Kaon Production and Interaction *

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Exclusive data on both the elementary kaon and antikaon production channels have been taken at the cooler synchrotron COSY in proton–proton scattering.

In the kaon–hyperon production an enhancement by one order of magnitude of the \( \Lambda/\Sigma^0 \) ratio has been observed at excess energies below \( Q = 13 \text{ MeV} \) compared to data at higher excess energies \( (Q \geq 300 \text{ MeV}) \). New results obtained at the COSY–11 facility explore the transition region between the regime of this low–energy \( \Sigma^0 \) suppression and excess energies of 60 MeV. A comparison of the energy dependence of the \( \Lambda \) and \( \Sigma^0 \) total cross sections exhibits distinct qualitative differences between both hyperon production channels.

Studies of kaon–antikaon production have been motivated especially by the ongoing discussion about the nature of the scalar resonances \( f_0(980) \) and \( a_0(980) \) coupling to the \( K\bar{K} \) channel. For the reaction \( pp \to ppK^+K^- \) a first total cross section value is reported at an excess energy of \( Q = 17 \text{ MeV} \), i.e. below the \( \phi \) threshold. Calculations obtained within an OBE model indicate that the energy dependence of the available total cross section data close to threshold is rather difficult to reconcile with the assumption of a phase–space behaviour modified predominantly by the proton–proton final state interaction.

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1. Introduction

In elementary hadronic interactions with no strange valence quark in the initial state the associated strangeness production provides a powerful tool to study reaction dynamics by introducing an “impurity” to hadronic matter. Thus, quark model concepts might be related to mesonic or baryonic degrees of freedom, with the onset of quark degrees of freedom expected for kinematical situations with large enough transverse momentum transfer.

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In close-to-threshold production experiments, effects of low energy scattering are inherent to the observables due to strong final state interactions. Consequently, the data allow to constrain microscopic interaction models especially in the case where direct scattering experiments are difficult to perform.

2. Exclusive Kaon–Hyperon Experiments in Proton–Proton Collisions

Exclusive data on Λ and Σ⁰ production in proton–proton scattering have been taken at the COSY–11 facility at equal excess energies close to threshold [1, 2]. In the energy range up to Q = 13 MeV the energy dependence is better described by a phase space behaviour modified by the proton–hyperon final state interaction (FSI) than by a pure phase space behaviour [2]. However, the most striking feature of the data is the observed Σ⁰ suppression with

\[ \mathcal{R}_{\Lambda/\Sigma} (Q \leq 13 \text{ MeV}) = \frac{\sigma(pp \rightarrow pK^{+}\Lambda)}{\sigma(pp \rightarrow pK^{+}\Sigma^0)} = 28^{+6}_{-9}, \quad (1) \]

while at excess energies \( \geq 300 \text{ MeV} \) this ratio is known to be about 2.5 [3]. Considering only π exchange, data on π induced hyperon production via \( \pi N \rightarrow K \Lambda (\Sigma^0) \) result in a ratio of \( \mathcal{R}_{\Lambda/\Sigma} \approx 0.9 \) [4], clearly underestimating the experimental value of (1). Kaon exchange essentially relates the ratio \( \mathcal{R}_{\Lambda/\Sigma} \) to the ratio of coupling constants squared \( g_{N\Lambda K}^2/g_{N\Sigma K}^2 \). Although there is some uncertainty in the literature on their values, a \( \Lambda/\Sigma^0 \) production ratio of 27 follows from the suitable choice of the SU(6) prediction [5], in good agreement with the experiment. However, effects of final state interaction as well as the importance of π exchange for Σ⁰ production are completely neglected by this simple estimate.

Inclusive \( K^+ \) production data in \( pp \) scattering taken at the SPES 4 facility at SATURNE at an excess energy of 252 MeV with respect to the \( pK^+\Lambda \) threshold show enhancements in the invariant mass distribution at the \( \Lambda p \) and \( \Sigma N \) thresholds of similar magnitude [6]. With only the \( K^+ \) being detected, it is not clear whether the enhancement at the \( \Sigma N \) threshold originates from \( \Sigma \) production. Qualitatively, a strong \( \Sigma N \rightarrow \Lambda p \) final state conversion might account for both the inclusive SPES 4 results as well as the \( \Sigma^0 \) depletion in the COSY–11 data. Evidence for \( \Sigma N \rightarrow \Lambda p \) conversion effects is known from exclusive hyperon data via \( K^- d \rightarrow \pi^- \Lambda p \) [7], and from hypernuclear physics, with \( \Sigma N \rightarrow \Lambda N \) as the dominating decay channel of \( \Sigma^- \)-hypernuclei [8].

