HYPERON PRODUCTION AT THE COSY–11 FACILITY

M. WOLKE
for the COSY–11 Collaboration

Institut für Kernphysik, Forschungszentrum Jülich
D-52425 Jülich, Germany

Abstract

Kaon–hyperon production in proton–proton scattering has been studied in the $pp \to pK^+\Lambda/\Sigma^0$ reaction channels close to threshold. At equal excess energies ($Q \leq 13$ MeV), Λ production is found to be favoured over Σ^0 production by a factor 28^{+6}_{-9} and thus exceeding the known high energy ($Q \geq 300$ MeV) ratio by an order of magnitude.

Experiments were performed using the internal COSY–11 facility at the cooler synchrotron COSY Jülich. Results are presented and physics implications for the underlying reaction mechanisms are discussed.

1 Introduction

The associated strangeness production close to threshold in proton–proton scattering probes the strangeness content of the nucleon on the sea–quark level, as the strange–antistrange quark pair creation is expected to depend on the strangeness content in the initial state. High momentum transfers involved in threshold production provide insight into the dynamics of the short range nucleon–nucleon force. At the same time, both the elementary kaon and antikaon production cross sections in proton–proton scattering, the latter being investigated at the COSY–11 installation as well [1], are important input parameters within the framework of transport model calculations used to describe the strangeness flow in heavy ion collisions.

At the internal COSY–11 facility [2] — designed for threshold meson production studies at the proton cooler synchrotron and storage ring COSY Jülich [3] — elementary kaon–hyperon production channels in the proton–proton interaction have been subject of recent experiments via the reactions $pp \to pK^+\Lambda$ and $pp \to pK^+\Sigma^0$.

Close to threshold, with extended interaction times due to vanishing relative momenta in the exit channel, effects of low energy elastic scattering are inherent to the experimental observables. Consequently, in threshold production strong final state interaction (FSI) effects allow to study low energy scattering, and the theoretical interpretation of experimental data is simplified with only few partial waves contributing.

2 The Reaction $pp \to pK^+\Lambda$ Close to Threshold

Total cross section values of the reaction $pp \to pK^+\Lambda$ obtained at the COSY–11 facility [4–6] are shown in figure 1 together with results at higher excess energies of the COSY–TOF installation [7] and an earlier BNL experiment [8].

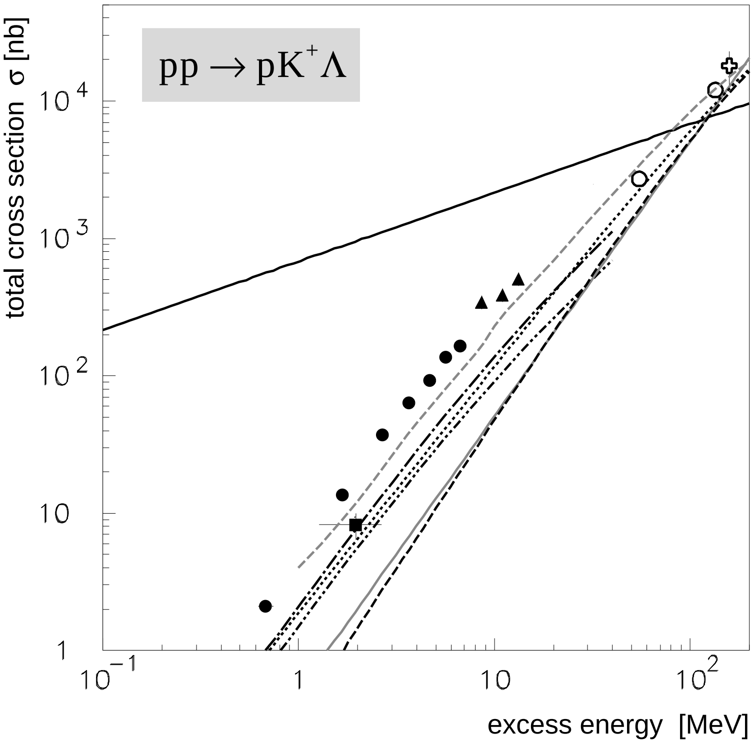

Fig. 1. Total cross section of the reaction $pp \to pK^+\Lambda$. Close–to–threshold data obtained at the COSY–11 facility [4–6] are marked by filled squares, circles and triangles, COSY–TOF [7] and BNL [8] results by open circles and crosses, respectively. In comparison, theoretical descriptions [9–12, 14, 15] are included, for details see text.

