Summary of the COSY-11 Measurements of Hyperon Production

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Abstract. The studies of hyperon production performed at COSY-11 are summarized. The results of the experiments in the reaction channels $pp \to pK^+\Lambda$, $pp \to pK^+\Sigma^0$, and $pp \to nK^+\Sigma^+$ are shown. Excitation functions from threshold up to about 90 MeV excess energies have been evaluated with high precision for the Λ and Σ^0 production. The Λp and $\Sigma^0 p$ final state interactions were extracted. The Σ^+ production was measured at 13 and 60 MeV excess energies.

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INTRODUCTION

The hyperon-nucleon interaction is less known than the one for the nucleon-nucleon system due to the difficulties in performing scattering experiments with the unstable hyperons. The existing YN-scattering data are rather limited [1, 2, 3, 4] and for a better understanding of the strong interaction in the nonperturbative region of the QCD an extension of the data base in the strangeness sector is very important. Besides hyperon-nucleon scattering, reactions into 3-body exit channels like: $NN \to NKY$ can be used to extract detailed information on the NY-subsystem. The YN interaction is only one aspect covered by these kinds of experiments which can be separated into three stages, the initial state interaction of the incoming nucleons, the associated strangeness production process and the final state interaction. Final state interaction happens between all exit particles and by separating a suitable kinematic region also the KN and KY interaction can be studied. Furthermore information about the contributing reaction mechanisms are obtained including the excitation of nucleon resonances which is also directed to the structure of these resonances. Most favourable for these studies are experiments close to the reaction threshold due to the low relative momenta and therefore long interaction times between the ejectiles. In order to get a detailed understanding of these elementary interactions involving strangeness differential cross sections as a function of spin and isospin degrees of freedom are required. A significant contribution to this kind of physics has been done by the hyperon production experiments at COSY-11.

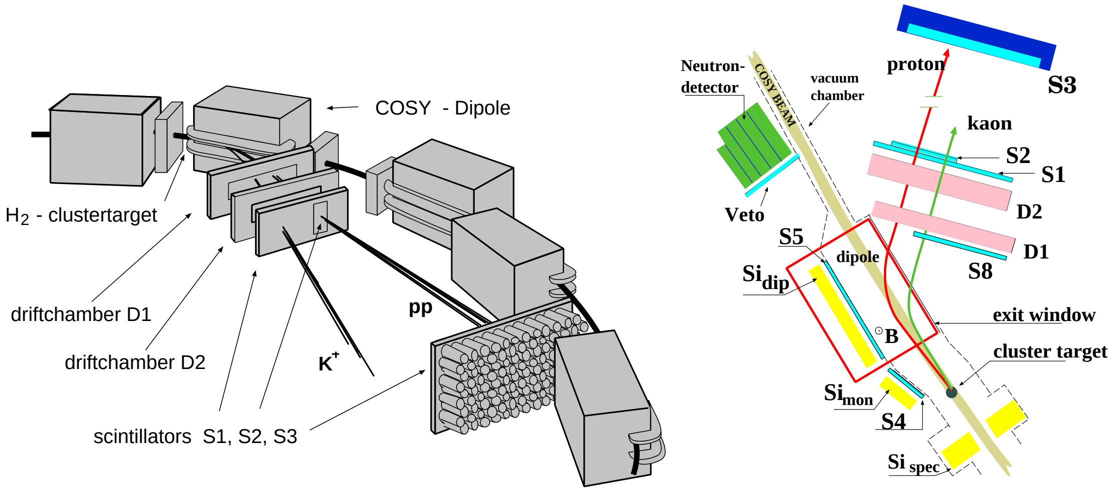

FIGURE 1. The COSY-11 detection system installed at a COSY machine dipole with the detector components relevant for the hyperon production studies. The left side shows a 3-d view of the arrangement and on the right side is a sketch of the detector components to illustrate the principle of operation. The S8 scintillator was only used for the $pp \to nK^+\Sigma^+$ reaction.

