COSY Proposal and Beam Request

Study of the energy dependence of the $pn \to K^+\Lambda n$ reaction close to threshold at ANKE

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Jülich, May 2010

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Abstract

It is proposed to measure the cross section for the $pn \to K^+\Lambda n$ reaction between the Λ and Σ thresholds by studying the coincidences between a K^+ detected in the ANKE range telescopes and a spectator proton emerging from the deuterium cluster-jet target and being caught in one of the Silicon Tracking Telescopes. This will provide (a) a clear signal that the reaction has taken place on the neutron and (b) a good measurement of the pn centre-of-mass energy on an event-by-event basis. The combination of the range and tracking telescopes offers unique possibilities to do such an experiment at ANKE.

In total **four weeks of beam time** are requested to perform the first studies of Λ-hyperon production close to threshold in proton-neutron collisions. Three weeks will be spent for the primary measurement plus one more week for detailed studies of the efficiencies of the range telescopes.

1 Introduction and Motivation

There have been extensive measurements of the $pp \to K^+\Lambda p$ cross section with various degrees of sophistication at COSY. These range from the study of the single-arm K^+ detection [1], K^+p correlation studies [2], to full reconstruction of the $K^+p\,(\Lambda \to p\pi^-)$ four-body final state [3].

In contrast, very little is known experimentally about K^+ production in proton-neutron collisions. There are only a few measurements of the $pn \to K^+p\Sigma^-$ reaction channel using high energy neutron beams (lowest data point collected at 3.4 GeV) with quite a large beam momentum spread of 200 MeV/c [4,5]. At these relatively high energies, the total cross section for $pp \to K^+p\Lambda$ is only a factor two higher then that for $pn \to K^+n\Sigma^-$. We have not found any information regarding measurements of the $pn \to K^+n\Lambda$ reaction channel in the literature.

There have been several experimental attempts to deduce the difference between K^+ production on the proton and neutron by using different nuclear targets and beams. In Ref. [6] a value of $\sigma_{pp}/\sigma_{pn} = 0.2 \pm 0.3$ was obtained with a 3 GeV proton beam colliding with different nuclear targets. Comparison of the K^+ production rate on a NaF target with proton and deuteron beams of energy 2.1 GeV/A lead to a ratio $\sigma(d\,\mathrm{NaF} \to KX)/\sigma(p\,\mathrm{NaF} \to KX) = 1.3 \pm 0.2$ [7]. The ratio of K^+ double-differential cross sections measured on carbon and hydrogen targets at 2.5 GeV led to the conclusion that $\sigma(pn \to K^+X) \approx \sigma(pp \to K^+X)$ [8]. An analysis of the K^+ double-differential cross section measured with a 2.02 GeV proton beam incident on a deuterium target gave a model-dependent estimate of $\sigma(pp \to K^+X)/\sigma(pn \to K^+X) \approx 0.25$ [9].

More reliable estimates of the $\sigma(pp \to K^+X)/\sigma(pn \to K^+X)$ ratio can be obtained by using data collected within the same experiment on hydrogen and deuterium targets [10]. At energies around 2.65 GeV, where the cross sections vary smoothly, the comparison of K^+ production in pd and pp reactions suggests that the rates for proton and neutron targets are broadly similar. At these energies, however, the data contain contributions from the production of the Σ and heavier hyperons in addition to the Λ. On the other hand, it is very difficult to use this method in the region that is close to the Λ threshold because the cross section then varies extremely fast with excess energy and the smearing due to the Fermi motion in the deuterium target removes most of the sensitivity in the comparison. As a consequence, in order to determine the Λ production cross section in proton-neutron collisions with a deuterium target, it will be necessary to measure the "spectator" proton p_{sp} in coincidence with other final particles. This is possible at ANKE, where dedicated silicon tracking telescopes (STT) have been constructed for this purpose and used successfully in experiments [11].

Theoretical models of the $pp \to K^+\Lambda p$ reaction are uncertain to the extent that there is not even agreement whether the production process is driven more by the exchange of strange or non-strange mesons and no solid conclusions can be drawn on this from the existing experimental pp data. The interpretation of experimental results collected by the COSY-TOF collaboration suggests the dominance of π exchange [3] while measurements of spin-transfer parameter D_{NN}

performed by the DISTO collaboration indicate that K-meson exchange is more important [12].

An analysis of the Λ production close to threshold was carried out within a model where only π and ρ exchange were considered [13]. The ratio of $K^+\Lambda$ production in pn collisions to that in pp varied significantly with the relative strengths of the ρ- to π-exchange contributions and values between ≈ 0.3 and 5 were allowed. The resonance model of Ref. [14] predicts that Λ production on the neutron is factor of two stronger than on proton. An effective Lagrangian model suggests that the ratio of $pn \to K^+n\Lambda$ to $pp \to K^+p\Lambda$ can be around 2.4 at ≈ 2 GeV [15]. Independent of any particular calculation, it is evident that the combination of pn and pp data would constrain greatly the theoretical models.