While the linear (solid line in fig. 1 [9]) and quartic (grey solid line [10]) parametrizations in terms of the maximum kaon momentum in the center–of–mass system describe the total cross section at higher excess energies, both descriptions fail to reproduce the close–to–threshold data by more than an order of magnitude.

In contrast, parametrizations from one–boson exchange models, taking into account pion and kaon exchange, reproduce the magnitude of the total cross section both at lower and at higher excess energies within a factor of two or three (grey dashed [11] and dotted [12] lines). However, interference effects of the exchange amplitudes as well as final state interactions, which are known to be important in threshold hyperon production from previous studies [13], are neglected.

A resonance model approach (dashed line [14]) — considering baryon resonances with masses up to $2\,\mathrm{GeV/c^2}$ coupling to the kaon–hyperon channel and π, η and ρ exchange — disagrees with the experimental data close to threshold. According to the authors, final state interactions are not taken into account and thus, the approach is neither expected nor aimed to describe the low cross section regime well.

Within a one–pion exchange model including the excitation of the first and second S_{11} nucleon resonance the $\mathrm{pp} \to \mathrm{pK}^+\Lambda$ total cross section is described by a dominant contribution of the $\mathrm{N}^*(1650)$ [15]. The scale of the excitation function is normalized to low energy data on the $\mathrm{pp} \to \mathrm{pp}\eta$ reaction, which in turn is described by the excitation of the $\mathrm{N}^*(1535)$ coupling strongly to the nucleon–η channel. The predictions in figure 1 (dash–dotted and dash–double–dotted lines) differ in the choice of low energy Λ–p scattering parameters [22,25] determining the proton–hyperon FSI.

In an analysis based on tree–level diagrams to describe constant transition matrix elements close to threshold [16], vector meson exchange, i.e. pointlike ω exchange alone or the combined $(\rho^0, \omega, \mathrm{K}^{*+})$ exchange, K^+ exchange, or π exchange exciting the $\mathrm{S}_{11}(1650)$ resonance added to the pseudoscalar and vector meson exchange diagrams are found to reproduce the threshold transition amplitude. It is concluded that more exclusive measurements, angular distributions and polarization observables, as recently reported at an excess energy of $430\,\mathrm{MeV}$ [17], are needed to discriminate the different $\mathrm{pp} \to \mathrm{pK}^+\Lambda$ reaction mechanisms.

3 The Λ/Σ^0 Cross Section Ratio

At equal excess energies — up to $13\,\mathrm{MeV}$ with respect to the hyperon production thresholds — total cross sections of the reactions $\mathrm{pp} \to \mathrm{pK}^+\Lambda/\Sigma^0$ have been measured at the COSY–11 facility [5,6]. No further data are available in this energy range.

The energy dependence is much better described by a phase space behaviour modified by the proton–hyperon FSI [15] than by a pure phase space calculation for both hyperon production channels (fig. 2). However, the most striking feature of the data is the observed Σ^0 suppression in the energy range close to threshold with

$$\frac{\sigma\left(\mathrm{pp} \to \mathrm{pK}^+\Lambda\right)}{\sigma\left(\mathrm{pp} \to \mathrm{pK}^+\Sigma^0\right)} = 28\,^{+6}_{-9},$$

while at excess energies $\geq 300\,\mathrm{MeV}$ this ratio is known to be about 2.5 [18].

