The pp→$K^+n\Sigma^+$ reaction near threshold

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Abstract

Inclusive K^+ production in proton-proton collisions has been measured at a beam energy of 2.16 GeV using the COSY-ANKE magnetic spectrometer. The resulting spectrum, as well as those corresponding to K^+p and $K^+\pi^+$ correlated pairs, can all be well described using consistent values of the total cross sections for the $pp \to K^+p\Lambda$, $pp \to K^+p\Sigma^0$, and $pp \to K^+n\Sigma^+$ reactions. While the resulting values for Λ and Σ^0 production are in good agreement with world data, our value for the total Σ^+ production cross section, $\sigma(pp \to K^+n\Sigma^+) = (2.5 \pm 0.6_{\text{stat}} \pm 0.4_{\text{syst}})\,\mu\text{b}$ at an excess energy of $\varepsilon = 129\,\text{MeV}$, could only be reconciled with other recently published data if there were a highly unusual near–threshold behaviour.

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The production of light hyperons 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 $pp{\to}K^+p\Sigma^0$ has been well measured and both follow phase–space, though modified in the former case by the $p\Lambda$ final–state interaction (FSI) [1]. On the other hand, little information is available on the $pp{\to}K^+n\Sigma^+$ reaction. The COSY-11 collaboration has recently published surprisingly high values for the total cross sections in this channel at excess energies of $\varepsilon = 13\,\text{MeV}$ and $60\,\text{MeV}$, *i.e.* at proton beam energies of $T_p = 1.826\,\text{GeV}$ and $1.958\,\text{GeV}$ [2]. According to these measurements, the ratios of the total cross sections $R(\Sigma^+/\Sigma^0) = \sigma(pp{\to}K^+n\Sigma^+)/\sigma(pp{\to}K^+p\Sigma^0)$ at these two energies are $230{\pm}70$ and $90{\pm}40$, respectively [3]. These experimental results are in striking contrast to published theoretical estimates [4]. However, it has been suggested that the inclusion in the production model of the previously ignored $\Delta^{++*}(1620)\ 1/2^-$ isobar, together with a strong $n\Sigma^+$ FSI, would allow one to achieve much better (factor 2–4) agreement with the COSY-11 data [5].

A model–independent estimate for $R(\Sigma^+/\Sigma^0)$ might be obtained from the isospin relation linking the different Σ production channels, the amplitudes for which satisfy:

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

This leads to a triangle inequality between the total cross sections [6]:

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

At $\varepsilon \approx 129\,\text{MeV}$ ($T_p = 2.16\,\text{GeV}$), $\sigma(pp{\to}K^0p\Sigma^+)$ [7] is nearly equal to $\sigma(pp{\to}K^+p\Sigma^0)$ [1] so that 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, though they were obtained closer to threshold, where no other $K^0p\Sigma^+$ data have been published[1].

The authors of Ref. [9] analysed published momentum spectra from inclusive K^+ production in pp collisions at different angles and beam energies, with the aim of extracting the contribution from the $K^+n\Sigma^+$ channel. For K^+ missing masses below the $N\Lambda\pi$ threshold, only contributions from the $K^+p\Lambda$, $K^+p\Sigma^0$, and $K^+n\Sigma^+$ channels are relevant. It was assumed that production in the first

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[1] There are, however, data taken with the COSY-TOF detector and presented in PhD theses [8].

two channels could be described by three–body phase–space, with possible modifications coming from the FSI. By subtracting these known contributions from the inclusive spectra, an estimate of the $pp \to K^+ n\Sigma^+$ cross section was deduced. The inclusive data available were restricted to relatively high excess energies, $\varepsilon > 170\,\mathrm{MeV}$, and had therefore no direct bearing on the COSY-11 results. However, the authors did conclude that there was no visible evidence for any strong $N\Sigma$ FSI.

Since the $p\Sigma^0$ and $n\Sigma^+$ systems are different mixtures of isospin $I = \frac{1}{2}$ and $\frac{3}{2}$, one cannot, on the basis of $pp \to K^+ p\Sigma^0$ data, exclude an anomalous threshold behaviour in $pp \to K^+ n\Sigma^+$ arising from a strong $n\Sigma^+$ FSI [5]. Further experimental studies of Σ^+ production are therefore necessary to clarify the situation. We here present the analysis of new experimental data taken at a proton beam energy $T_p = 2.157\,\mathrm{GeV}$.