THE EXPERIMENTAL SETUP FOR STRANGENESS PRODUCTION AT COSY-11

The internal COSY-11 installation [5] at COSY [6] was designed for near threshold meson production studies. It used a COSY machine dipole as magnetic spectrometer and included scintillation detectors and drift chambers to reconstruct particle tracks of positively charged particles and measure their velocities in order to determine their four-momentum components with high precision. A sketch of the setup is given in fig. 1 and for more details see [5].

In the case of hyperon production via the reaction channels $pp \to pK^+\Lambda/\Sigma^0$ the proton velocities are measured with the scintillator hodoscopes S1 and S3 but for the kaon the $\sim$ 9 m flight path to S3 is too long. Most of the kaons would decay before reaching S3. Here the flight path from the target to S1 is used where the start time is calculated from the measured proton momentum. The particle identification is worse than in the proton case due to the much shorter flight path but its still sufficient to separate most of the pions and protons from the kaons. The hyperon four-momentum $P_{hyperon}$ is determined by the missing mass technique: $P_\Lambda = P_{beam} - P_p - P_{K^+}$ with the known beam P_{beam} and the measured proton P_p and kaon P_{K^+} four-momenta. This method results in a rather clean separation of the hyperon production events as can be seen from fig. 2 left for an event sample of Λ production at 7 MeV excess energy. In the case of the Σ^0 production its similar but the background level is higher as can seen from fig. 2 up right which shows the missing mass squared distribution in the kaon band at an excess energy of 7 MeV for $pp \to pK^+\Sigma^0$. In parallel to the Σ^0 production also Λ production at about 80 MeV higher excess energies is measured.

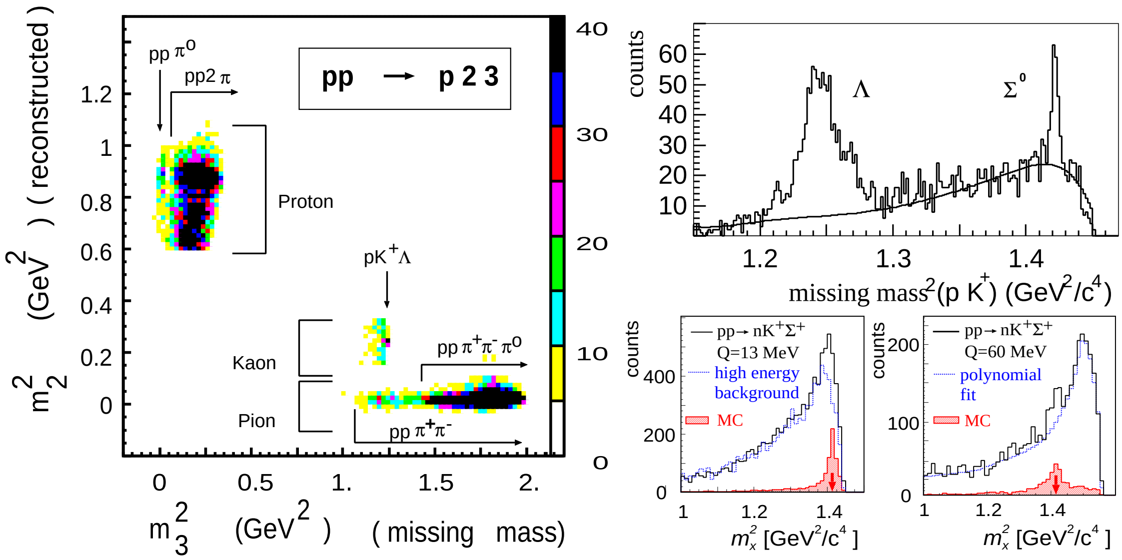

FIGURE 2. Invariant mass of the second track as a function of the missing mass for Λ production at 7 MeV excess energy (left). Missing mass squared distribution for Σ^0 production at 7 MeV excess energy (up right). Missing mass squared distributions for Σ^+ production at 13 and 60 MeV excess energy (down right) with the applied background subtraction and the expected distributions of Σ^+ production from Monte Carlo.