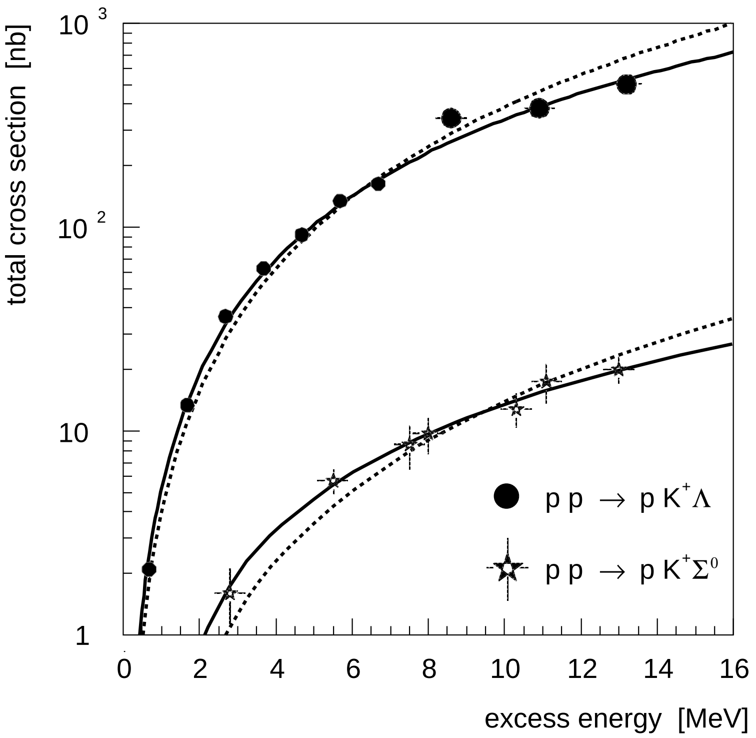

Fig. 2. Total cross sections for the reactions $\mathrm{pp} \to \mathrm{pK}^+\Lambda/\Sigma^0$ [5,6]. The energy dependence is much better described by the available phase space modified by the proton–hyperon final state interaction (solid line [15]) than by a pure phase space calculation (dashed line).

Considering only π exchange a ratio of ≈ 0.9 [19], resulting from $\pi\mathrm{N} \to \mathrm{K}\Lambda\,(\Sigma^0)$ data in the Born term approximation with N denoting a nucleon, clearly underestimates the experimental result. Kaon exchange essentially relates the hyperon production to the ratio of coupling constants $g^2_{\mathrm{N}\Lambda\mathrm{K}}/g^2_{\mathrm{N}\Sigma\mathrm{K}}$, which are rather uncertain in the literature. With a suitable choice of the SU(6) prediction, a production cross section ratio of 27 seems to be in good agreement with the experiment, but effects of final state interaction as well as the importance of π exchange are completely neglected by this simple estimate.

Inclusive K^+ production data in proton–proton scattering at an excess energy of 170 MeV [20] show enhancements in the invariant mass distribution at the Λp and the ΣN mass of similar magnitude. Qualitatively, the effect of a strong final state $\Sigma N \to \Lambda p$ conversion, known from exclusive hyperon production in K^-d scattering [21], might account for both these inclusive results as well as the Σ^0 depletion in the COSY–11 data.

However, in a recent more detailed theoretical calculation within the framework of the Jülich meson exchange model [19], taking into account both π and K exchange diagrams and rigorously including the FSI in a coupled channel approach, a strong effect of a final state conversion is rather excluded. Instead, while Λ production is found to be dominated by kaon exchange, both π and K exchange turn out to contribute to the Σ^0 channel with similar strength: In result, a destructive interference of these exchange diagrams might explain the Σ^0 suppression close to threshold [19]. It should be noted that contributions from direct production and heavy meson exchanges have been neglected so far in these calculations but might incluence the Λ/Σ^0 production ratio [14, 16].

4 Low Energy (Λp) Scattering Parameters

With experimental observables being significantly influenced by the strong final state interaction, as discussed for the energy dependence of the hyperon production cross sections in the previous section, threshold experiments allow to study low energy elastic scattering. In case of the Λ–p system, direct Λ–p scattering experiments are difficult to perform due to the short Λ lifetime and results are only available at excess energies above 3.8 MeV [22, 23]. In contrast, the FSI approach from threshold $pK^+\Lambda$ production [24] covers an energy range down to threshold. However, with both unpolarized beam and unpolarized target only spin averaged values for the low energy scattering parameters, i.e. scattering length $\overline{a}$ and effective range $\overline{r}$, can be extracted from the data, although the spin dependence is expected to be small [25, 26].

Assuming the s–wave energy dependence of the production cross section close to threshold to be determined by the available phase space volume modified by the (pK^+) Coulomb repulsion and the strong (pΛ) interaction, low energy Λ–p scattering parameters have been determined from the influence on the differential occupation of Dalitz plot distributions (for details of the applied technique see [24]). As in the analysis scattering length and effective range turn out to be strongly correlated, only the combination of values in the ($\overline{a}$,$\overline{r}$) plane is constrained. Available experimental and theoretical values [21–23, 25–27] are located close but slightly outside the constraint of a 99 %

confidence level contour (fig. 3).