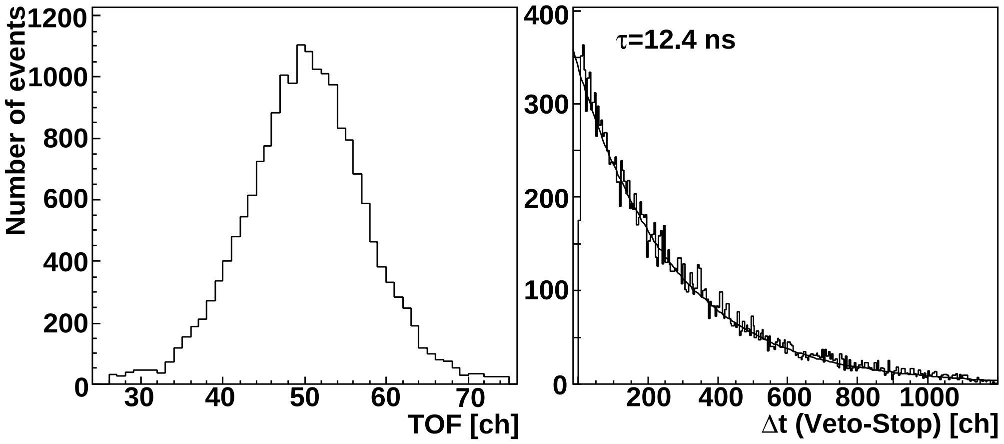

Fig. 1. The time of flight (TOF) between start and stop counters for inclusive K^+ production in pp collisions at 2.16 GeV (left panel). Time difference (Δt) between the detection of the K^+ meson in the stop counter and a decay π^+ or μ^+ in the corresponding veto counter of the same telescope (right panel). The solid line, which corresponds to the 12.4 ns lifetime of the K^+, reproduces well the data.

The experiment was carried out using the magnetic spectrometer ANKE [10] at the COoler–SYnchrotron COSY-Jülich [11], with an internal cluster–jet target which had an average density of $\sim 2\times10^{14}\,\mathrm{cm}^{-2}$ [12]. Only two of the ANKE detection systems were needed for the analysis of these data. The positive side system (PD), used for the K^+ and π^+ detection, consists of 23 thin start counters, placed close to the vacuum chamber window, two multiwire proportional chambers (MWPCs), and 21 stop counters for time–of–flight (TOF) measurements. The efficiency of the particle identification by the time–of–flight method, which is independent on the type of particle, was 98%. The efficiency of the track reconstruction using the MWPCs was 95% for kaons and 85% for pions when averaged over the momentum range of the detected particles. The first 15 stop counters are part of range telescopes used for the identification of the K^+. Each of these telescopes consists of a stop counter, energy–loss counter, two passive degraders and a veto counter. The thickness of the passive degraders in each telescope is chosen such that the K^+ deposits the maximum energy in the energy–loss counter and stops either at the edge of the counter or in the second passive degrader. Delayed signals for the kaon decay products are then registered by the so–called veto counter. This method (see Fig. 1) allows one to identify the K^+-mesons by suppressing a background that is up to 10^6 times higher. Such data by themselves are sufficient for the determination of the inclusive kaon spectrum. The efficiency of the kaon identification by this method, which varies between 10–30%, depending on the telescope number, is known with a precision, dominantly statistical, of $\sim 15\%$. Details of the particle identification analysis using the delayed–veto technique are to be found in Ref. [13].

The ANKE forward detector system (FD) [14] was used for both the K^+p correlation measurements and luminosity determination. The FD consists of two layers of plastic scintillator and a set of three multiwire proportional chambers placed downstream of the magnet. The efficiency of the FD MWPCs, which was about 85%, was known with an accuracy of approximately 1%. The luminosity was determined by selecting proton–proton elastic scattering events in the angular range $6.8^\circ < \theta_{\rm lab} < 8.8^\circ$ on the basis of a dedicated pre–scaled trigger. This is described in some detail in Ref. [15], where the same data set was used for the investigation of ω–meson production. The overall systematic uncertainty in the absolute normalisation was estimated to be of the order of 6% [15]. It is estimated that the amount of background in the K^+p and $K^+\pi^+$ coincidence spectra is less then 2%. For the acceptance calculations, a model of the ANKE system has been implemented within the GEANT4 simulation package [16]. This contributes an overall uncertainty of about 5%.

