Total Cross Section of the Reaction $pp \longrightarrow pK^+\Lambda$ Close to Threshold

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Abstract:

The energy dependence of the total cross section for the $pp \longrightarrow pK^+\Lambda$ reaction was measured in the threshold region covering the excess energy range up to 7 MeV.
Existing model calculations describe the slope of the measured cross sections well, but are too low by a factor of two to three in rate.
The data were used for a precise determination of the beam momentum of the COSY-synchrotron.

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1 Introduction

The associated strangeness production in pp collisions is of fundamental interest and provides a possibility to study various theoretical models of the strangeness dissociation mechanism [1].

In this contribution we present data on the production of the hyperon - kaon pair via the $pp \longrightarrow pK^+\Lambda$ elementary reaction. In the covered excess energy range up to about 7 MeV predominantly only S-waves contribute to the reaction mechanism process.

At threshold in particular, effects of final state interactions (FSI) are significant and have to be taken into account. Experimental data on the reaction $pp \longrightarrow pK^+\Lambda$ makes it possible to separate the effects of $FSI_{p-\Lambda}$ and to investigate various meson exchange models of the nucleon-hyperon interaction [2, 3].

The knowledge of the kaon production cross section in the elementary N-N interaction is important for studies of the production of hyper-nuclei in nucleon interactions with nuclei [4, 5].

Furthermore this elementary process is of great interest as input for investigations of the strangeness production mechanism in heavy ion collisions, which may provide information about hot, dense nuclear matter or the possible existence of a quark-gluon plasma [6].

2 Experiment

The measurement of the $pp \longrightarrow pK^+\Lambda$ reaction was performed at the COSY-Jülich synchrotron [7], using the internal target facility COSY-11 [8]. In fig. 1 a sketch of the experiment is shown.

The outgoing protons and positively charged kaons were identified by means of particle momentum reconstruction combined with a time of flight measurement. The four-momentum of the unobserved Λ-hyperon was calculated from conservation principles. Details of the applied experimental technique are given elsewhere [8, 9]. Measurements were performed at seven excess energies between $\varepsilon = 0.9$ MeV and $\varepsilon = 6.9$ MeV according to the nominal COSY beam momentum. Examples of (pK^+) missing mass spectra, including one measurement below threshold, are shown in fig. 2. The broadening of the Λ peak is understood as an error propagation in the missing mass determination.

The geometrical acceptance of the COSY-11 detection system was calculated using Monte-Carlo simulations based on the code GEANT-3. The three-body phase space distribution was folded with the proton-Λ final state interaction, applying the Jülich model A from ref. [2]. Within the present range of the excess energy the geometrical acceptance decreases with increasing beam momentum from 30% to 5%. The proton-Λ FSI has a relative influence of less than 3% on the acceptance and does not significantly depend on the used model. The overall detection efficiency $E_{ff}(\varepsilon)$ is about three times smaller, mainly due to the decay of the K^+ mesons in flight before reaching the triggering scintillator S1.

The integrated luminosity (I_0) was determined by normalizing the simultaneously recorded and extracted p+p elastic scattering to the cross sections measured by the EDDA collaboration [10].

3 Determination of the excess energy

Due to the observed rapid variation of the cross section near threshold, a precise knowledge of the beam momentum is crucial for the precision of this experiment. The uncertainty in the absolute beam momentum is mainly caused by the uncertainty of the effective beam orbit length and amounts to $\Delta p/p = 10^{-3}$. Thus, at 2.35 GeV/c beam momentum the uncertainty is $\Delta p = 2.4$ MeV/c which may cause a systematic offset in the excess energy of the outgoing $pK^+\Lambda$ system as large as $\Delta\varepsilon \simeq 800$ keV. On the other hand, the small variation of the beam momentum of about 20 MeV/c for the present excitation function measurement between 2.342 GeV/c and 2.360 GeV/c is controlled by measuring the revolution frequency in COSY with the extreme relative precision of again 10^{-3}. This allows a precision of 20 keV/c in momentum steps and the common $\Delta\varepsilon$ offset is essentially the same for all seven measurements since these were carried out with the same beam optics. A change of excess energy $(\varepsilon_i - \varepsilon_{i+1})$ between two measurements is known with an uncertainty of only 10 keV.