The complementary experimental information from Λ–p elastic scattering allows to extract separate values for the spin averaged Λ–p scattering parameters in a combined fit constrained by the Dalitz plot analysis.

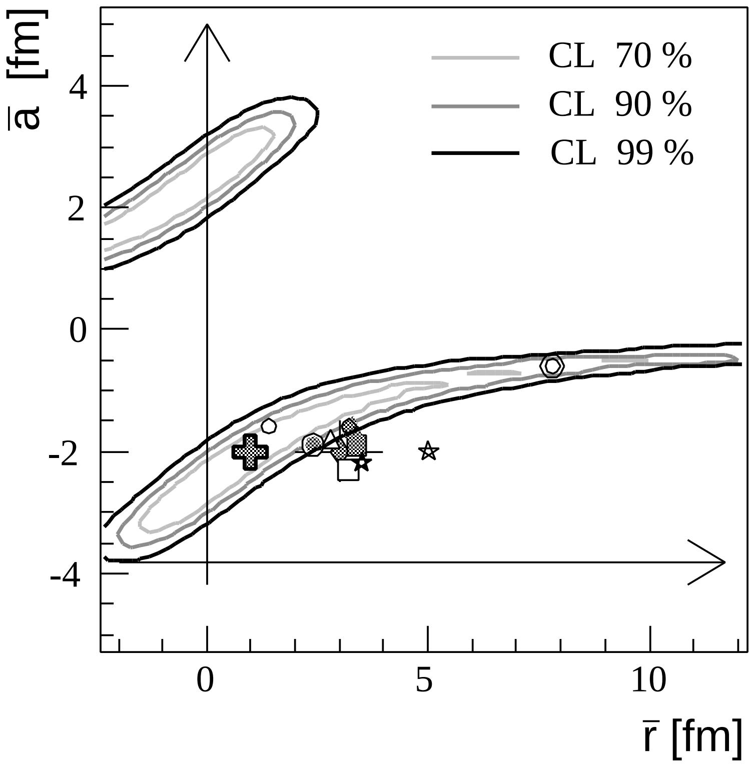

Fig. 3. Constraints on low energy Λ–p scattering parameters based on close–to–threshold COSY–11 data on the reaction $pp \to pK^+\Lambda$ [5,24] in comparison with available literature values [21–23, 25–27]. Unphysical solutions at positive values of the scattering length implying a (Λp) bound state are to be excluded. Separate spin averaged values $\bar{a} = -2.0\,\mathrm{fm}$ and $\bar{r} = 1.0\,\mathrm{fm}$ result from a combined fit with Λ–p elastic scattering data [24] and are indicated by the filled cross.

Although — due to the strong coupling of parameters — errors are difficult to derive, the combined fit allows to extract new values of the spin averaged scattering length and effective range [24]

$$\bar{a}_{\Lambda p} = -2.0\,\mathrm{fm},\ \bar{r}_{\Lambda p} = 1.0\,\mathrm{fm}.$$

5 Recent Developments and Future Aspects

Further experiments and theoretical studies appear to be necessary to extend our knowledge on the elementary strangeness production and the hyperon–

nucleon interaction.

A measurement of the (ΛK^+) invariant mass distribution at excess energies of about 100 MeV might give insight into the relevance of different resonance contributions [28] to Λ production in proton–proton scattering, the energy range is covered by experiments presently performed at the COSY–TOF facility. Threshold production is expected to be sensitive on the excitation of particular resonances as well, as FSI effects clearly visible in the physical observables depend on the relative energy in two–particle subsystems of the $pK^+\Lambda$ final state [29]. With its high precision and complementary experimental facilities, COSY Jülich provides the appropriate tool for future studies.

Very recently, the measurement of the Λ/Σ^0 production cross section ratio has been extended at the COSY–11 installation to excess energies between threshold and the high energy range to determine its energy dependence. Data are presently analysed and at the same time, an extension of the previous theoretical calculations is prepared to cover the energy range investigated by the experiment [30]. The energy dependence of the cross section ratio as well as hyperon production studies in complementary isospin configurations, i.e. the ($nK^+\Sigma^+$) final state with an expected opposite interference pattern of π and K exchange [19], planned at the COSY–11 facility for the near future, will further constrain the interpretation of data.

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