Information on Σ^+ production was obtained from three simultaneously measured observables, *viz.* the K^+p, $K^+\pi^+$ coincidence spectra and the K^+ inclusive double–differential cross section, and we first briefly outline the overall approach.

The measured missing–mass spectrum of the detected K^+p pairs allows one to fix the strength of the different K^+ production channels at this energy. Since the decay $\Sigma^+ \to p\pi^0$ is also possible (branching ratio BR 51.6%), this spectrum also contains some information on the Σ^+ production total cross section, $\sigma(\Sigma^+)$.

The $pp \to K^+ n \Sigma^+$ reaction can be cleanly identified either by using K^+n coincidences, as at COSY-11 [2], or by detecting $K^+\pi^+$ pairs, where the π^+ arises from the decay $\Sigma^+ \to \pi^+ n$ (BR 48.3%). Although the $pp \to K^+ n \Lambda \pi^+$ reaction is another potential source of $K^+\pi^+$ coincidences, even at the much higher energy of 2.85 GeV its production is only about 4% of that of Σ^+ [6]. The contribution of this channel to the final distributions is therefore estimated to be less than 2%.

The inclusive K^+ double–differential cross section depends upon all possible production channels, though the contribution from the $pp \to K^+ n \Sigma^+$ reaction at 2.16 GeV represents only a small fraction of the total. Therefore, within our systematic errors, only an upper limit on $\sigma(\Sigma^+)$ can be extracted from the inclusive data at this energy. Nevertheless, this spectrum does provide a valuable check on the consistency of the whole analysis by using simulations where the individual weights of the channels are fixed by the total cross sections extracted from the correlation data.

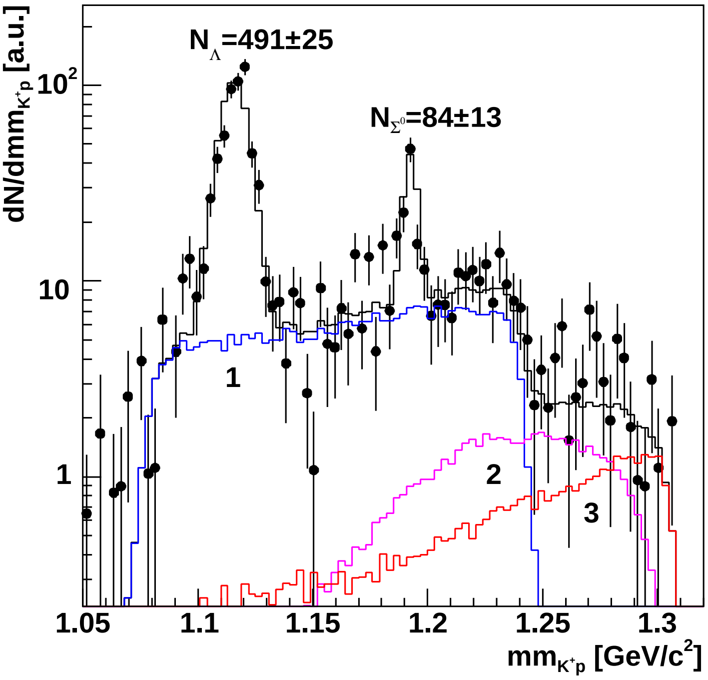

Fig. 2. Missing–mass distribution of K^+p pairs produced in pp collisions at 2.16 GeV. Experimental data are shown by full circles (resolution $\sim$ 3 MeV/c^2). The two peaks correspond to direct protons from the $pp \to K^+ p \Lambda/\Sigma^0$ reactions. The continuum contributions of secondary protons arising from the $pp \to K^+ p\,(\Lambda \to \pi^- p)$ (histogram 1), $pp \to K^+ p(\Sigma^0 \to \gamma\Lambda \to \gamma\pi^- p)$ (histogram 2), and $pp \to K^+ n(\Sigma^+ \to \pi^0 p)$ (histogram 3) have been obtained in Monte Carlo simulations. The sum of all contributions, including the two direct peaks, is shown by the solid histogram.