With the addition of a neutron detector, installed for studies at a deuteron target, another hyperon channel was accessible at COSY-11, namely the $pp \to nK^+\Sigma^+$ reaction. Here the peak to background ratio was less favourable, see fig. 2 down right, because no proton is in the exit channel to produce a precise timing signal. The neutron detector provided the time and position of the point of the first neutron interaction producing a charged ejectile from which the neutron momentum was calculated. The absolute time calibration was performed with γ's by selecting $pp \to pp\pi^0$ events with the π^0 decaying within the target into two γ's from which the event start time was calculated. For the K^+ time of flight measurement the additional S8 scintillator was used with a distance of only 1.9 m to S1. The Σ^+ with a $c\tau$ of 2.4 cm couldn't be measured directly but its four-momentum was determined by a missing mass analysis.

Further hyperon channels are not feasible at COSY-11. In principle also the ($n\Lambda$) and ($n\Sigma^0$) system could be studied by using a deuteron target but the additional detection of the spectator proton would reduce the efficiency drastically. Also hyperon decay products could in principle be measured but the efficiency was extremely low.

In all measurements the luminosity was determined by elastic pp-scattering detected in parallel to the hyperon production. For the detection of the second proton a Si-pad detector combined with a scintillator ($Si_{mon}/S4$ in fig. 1) was installed. For studies with a polarized beam the polarization has to be determined. Two detection systems served for this aim: In addition to the COSY polarimeter a pair of wire chambers and scintillators were installed above and below the beam close to the target to measure the elastic pp-scattering at $\phi = 90°$ which is independent of the polarisation.

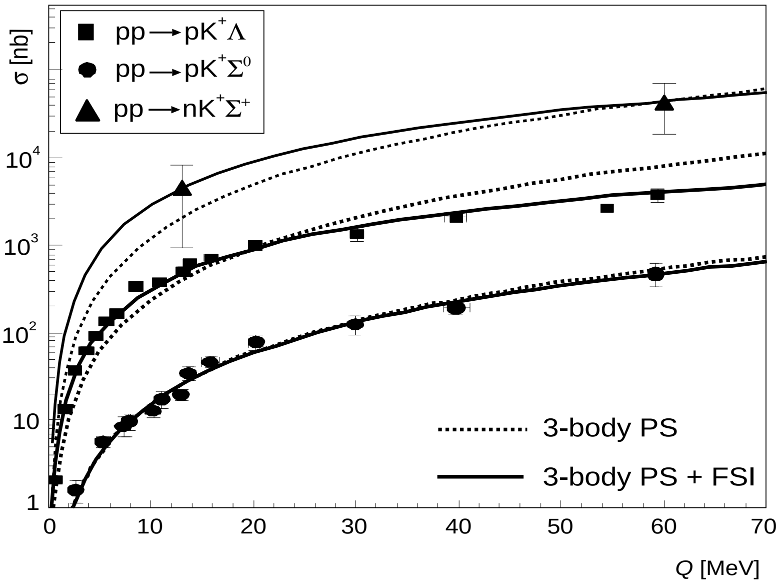

FIGURE 3. The $pp \to pK^+\Lambda$, $pp \to pK^+\Sigma^0$ and $pp \to nK^+\Sigma^+$ cross sections as a function of the excess energy Q [11, 12, 13, 31]. The lines show the calculations corresponding to 3-body phase space with (solid line) and without (dashed line) final state interaction.