In exploratory calculations performed within the framework of the Jülich meson exchange model [4], taking into account both π and \( K \) exchange
diagrams and rigorously including FSI effects in a coupled channel approach, a final state conversion is rather excluded as dominant origin of the observed \( \Sigma^0 \) suppression. While \( \Lambda \) production is found to be dominated by kaon exchange — in agreement with the exclusive DISTO spin transfer results at higher excess energies \([9]\) — both \( \pi \) and \( K \) exchange turn out to contribute to the \( \Sigma^0 \) channel with similar strength. It is concluded \([4]\), that a destructive interference of \( \pi \) and \( K \) exchange diagrams might explain the close-to-threshold \( \Sigma^0 \) suppression and a good agreement with the COSY–11 total cross section results is obtained after including an overall reduction due to the \( pp \) initial state interaction.

An experimental study of \( \Sigma \) production in different isospin configurations should provide a crucial test for the above interpretation: For the reaction \( pp \rightarrow nK^+\Sigma^+ \) an opposite interference pattern is found as compared to the \( pK^+\Sigma^0 \) channel, i.e. the \( nK^+\Sigma^+ \) channel is enhanced for a destructive interference of \( \pi \) and \( K \) exchange. Measurements close to threshold are planned at the COSY–11 facility in future.

Contributions from direct production as well as heavy meson exchanges have been neglected so far in these calculations \([4]\) but might influence the \( \Lambda/\Sigma^0 \) production ratio \([10,11]\).

Employing both a \( \pi \) and \( K \) exchange based meson exchange model neglecting any interference of the amplitudes and the resonance model of \([10]\) the data on the \( \Lambda/\Sigma^0 \) production ratio are described within a factor of two of the experimental error bars \([12]\). The same holds for OBE calculations performed by Laget \([13]\), in which the relative sign of \( \pi \) and \( K \) exchange is chosen to maximize the cross section. It should be noted that the latter approach both reproduces the polarization transfer results reported by the DISTO collaboration \([9]\) and accurately describes \( YN \) invariant mass distributions of the inclusive SPES 4 measurements \([6]\).

Within an effective Lagrangian approach both \( \Lambda \) and \( \Sigma^0 \) production are found to be dominated close to threshold by \( \pi \) exchange followed by an excitation of the \( N^*(1650) \) resonance \([14]\), in contrast to the resonance model approach considered in \([12]\), where the influence of the \( N^*(1650) \) on the \( \Sigma^0 \) channel has not been taken into account, and it is rather the \( N^*(1710) \) that determines \( \Sigma^0 \) production close to threshold and both reaction channels at higher excess energies.

Recently, preliminary Dalitz plot distributions obtained at the COSY–TOF facility have been presented for the reaction \( pp \rightarrow pK^+\Lambda \) at an excess energy of 171 MeV \([15]\). Qualitatively, the data are reproduced by calculations by A. Sibirtsev considering resonance excitation and effects of \( p\Lambda \) final state interaction, giving evidence for a dominant influence of the \( N^*(1650) \) resonance at this excess energy.

Measurements on the \( \Lambda/\Sigma^0 \) production ratio in proton–proton collisions
have been extended up to excess energies of $Q = 60\,\text{MeV}$ at the COSY–11 installation \cite{16}. In comparison to the experimental data, in figure 1 calculations are included obtained within the approach of \cite{4} assuming a destructive interference of $\pi$ and $K$ exchange with different choices of the microscopic hyperon nucleon model to describe the interaction in the final state \cite{17}.

![Graph of Λ/Σ^0 production ratio in proton–proton collisions as a function of the excess energy.](image)

Fig.1. $\Lambda/\Sigma^0$ production ratio in proton–proton collisions as a function of the excess energy. Experimental data within the shaded area, which corresponds to the range given in relation (1), are from \cite{2}, data at higher excess energies from \cite{16}. Calculations \cite{17} are performed within the Jülich meson exchange model, assuming a destructive interference of $K$ and $\pi$ exchange and employing the microscopic $YN$ interaction models Nijmegen NSC89 (dashed line \cite{18}) and the new Jülich model (solid line \cite{19}), respectively.

As emphasized in \cite{4}, the result depends on the details — especially the off–shell properties — of the hyperon–nucleon interaction employed, although the actual choice does not alter the general result in \cite{4} of only a destructive interference of $\pi$ and $K$ exchange explaining the experimentally observed suppression of the $\Sigma^0$ signal close to threshold. At the present stage both the good agreement found for Jülich model A \cite{20} with the close–to–threshold result \cite{11} and for the Nijmegen model (dashed line in fig. 1) with the energy dependence of the cross section ratio should rather be regarded as accidental. In the latter case an SU(2) breaking in the $^3S_1$ $\Sigma N$ channel had to be introduced \cite{18}. Consequently, the relation between the $\Sigma^0 p$ amplitude and the $\Sigma^+ p$ and $\Sigma^- p$ channels becomes ambiguous.
Only one of the choices leads to the good agreement with the data, whereas the other one results in a completely different prediction [21].