The K^+p missing–mass spectrum presented in Fig. 2 shows two prominent peaks corresponding to Λ and Σ^0 production. In addition there is a continuum resulting from the detection of protons from the $\Lambda \to \pi^- p$ (BR 63.9%) and $\Sigma^0 \to \gamma\Lambda \to \gamma p \pi^-$ (BR 100%) decays, as well as a contribution from the $\Sigma^+ \to p\pi^0$ decay. This continuum is described well by our simulations.

Following the authors of Ref. [17], a simple model has been developed for the $pp \to K^+ p \Lambda$ reaction. This assumes that the $N^*(1650)$-resonance is the dominant contribution to Λ production and that the $p\Lambda$ FSI [1] has a significant effect on the experimental observables. In addition we use the angular distribution of the vertex-proton, as measured with the COSY-TOF detector [18]. A pure phase–space model has been used for the $pp{\rightarrow}K^+p\Sigma^0$ and $pp{\rightarrow}K^+n\Sigma^+$ reactions since there is no strong evidence for significant $p\Sigma^0$ or $n\Sigma^+$ FSI effects [1,9]. Such a model is consistent with our data.

The number of events extracted from the measured missing–mass spectrum of Fig. 2, together with our values for the total acceptances, luminosity, and efficiencies, yields total cross sections of $\sigma(\Lambda) = (23.2 \pm 3.7_{\rm stat} \pm 5.8_{\rm syst})\,\mu$b and $\sigma(\Sigma^0) = (2.6 \pm 0.6_{\rm stat} \pm 0.4_{\rm syst})\,\mu$b for Λ and Σ^0 production, respectively. Only the direct K^+p events are used for the determination of the total cross sections as their numbers are well known (peaks in Fig. 2). These values are in good agreement with the parameterisation of the world data set presented in Fig. 5. The systematic error in the Λ case includes not only errors from the luminosity, background, efficiency and acceptance determination, but also 10% due to the use of different model assumptions.

The high–mass part of the missing–mass spectrum in the Fig. 2 is sensitive to $R(\Sigma^+/\Sigma^0)$. A good description of the spectrum can be obtained if $R(\Sigma^+/\Sigma^0) \approx 1.5$. However our statistics do not permit us to draw meaningful conclusions on the associated error.

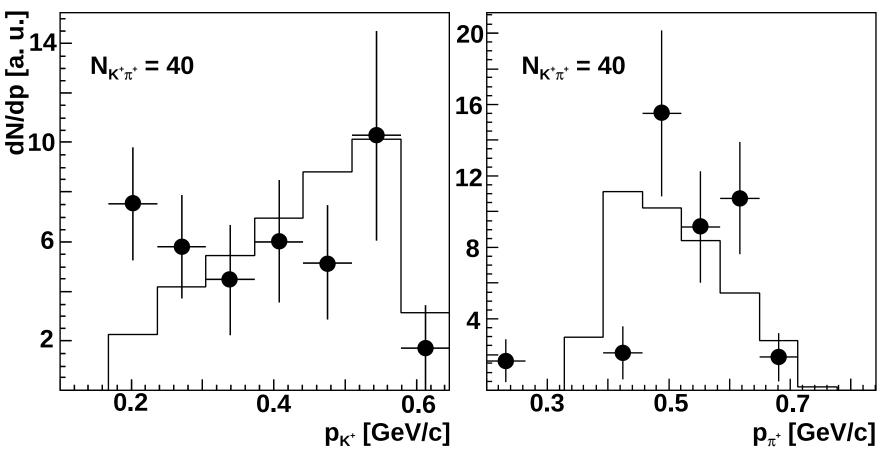

Fig. 3. Momentum distributions of K^+ and π^+ from the $pp \rightarrow K^+\pi^+X$ reaction at 2.16 GeV. The solid histograms correspond to simulations of the $pp \rightarrow K^+n(\Sigma^+ \rightarrow \pi^+n)$ reaction in the phase–space model.