To extract the value of $\Delta\varepsilon$ for the actual measurement the $pp \longrightarrow pK^+\Lambda$ data themselves were used. We may write:

$$N/I_0 \quad = \quad E_{ff}(\varepsilon) \cdot \sigma(\varepsilon) \tag{1}$$

where N stands for the number of measured $pK^+\Lambda$ events. The left side is completely determined by the experiment, whereas the right hand side consists of the product of the known detection efficiency and the energy dependent cross section. Close to threshold the cross section follows in first order the three body phase space distribution: $\sigma(\varepsilon) \sim \int d\rho_3 \sim \varepsilon^2$. Corrections due to the Coulomb interaction $f_c(q_{p_K})$ and to the dominant p-Λ final state interaction $f_{FSI}(q_{p_\Lambda})$ (see Watson's model [11]) modify smoothly this dependence according to:

$$\sigma(\varepsilon) \quad \sim \quad \int f_c(q_{p_K})\ f_{FSI}(q_{p_\Lambda})\ d\rho_3 \tag{2}$$

Only the charged particles, the proton and kaon, undergo Coulomb repulsion. According to the approach used for the symmetric (pp) subsystem [12] in the $pp \longrightarrow pp\pi^\circ$ reaction, the modification of the cross section due to the Coulomb repulsion is essentially given by the Coulomb penetration factor $f_c(q_{p_K})$. For the (pK$^+$) subsystem it is given by:

$$f_c(q_{p_K}) = \frac{2\pi\gamma_q}{e^{2\pi\gamma_q} - 1}; \qquad \gamma_q = \frac{\alpha \cdot \mu_{p_K}}{q_{p_K}};$$

$$q_{p_K} = \sqrt{2 \cdot \mu_{p_K} \cdot \varepsilon_{p_K}}; \qquad \varepsilon_{p_K} = \sqrt{S_{p_K}} - m_p - m_K \tag{3}$$

where q_{p_K} is the momentum in the proton-kaon CM subsystem, depending on the squared sum of the p and the K^+ four-momenta (S_{p_K}), the reduced mass μ_{p_K} and the fine structure constant α.

In terms of the FSI in principle three interactions should be considered, namely the subsystems: $p-\Lambda$, $K-\Lambda$, and $p-K$. Since the first one appears to be more than an order of magnitude stronger than the other two [13, 14] we concentrate on the dominant proton-Λ final state interaction only, which depends on the $p-\Lambda$ momentum $q_{p\Lambda}$. Close to the reaction threshold $f_{FSI}(q_{p_\Lambda})$ is:

$$f_{FSI}(q_{p_\Lambda}) \quad \sim \quad \frac{1}{q_{p\Lambda}^2 + (r \cdot q_{p\Lambda}^2/2 - 1/a)^2} \tag{4}$$

with the scattering length a = – 1.6 fm and the effective range parameter r = 2.3 fm taken from the Jülich model A given in ref. [2].

Qualitatively the influence of the two correction functions on the energy dependence of the total cross section, shown in fig. 3 , are arbitrarily normalized.

Denoting the nominal value of the excess energy by $\tilde{\varepsilon}$, calculated from the beam momentum given to us by the COSY team, we rewrite equation 1 to :

$$N/I_0 \quad = \quad E_{ff}(\tilde{\varepsilon} - \Delta\varepsilon) \cdot \sigma(\tilde{\varepsilon} - \Delta\varepsilon) \tag{5}$$

Figure 4 compares the threshold behavior with and without both Coulomb distortion effects and the final state interaction. It is obvious that the shape of the data is much better described when including these effects. The offset in the excess energy was obtained from a fit of equation (5) [inserting equations 2–4] to the data resulting in a smaller real excess energy by $\Delta\varepsilon$=220 ± 60 keV with respect to the one calculated from the nominal beam momentum. The equivalent shift in the nominal COSY beam momentum is Δp=660±180 keV/c and is still four times smaller than the Δp/p uncertainty typically estimated for the COSY beam.