Calculations using the new Jülich model (solid line in fig. 1 [19]) do not reproduce the tendency of the experimental data. It is suggested in [17] that neglecting the energy dependence of the elementary amplitudes and assuming S–waves in the final state might no longer be justified beyond excess energies of 20 MeV.

Total cross sections for the reactions \( pp \rightarrow pK^+\Lambda/\Sigma^0 \) obtained at the COSY–11 (circles and squares [1, 2, 16]) and COSY–TOF (triangle [22]) facilities up to excess energies of \( Q = 60 \) MeV are shown in figure 2.

![Fig. 2. Total cross sections of the reactions \( pp \rightarrow pK^+\Lambda/\Sigma^0 \) (solid circles and squares from [1, 2], solid triangle from [22], open symbols from [16]) as functions of the excess energy. Dotted and solid lines denote fits of the energy dependence assuming a pure phase space behaviour and a phase space dependence modified by the proton–hyperon FSI parameterized according to [23]. In addition to the absolute normalization, the latter allows to vary low energy scattering parameters via the energy of a nearby virtual bound state.](image)

Obviously, in case of \( \Lambda \) production, the energy dependence of the total cross section is much better described by a phase space behaviour modified by the p\( \Lambda \) final state interaction than by pure phase space. However, unlike the findings of [2] based on the at that time available data up to excess energies of \( Q = 13 \) MeV, in the energy range up to \( Q = 60 \) MeV \( \Sigma^0 \) production is equally well described neglecting any FSI effect.

Presently, the origin of this qualitatively different behaviour of the hyperon production channels is not understood: Proton–hyperon final state interactions might be less important in case of \( \Sigma^0 \) production compared to \( \Lambda \) production as already concluded in [24]. On the other hand, a fit of the energy dependence considering phase space and final state interaction effects...
implies the dominance of S–wave production and energy independent reaction dynamics, which might no longer be justified as mentioned above [17]. Within the statistics of the present experiment, P–wave contributions can be neither ruled out nor confirmed at higher excess energies for Σ⁰ production. Consequently, high statistics Σ⁰ data would be needed in future to study the influence of higher partial waves experimentally.

Qualitatively, a dominant production via resonance excitation — as investigated within the resonance model approach [10] — might provide a mechanism leading to different partial wave contributions, if Λ and Σ⁰ production close to threshold were dominated by the S_{11} N*(1650) and P_{11} N*(1710) resonances, respectively.

3. Elementary Antikaon Production

Studies on the reaction pp → ppK⁺K⁻ close to threshold have been motivated by the continuing discussion on the nature of the scalar resonances f₀(980) and a₀(980) [25]. Within the Jülich meson exchange model for ππ and πη scattering the K𝐾 interaction dominated by vector meson exchange gives rise to a bound state in the isoscalar sector identified with the f₀(980) [26]. Both shape and absolute scale of ππ → K𝐾 transitions crucially depend on the strength of the K𝐾 interaction, which in turn is a prerequisite of a K𝐾 molecule interpretation of the f₀(980). Similar effects might be expected for the elementary kaon–antikaon production in proton–proton scattering, and first results of exploratory microscopic calculations have recently been presented [27].

3.1. Experimental Results

A first total cross section value for the elementary antikaon production below the Φ threshold in proton–proton scattering has been extracted from exclusive data taken at the COSY–11 installation at an excess energy of Q = 17 MeV with

\[ \sigma_{pp → ppK⁺K⁻} \ (Q = 17 \text{ MeV}) = 1.80 ± 0.27^{+0.28}_{-0.35} \text{ nb}, \]  

including statistical and systematical errors, respectively [28].

The experimental technique is based on the measurement of the complete four–momenta of positively charged ejectiles. Figure 3a) shows the missing mass squared with respect to an identified (ppK⁺) subsystem: A sharp peak at the charged kaon mass corresponding to a resolution of ≈ 2 MeV/c² (FWHM) is clearly separated from a broad distribution in the region of lower missing masses. The latter can be explained by misidentifying pions from pp → pπ⁺X events as kaons, where X denotes a system of undetected particles. In addition, the excitation of hyperon resonances via
\( pp \rightarrow pK^{+} \Lambda(1405)/\Sigma(1385) \) may contribute, with one of the identified protons originating from the hyperon resonance decay, shifting the missing mass with respect to the \((ppK^{+})\) subsystem to lower values (as discussed in detail in [28]). Considering both effects, the broad distribution is well reproduced as indicated in figure 3a).

![Fig. 3](image)

**Fig. 3.** Missing mass squared with respect to an identified \((ppK^{+})\) subsystem at an excess energy of 17 MeV above the \(pp\rightarrow ppK^{+}K^{-}\) threshold a) without and b) with \(K^{-}\) detection. In a) the distribution at lower missing mass values is reproduced considering the possible misidentification of pions as kaons as well as the excitation of hyperon resonances (black solid line).