The momentum distributions of the detected $K^+\pi^+$ pairs are presented in Fig. 3. Simulations carried out within the framework of the phase–space model show modest agreement with the limited experimental data. From the number of detected events the total cross section is determined to be:

$$\sigma_{\rm tot}(\Sigma^+) = \Big(2.5 \pm 0.6_{\rm stat} \pm 0.4_{\rm syst}\Big)\ \mu{\rm b}\,, \qquad (3)$$

where both the statistical and systematic uncertainties are indicated. This value leads to a ratio of total cross sections for the two Σ channels $R(\Sigma^+/\Sigma^0)$ that is consistent with unity. It is important to stress here that the inclusion of a strong $n\Sigma^+$ FSI and a Δ^{++} resonance into our Σ^+ production model would change our total acceptance for this reaction channel by less than 20%.

The ratio of the Σ^+ and Σ^0 count rates, $N_{\Sigma^+}/N_{\Sigma^0}$, is practically independent of the conditions of the experiment (luminosity, telescope efficiencies *etc.*). It can therefore be used as a cross check on the value of $\sigma(\Sigma^+)$ extracted from the analysis of $K^+\pi^+$ coincidences. The $\sigma(\Sigma^+)/\sigma(\Sigma^0)$ ratio depends on the acceptances (A) and number of detected events ($N_{K^+\pi^+}$ for the Σ^+, and N_{K^+p} from direct proton for Σ^0):

$$\frac{\sigma(\Sigma^+)}{\sigma(\Sigma^0)} = \frac{N_{K^+\pi^+(\Sigma^+)}}{N_{K^+p(\Sigma^0)}} \times \frac{\mathrm{A}_{K^+p(\Sigma^0)}}{\mathrm{A}_{K^+\pi^+(\Sigma^+)}} \times \frac{1}{\mathrm{BR}_{\Sigma^+\to\pi^+n}} \,. \tag{4}$$

Using the numbers of events extracted from the experimental spectrum, together with estimates of the total acceptances, we obtain the following ratio of the Σ^+/Σ^0 total cross sections:

$$\frac{\sigma(\Sigma^+)}{\sigma(\Sigma^0)} = \frac{(40\pm7)}{(84\pm13)} \times \frac{4.5\times10^{-4}}{5.1\times10^{-4}} \times \frac{1}{0.48} = 0.9\pm0.2\,. \tag{5}$$

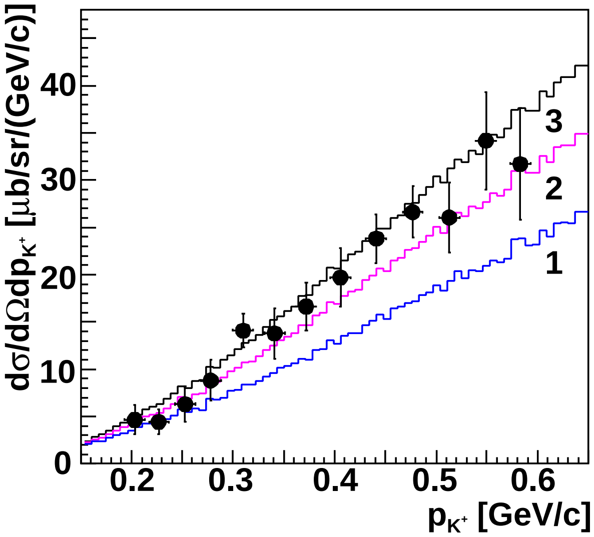

Fig. 4. Inclusive K^+ momentum spectrum for $\theta_K^{\mathrm{lab}} < 4^\circ$ resulting from pp collisions at 2.16 GeV. The simulation of $pp\to K^+p\Lambda$ with $\sigma(\Lambda) = 23.2\,\mu$b is shown by histogram 1. The addition of the contribution from the $pp\to K^+p\Sigma^0$ reaction using a total cross section of $\sigma(\Sigma^0) = 2.6\,\mu$b leads to histogram 2. The total, corresponding to the further inclusion of the $pp\to K^+n\Sigma^+$ reaction channel with $\sigma(\Sigma^+) = 2.5\,\mu$b, is shown by histogram 3.

The ratio of the Σ production cross sections that follows from Eq. (5) is consistent with that derived from the total cross sections obtained from different correlations spectra, as well as that estimated from the analysis of the K^+p missing–mass spectrum. It is also reassuring that our simulation of the inclusive K^+ spectrum, shown in Fig. 4, reproduces so well the experimental data. This means that the relation between the inclusive and correlation data seems to be well understood.