4 Results and Discussion

The obtained values for the $pp \longrightarrow pK^+\Lambda$ cross sections at the corrected excess energies $(\tilde{\varepsilon}_i - \Delta\varepsilon)$ and with the FSI taken into account for the acceptance determination, are shown in table 1. The statistical errors range from 5% to 9% for all data points. The systematic error includes a 4% error in absolute normalization of the EDDA $pp \longrightarrow pp$ data [10] and the uncertainties of the COSY-11 acceptance determination for both $pp \longrightarrow pp$ and $pp \longrightarrow pK^+\Lambda$ reactions; each being estimated to be 5%.

Different models for the energy dependence of the $pp \longrightarrow pK^+\Lambda$ cross section have been suggested. As can be seen from fig. 5, where the present and previously published data [9, 19] are depicted in two dimensional logarithmic scales, both the square root and the quadratic excess energy approximations of J. Randrup and C.M. Ko [15] and B. Schürmann and W. Zwermann [16], respectively, fail by more than an order of magnitude in describing the present data at threshold.

The data point from our previous measurement [9] appears either to be too low in cross section by a factor of about 2.5 and/or is associated to a wrong excess energy. Utilizing fully the uncertainty of the COSY beam momentum as $\Delta p/p = 10^{-3}$, which converts to an uncertainty of the excess energy to $\Delta\varepsilon = \pm$ 800 keV, the former data point is still consistent with the present results. With only one measurement the determination of the real beam momentum was not possible. In addition, a 30% increase for the present value of the cross section is due to an improved determination of the defocusing features of the fringe field of the dipole magnet.

Recently, G. Fäldt and C. Wilkin [17] presented a one pion exchange model which assumes a dominant role of the second S_{11} resonance, the N* (1650), for the K^+ production in p+p interaction. This interpretation is analogous to the η production, which is supposed to be mediated mainly via the first S_{11} resonance, the N* (1535). These two N* resonances are distinguished by a rather large branching ratio into K Λ and η N, respectively. If the two systems η N and K Λ are dominated by these two N^* resonances, the forms of the production operators and all the spin - angular momentum algebra are identical, and the observation of an η or a K merely tags which of the two S_{11} resonances has been excited [17]. The two curves in fig. 5 are due to different Λp scattering parameters used by G. Fäldt and C. Wilkin [17], within a common factor of two to three the data are reproduced.

A similar, more extended model was presented by Sibirtsev [18]. In his calculation of the $NN \longrightarrow$ NYK cross section the one-pion as well as the one-kaon exchange diagrams are included. The amplitudes of the elementary processes ($\pi N \longrightarrow$ KY, KN $\longrightarrow$ KN) are based on phenomenological parametrizations. Contrary to the model of G. Fäldt and C. Wilkin [17], effects of the FSI are, however, not taken into account in Sibirtsev's calculations [18]. Beside the S_{11} $N^*(1650)$ these authors also include other N^* resonances with masses lower than 2000 MeV which decay into kaon - hyperon channels; but they neglect interference terms. Again the absolute rate differs by a factor of 2.5 whereas the shape of the experimental excitation function is well reproduced.

In conclusion, total $pp \longrightarrow pK^+\Lambda$ cross sections have been measured in the threshold region for excitation energies less than 7 MeV. It has been shown that the slope of the measured values for the absolute cross section follows rather the prediction including the p-Λ FSI than the pure phase space calculation, see fig. 4 for comparison. Model calculations including light and heavy boson exchange as well as intermediate N^* resonances seem to give a good account for the shape of the excitation function, but differ in magnitude by a factor of two to three. Further investigations on both the experimental side and the theoretical description are required for a deeper understanding of the reaction mechanism and the strangeness dissociation processes. For this measurements the average value of the COSY beam momentum was determined such that a precision of 60 keV for the excess energy is achieved. This procedure should be applied in each close to threshold measurement.