EXPERIMENTAL RESULTS

When COSY-11 went into operation in 1996 no data were available for Λ and Σ hyperon production close to the reaction threshold. For the reaction channel $pp \to pK^+\Lambda$ above 300 MeV/c excess energy data were existing mostly from bubble chamber measurements at CERN [7]. On the theoretical side parametrizations of the excitation function were on the market which differ close to threshold by several orders of magnitude [8, 9]. For the Σ production the situation was similar, there were no data available below a few hundred MeV excess energy.

The first hyperon production studies at COSY-11 were performed for the Λ channel. The excitation function for the $pp \to pK^+\Lambda$ reaction was measured in several beam times for excess energies between 0.7 MeV and 90 MeV [10, 11, 12, 13]. Compared to the parametrization of [8, 9] the data differ by more than an order of magnitude but with the COSY activities in the hyperon channel several theory groups were triggered to develop improved models which describe the data much better [14, 15, 16, 17, 18, 19]. In fig. 3 the threshold data are shown in a linear excess energy scale including the expected phase space behavior with and without NY-FSI adjusted to the data. It is clearly seen that close to threshold a pure 3-body phase space description is insufficient for the case of the Λ hyperon production. The final state interaction between proton and Λ has to be taken into account. To include FSI the Fäldt-Wilkin parametrization has been used [17, 20].

Similar data were taken for the Σ^0 production channel $pp \to pK^+\Sigma^0$ [12, 13]. In a first study for excess energies around 15 MeV the obtained results (fig. 4) show the remarkable feature that the cross section ratio $\sigma_\Lambda/\sigma_{\Sigma^0}$ gives a factor of 28 instead of

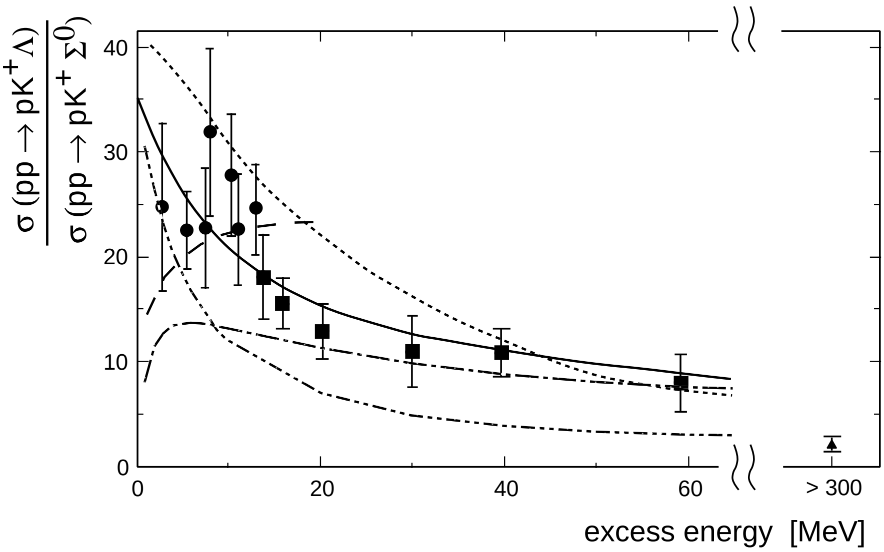

FIGURE 4. Cross section ratio for Σ^0 and Λ production in the threshold region compared to different model predictions. The data are from COSY-11 (solid circles [12], solid squares [13]) and a mean value from [7] (solid triangle). The curves represent calculations within different models, π and K exchange with destructive interference [22] (dashed line), incoherent π and K exchange [23] (dashed-dotted), meson exchange with intermediate N^* excitation [23, 19] (dashed-double-dotted) and effective Lagrangian approach including N^* excitation [24, 25] (dotted line). The solid line is the ratio of the phase space behavior including Λp FSI.

$\sim$ 2.5 known from high energy data above 300 MeV excess energy expected from isospin relations. The first step to understand this behavior was the extension to higher excess energies to see the transition from this unexpected high ratio to the value of 2.5.