Requiring furthermore a \(K^{-}\) consistent hit in the dedicated negative particle detection system of the COSY–11 facility [29], the identification of the four particle final state becomes (almost) completely free of background, as demonstrated in figure 3b). The reduction in counting rate for the \(K^{-}\) signal is due to acceptance and decay losses and in excellent agreement with expectations from Monte Carlo simulations.

However, the available statistics of \(K^{+}K^{-}\) events extracted at the excess energy of \(Q = 17\) MeV is not sufficient to distinguish between a non–resonant \(K^{+}K^{-}\) production and resonant production via the scalar resonances \(f_{0}(980)\) and \(a_{0}(980)\) from differential observables, e.g. the \(pp\) missing mass distribution [30].

3.2. Energy Dependence of the Total Cross Section

The total \(\eta, \omega\) and \(\eta'\) production cross sections show very similar dependences on the excess energy: At excess energies \(100 \leq Q \leq 1000\) MeV the energy dependence of the total cross section is dominated by three–body phase space \((\sigma \propto Q^{2})\). The deviation from a \(Q^{2}\) dependence below 100 MeV arises from the interaction between the final state protons and possibly be-
tween the final state proton and meson, the latter clearly observed in case of the \( pp \rightarrow ppp\eta \) reaction.

These features are well illustrated by the data \[3, 31\] on the reaction \( pp \rightarrow ppp\eta' \), where the possible effect due to the \( p\eta' \) FSI is expected to be almost negligible. Figure 4a) shows the data available for the \( pp \rightarrow ppp\eta' \) cross section as a function of excess energy \( Q \). The phase space dependence (dashed line) apart from the normalization constant reproduces the data at \( Q \geq 100 \text{ MeV} \). Calculations \[32\] obtained within one–boson exchange models neglecting the \( pp \) FSI explicitly follow the phase space dependence (solid line), while the effect of the \( pp \) FSI is indicated by the dotted line.

![Graphs showing \( pp \rightarrow ppp\eta' \) and \( pp \rightarrow ppK^+K^- \) cross sections](image)

Fig. 4. a) The \( pp \rightarrow ppp\eta' \) cross section as a function of excess energy. The data are from \[3, 31\], the dashed line shows the phase space \( Q^2 \)-dependence, the solid line indicates calculations without FSI \[32\], the dotted line shows the parameterization of the \( pp \) FSI. b) The \( pp \rightarrow ppK^+K^- \) cross section. The data are from \[28, 33\], the solid line shows the calculations of \[34\], the dashed line indicates the phase space \( Q^{7/2} \)-dependence.

Data on the \( pp \rightarrow ppK^+K^- \) total cross section obtained at the COSY–11 \[28\] and DISTO \[33\] facilities below and above the \( \Phi \) production threshold, respectively, are in reasonable agreement with one–boson exchange calculations \[34\] without FSI effects (solid line in figure 4b)). Contrary to \( \eta \), \( \omega \) and \( \eta' \) production the calculations for \( K^+K^- \) production differ significantly from the four–body phase space behaviour (dashed line). The latter effect can be understood in terms of the energy dependence of the elementary scattering amplitudes which determine the energy dependence of the \( pp \rightarrow ppp\eta' \) and \( pp \rightarrow ppK^+K^- \) total cross sections: While the \( \pi N \rightarrow \eta'N \) amplitudes are almost independent of the invariant \( \pi N \) energy, \( K^+p \) and especially \( K^-p \) scattering data exhibit a substantial energy dependence \[35\].
Comparing the COSY–11 result with the calculations shown by the solid line in figure 4b) — neglecting FSI — one might detect no room for final state interaction effects. Contrary to this, η, ω and η' production indicate strong FSI imprints at excess energies Q ≤ 100 MeV (fig. 4a).

Presently it is not clear whether the absence of the FSI influence in the pp → ppK⁺K⁻ reaction might be explained by a partial compensation of the pp and K⁻p interaction in the final state or by the additional degree of freedom given by the four–body final state. In the latter case FSI effects are expected to be more pronounced at energies very close to the K⁺K⁻ production threshold. It should be noted, that in the presence of two strongly interacting particles in the final state — pp and K⁻p — a factorization in terms of two–body interactions might no longer be valid and one would face a four–body problem. Thus, further measurements provide a unique opportunity to get insight into the problem experimentally.

Data taking at excess energies closer to threshold and slightly below the Φ production threshold, i.e. at excess energies of 10 MeV and 28 MeV with respect to the K⁺K⁻ threshold, has been successfully completed early this year at the COSY–11 facility and data analysis is presently in progress.

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