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ε [a]) (MeV)	events $pK^+\Lambda$	background	σ (nb)			σ/ε^2 (nb/MeV^2)
0.68	216	27	2.1	$\pm$ 0.2		4.54
1.68	598	58	13.4	$\pm$ 0.7		4.75
2.68	378	58	36.6	$\pm$ 2.6		5.10
3.68	836	151	63.0	$\pm$ 3.1	$\pm$ 14%	4.65
4.68	412	68	92.2	$\pm$ 6.5		4.21
5.68	290	39	135.	$\pm$ 11.		4.18
6.68	449	76	164.	$\pm$ 10.		3.68

[a] known with an accuracy of 60 keV

Table 1: Total cross section for the $pp \longrightarrow pK^+\Lambda$ reaction. For each excess energy (ε) the number of the $pK^+\Lambda$ events, the estimated number of background events and the extracted cross section are given. The statistical and systematical errors are listed, respectively. The last column shows the ratio of the cross section over the square of excess energy, the constant value of 4.4 ± 0.7 demonstrates the approximate phase space like increase of the total cross section with increasing excess energy.

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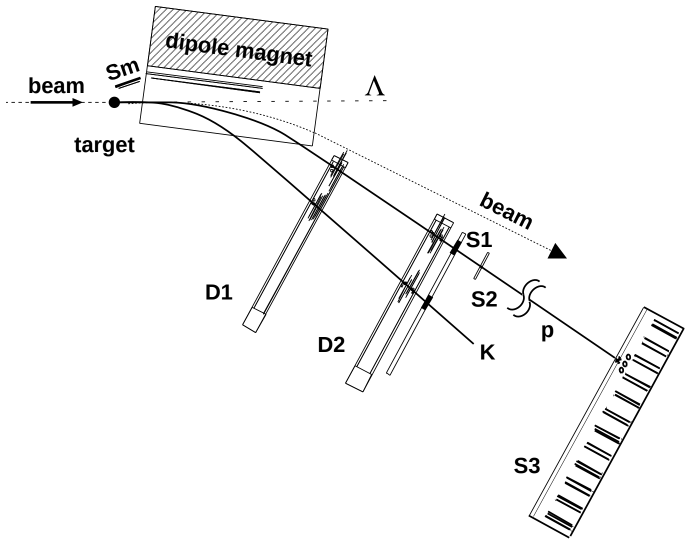

Figure 1: Sketch of the COSY-11 setup used for the $pp \longrightarrow pK^+\Lambda$ detection. The positively charged particles, i.e. proton and kaon, are measured by drift chambers (D1,D2) and scintillation detectors (S1,S3). The Λ-particle and its decay products are not registered, only the direction of the Λ-particle is displayed in the figure. The monitor scintillator (Sm) is used for the coincident detection of elastically scattered protons.

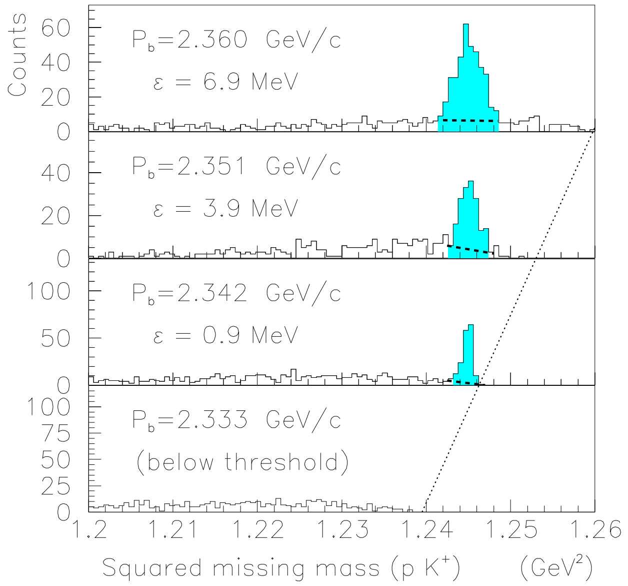

Figure 2: Squared missing mass (MM^2) of the pK^+ subsystem measured at three different nominal COSY beam momenta. The indicated peaks correspond to the mass of the Λ - particle from the $pp \longrightarrow pK^+\Lambda$ reaction. The dashed line depicts the background level. The dotted line marks the kinematical limit of the MM^2 spectra.

