Σ^+ calculation was also carried out using a value suggested by the COSY11 data [2], $\sigma(pp \rightarrow K^+\Sigma^+ n) = 4.5\,\mu$b.

a sharp peak at around 500MeV/c. Due to the energy release in the $Sigma^+$ decay, the pion angle can be quite wide even close to threshold and the angular acceptance is only about 7%. The results expected for the different components of the inclusive K^+ spectrum within the phase–space model at the lowest energy requested in the proposal (1.826 GeV) are shown in Fig. 9. Two simulations are presented for Σ^+ production. The first is based upon the Σ^+ cross section that we found at 2.16 GeV and extrapolated to lower energy, assuming a phase–space variation and ignoring any possible FSI. The other is deduced from the values quoted in the COSY11 publication [2]. Our beam–time request is based upon the more conservative lower values shown in this figure.