Our value of the Σ^+ production cross section at $\varepsilon = 129\,\mathrm{MeV}$ falls well within the boundaries fixed by isospin invariance that are shown in Fig. 5. It is also in agreement with the point measured with the COSY-TOF detector at this energy [19]. Compared to this the two COSY-11 points, which were taken closer to the threshold, look extremely high, though it must be stressed that a thesis, reporting earlier work carried out at COSY-TOF, also found much stronger Σ^+ production than Σ^0 at $\varepsilon = 96\,\mathrm{MeV}$ [20].

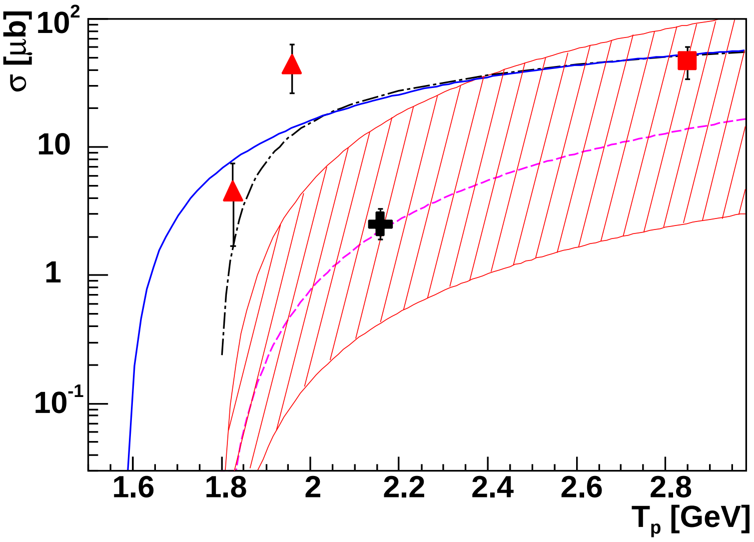

Fig. 5. Total hyperon production cross sections as a function of beam energy. Our value for $\sigma(pp\to K^+n\Sigma^+)$ at 2.16 GeV is shown by a cross. Results for the $pp\to K^+n\Sigma^+$ reaction measured by COSY-11 [2] and at higher energy in a bubble–chamber experiment [6] are represented by triangles and a square, respectively. The lines show the normalised three–body phase space dependence for the $pp\to K^+p\Lambda$ (solid line) and $pp\to K^+p\Sigma^0$ (dashed line) with FSI effects in the Λ case, as described in Ref. [1]. Both reproduce well the available experimental data. The estimate for the $pp\to K^+n\Sigma^+$ total cross section from Ref. [5] is shown by the dot–dashed curve. The region restricted by the triangle inequality of Eq. (2) is shown by the hatched area.

In summary, we have presented new measurements of the $pp\to K^+n\Sigma^+$ total cross section at 2.16 GeV that are not dependent upon the detection of the final neutron. From the analysis of the K^+p and $K^+\pi^+$ correlated pairs, the total cross sections for the production of Λ, Σ^0 and Σ^+ have been extracted. The values of $\sigma(\Lambda)$ and $\sigma(\Sigma^0)$ are in reasonable accord with the trends of the experimental data defined at other energies. Our value of $\sigma(\Sigma^+)$ at $\varepsilon = 129\,\mathrm{MeV}$ satisfies well the triangle inequality of Eq. (2). Furthermore, the inclusive double–differential cross section is well described using the values of the total cross sections for the individual K^+ production channels determined in this work from the correlation studies. This shows an overall consistency of the methodology.

Our data show that at $\varepsilon \approx 128\,\mathrm{MeV}$ the Σ^+ and Σ^0 production rates are rather similar and the naive expectation would be that this would continue as the threshold is approached. However, the value of the total Σ^+ cross section reported by the COSY-11 collaboration at $\varepsilon = 60\,\mathrm{MeV}$ is over an order of magnitude larger than ours. Taken at face value, the two measurements would imply a very large threshold anomaly. Even if this seems to be very unlikely, it can and must be checked, and this is foreseen with our method [21].

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