In order to reduce systematical errors further data were taken in the supercycle mode of COSY operation which allows to switch the beam momentum betweeen two successive COSY cycles. One cycle for Λ production was followed by a few cycles for Σ^0 production at the same excess energy. The data are also given in fig.3.

In the Σ^0 case there is no need for any FSI, an inclusion of (pΣ) FSI doesn't give any improvement of the χ^2 in the fit. The difference between the (pΣ) and (pΛ) system is best seen in the cross section ratio which is shown in fig. 4. The cross section ratio $\sigma_\Lambda/\sigma_{\Sigma^0}$ goes smoothly down to the low energy value.

The question arises whether the whole enhancement in the Λ channel is due to the strong (pΛ) FSI as proposed by [21] or the production process itself gives some enhancement for the Λ channel. If its a pure FSI effect why is the (pΛ) so much larger than the (pΣ) FSI? When the first data on the cross section ratio were published several theory groups tried to describe the data in different models: coherent or incoherent π and K exchange or in addition an intermediate resonance excitation. Most of them indeed show a trend of increasing ratio towards the threshold, see fig. 4, but there is no clear preference of any description suggested.

More data are needed to understand the hyperon production process as for instance data in other isospin channels. To illustrate this lets consider a specific model. In the Jülich model [22] the $pp \to pK^+\Lambda/\Sigma^0$ reactions are described by only pion and kaon exchange where a reduction of the Σ^0 cross section results from a destructive interference of the pion and kaon amplitudes. Calculations for the $pp \rightarrow nK^+\Sigma^+$ channel within this model show a big difference between a destructive ($\sigma_{pp\rightarrow nK^+\Sigma^+}/\sigma_{pp\rightarrow pK^+\Sigma^0} = 3.1$) and a constructive ($\sigma_{pp\rightarrow nK^+\Sigma^+}/\sigma_{pp\rightarrow pK^+\Sigma^0} = 0.34$) interference. A similar high sensitivity is expected also in other models which include nucleon resonances.

Therefore the study was extended to the Σ^+ production in order to disentangle the different production mechanisms [26]. From the experimental point of view a clean separation of the $pp \rightarrow nK^+\Sigma^+$ channel was difficult due to the high background level which resulted in large error bars for the cross section determination. However, in spite of the large errors the measured cross sections exceed the highest predictions from models [22, 23, 19, 27] by at least an order of magnitude. The data points are shown in fig. 3. This interesting but not yet understood result confirms the need for more data in the hyperon sector.

As mentioned in the introduction the three body final state allows to study within some approximation the individual two body subsystems. This was done by a Dalitz plot analysis of the COSY-11 Λ production data in order to extract the Λ-p scattering length [28]. Within such an analysis with unpolarized beam and target it is not possible to separate the spin singlet and spin triplet components of the scattering length. Only spin averaged values for scattering length $\bar{a}$ and effective range $\bar{r_0}$ could be determined with values of $\bar{a} = -2.0\,fm$, $\bar{r_0} = 1.0\,fm$. The analysis was done in an effective range expansion which, however, is only applicable for systems where the scattering length is significantly larger than the effective range. Furthermore the procedure exhibits strong correlations between the effective range parameters a and r that can only be disentangled by including ΛN elastic cross sections data.

A new method to determine the scattering length was developed by the Jülich theory group which is based on a dispersion relation technique [29, 30]. The advantage of the technique is that the error in the relation between scattering length and experimental observable due to the derivation in the model is well under control and is below 0.2 fm. Furthermore observables have been derived where spin singlet ($(1+A_{xx}+A_{yy}+A_{zz})\cdot\sigma_{\Theta(K)=90^\circ}$) and spin triplet ($A_{0y}\cdot\sigma_{\Theta(K)=90^\circ}$) contributions are separated. The measurement of a separate spin singlet contribution requires all spin correlation coefficients (A_{ii}), i.e. polarized beam and polarized target, but for the spin triplet component the asymmetry A_{0y} is sufficient if a special kinematic condition, kaon emission around 90 deg. is selected.