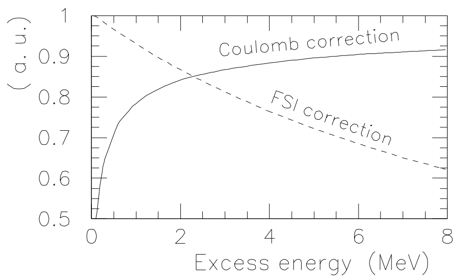

Figure 3: Shape distribution of the Coulomb and FSI corrections in arbitrary units, calculated as $\int f_c\, d\rho_3 / \int d\rho_3$ and $\int f_{FSI}\, d\rho_3 / \int d\rho_3$ resulting from equations (3) and (4), respectively.

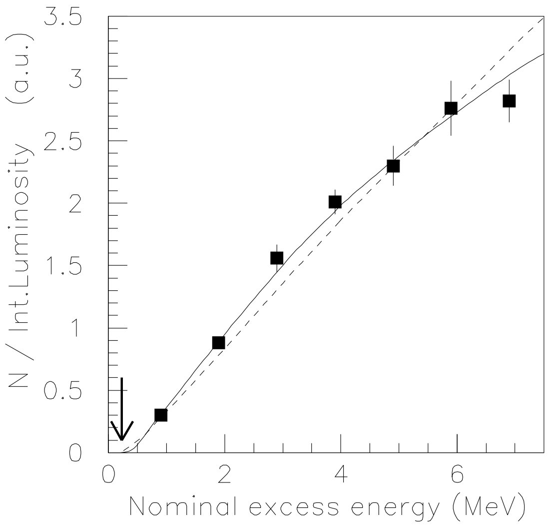

Figure 4: Determination of the beam momentum by means of the experimentally measured $pp \longrightarrow pK^+\Lambda$ event rate. The solid line depicts the best fit of $\Delta\varepsilon$ from equation 5 to the data. The dashed one is the pure phase space prediction. The arrow corresponds to the resulting offset of $\Delta\varepsilon = 220 \pm 60\ keV$.

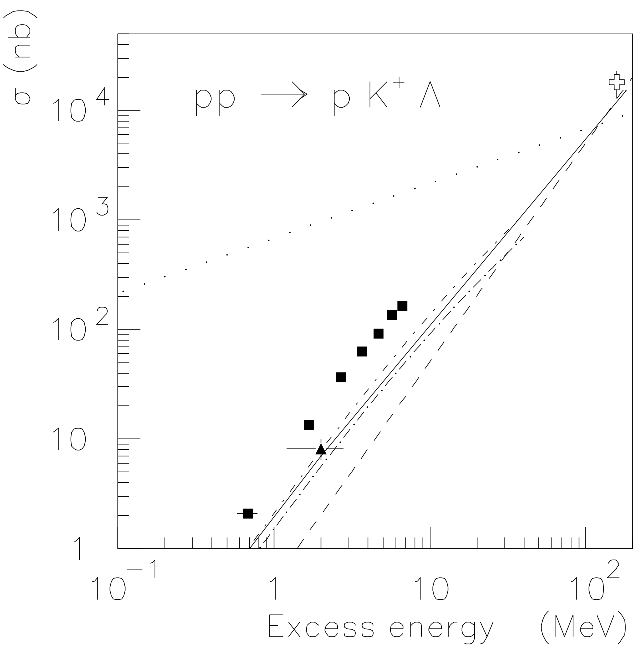

Figure 5: Data and different models describing the energy dependence of the $pp \longrightarrow pK^+\Lambda$ total cross section. The parametrization of Randrup et al. is depicted as a dotted line, of Schürman et al. as a dashed one, of Sibirtsev et al. as a solid and of Fäldt and Wilkin as two types of dash-dotted. Tha data of Fickinger are marked as a cross, of Balewski at al. as a triangle and the present one as squares.