In order to extract the spin triplet scattering length of the Λp system a measurement with polarized beam has been performed at COSY-11. The experiment aimed for a precision of the scattering length in the same order as the theoretical uncertainty of about 0.2 fm. The error is given by the statistical uncertainty and by the size of the asymmetry which is not known in this excess energy region.

From first results of the analysis the asymmetry seems to be rather small which would result in large errors on the scattering length but the data evaluation is still going on and final results have to be awaiten.

Besides COSY-11 also other COSY experiments studied hyperon production. The TOF collaboration uses a large acceptance non magnetic detection system with a decay spectrometer for the delayed strange particle decays resulting in a high selectivity for the hyperon reaction channels. Various reactions were studied like $pp \to pK^+\Lambda$ [31, 32], $pp \to pK^+\Sigma^0$, $pp \to pK^0\Sigma^+$ [33], and $pp \to nK^+\Sigma^+$ but at somewhat higher excess energies than COSY-11. For the $pp \to pK^+\Lambda$ reaction channel at excess energies of 85, 115 and 171 MeV Dalitz plot analyses have been performed which show clearly the excitation of nucleon resonances contributing to the production process [32]. But to what extent the resonance excitation contributs to the COSY-11 data close to threshold is not clear. At the BIG KARL magnetic spectrometer an inclusive measurement of $pp \to pK^+\Lambda$ reaction was done by detecting the kaon with high momentum resolution in order to determine the $p\Lambda$ scattering parameters. The analysis gives constrains on the singlet and triplet scattering length where $|a_s| > |a_t|$ [34] but to separate singlet and triplet contribution measurements with polarized beam and target are needed. Furthermore at ANKE, an internal magnetic spectrometer, hyperon production studies have started. The kaon detection is done by measuring the delayed decay of stopped kaons which gives a very high selectivity for kaons. Data of the $pp \to nK^+\Sigma^+$ reaction have been taken at 93 and 128 MeV excess energy which don't show such a high cross section as the COSY-11 data at lower excess energies but are consistent with model predictions [35]. These studies will be continued at lower excess energies [36].

CONCLUSION

The hyperon production studies of the COSY-11 collaboration resulted in precise cross section data of the reaction channels $pp \to pK^+\Lambda$ and $pp \to pK^+\Sigma^0$ from the production threshold up to about 90 MeV excess energy where no data were available at all. These cross section data are important ingrediants for calculations in different fields like heavy ion collision studies, hypernuclei production or neutron star formation.

The excitation functions allowed to extract the NY final state interaction which is related to the NY interaction strength parameterized by the scattering length. Models of the hyperon-nucleon scattering mostly rely on SU(3) symmetry relations for the coupling constants and fit the model to the data. There is need for an improved data base in this strangeness sector for a better understanding of the strong interaction in this domain of non perturbative QCD.

For the $p\Lambda$ system a strong $p\Lambda$ FSI is clearly seen whereas the $p\Sigma^0$ seems to show no FSI although the quark content of both systems is the same. But for a clear picture also the other Σ isospin channels have to be studied. A first attempt has been done with the measurement of the $pp \to nK^+\Sigma^+$ reaction cross sections which exceed largely the model predictions. The large error bars indicate somehow the limit of the COSY-11 facility for these studies. An improved detection technique has to be applied for further investigations.

Studies of the hyperon channels have to be continued. There are still many open questions and more differential observables including the spin and isospin degrees of freedom are needed to disentangle the contributing production mechnisms and to improve the knowledge on the YN-interaction. At ANKE and at the TOF experiment [37] further studies are proposed and in the near future certainly also WASA at COSY will be used for such investigations. With its large solid angle coverage for charge and neutral particles in principle all hyperon channels can be studied in detail.

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