2 Experimental techniques

The ANKE spectrometer is very well suited for the proposed measurements. In the region below the ΣN thresholds, a well identified K^+ would be a signal for Λ production. Our aim therefore is to measure the production on the neutron in a deuterium target, by detecting a spectator proton in coincidence with a K^+, *i.e.* study the $pd \to p_{\rm sp}K^+X$ reaction.

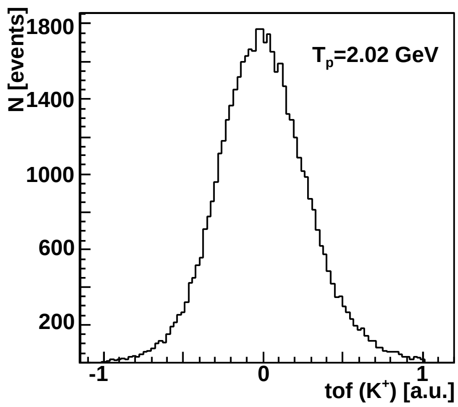

Figure 1: The K^+ time-of-flight spectra measured with delayed-veto for a 2.020 GeV proton beam incident on a deuterium target.

One of the primary aims when designing ANKE [16] was the measurement of the double-differential cross sections for subthreshold K^+ production on nuclear targets [17]. For this purpose the ANKE magnetic spectrometer is equipped with fifteen K^+ range telescopes which allow K^+ identification even when the background from protons or π^+ is 10^5 times higher [18]. By using the delayed-veto technique, K^+ mesons can be reliably identified from the threshold of Λ production while measurements below the threshold should give an estimate of a possible background in the spectra obtained at small positive values of excess energies. In Fig. 1 K^+ time-of-flight (TOF) spectra measured in pd collisions at 2.02 GeV and integrated over all the telescopes are presented. The moderate background under the K^+ peak (less then 5%) can be further subtracted from TOF spectra measured in an individual telescope.

Use of the delayed-veto technique requires a dedicated measurement to be undertaken with a hydrogen target in order to determine accurately the telescope efficiency. Due to the relatively low count rates expected for $K^+p\pi^-$ correlation, it is not possible to combine together measurements of the reaction of interest with those of the efficiency determination. Clearly, any uncertainties in the telescope efficiencies reflect directly on the resulting cross section determination.

The deuterium cluster-jet target [19] and two (left and right) ANKE spectator telescopes [20] will be used in the experiment. The detection of the spectator proton in the $pd \to p_{\rm sp}K^+\Lambda n$ reaction serves two purposes. It firstly ensures that, to a good approximation, the reaction took place on the neutron, which means that one does not have to attempt a subtraction of proton data that had been obtained in a separate experiment. In addition, it is important to note that the pn centre-of-mass energy, and hence the excitation energy Q of the reaction, is fixed completely by the measurement of the angle and momentum of the spectator proton. Although the current equipment would allow a resolution in Q of a few MeV, the statistics obtained in an experiment might result in the need to use a bigger bin size. A spectator detection system configuration similar to one employed in Exp. #175 will be used for proposed measurements.

In order to extract the total cross section for the K^+ production reaction, two methods of normalisation will be used. Identification of pd elastic events, using a dedicated prescaled trigger, will be used as a monitor throughout all the experiment, and Schottky measurements [21]. This latter method, recently established at COSY, provides a continuous measurement of beam energy loss. Combined with accurate measurements of the momentum compaction factor, this then allows a determination of the luminosity to be made with a precision of better then 5%, which is not possible using only pd elastic scattering data.

3 Simulations

Count rate estimations based on the AnkeGeant4 simulation package have been carried out [22]. A luminosity of 5×10^{30}, similar to the one that was available during the run of Exp. #175 [11], was used in the simulations. Realistic values for the range telescope efficiencies (varying from 30% to 10%, depending upon telescope number), MWPC (90%) and spectator (90%) were assumed. The probability for K^+ decay in flight was taken in to account using standard GEANT4 procedures. In the absence of other information, it was assumed for the count rate estimates that $\sigma(pp \to K^+p\Lambda) = \sigma(pn \to K^+n\Lambda)$ at the same excess energy. The parameterisation of the energy dependence of the $\sigma(pp \to K^+p\Lambda)$ total cross section was given in Ref. [23]. The $n\Lambda$ final state interaction has been taken in to account using a Jost function:

$$| FSI |^2 = \frac{q_{\Lambda n}^2 + \beta^2}{q_{\Lambda n}^2 + \alpha^2}, \qquad (3.1)$$

where $q_{\Lambda n}$ is the relative momentum in the Λn system. The spin-averaged parameters $\alpha = -70$ MeV/c and $\beta = 200$ MeV/c are similar to the those quoted in Ref. [1]. Regarding this latter point, production on the neutron and proton might lead to different populations of spin-triplet and -singlet $n\Lambda$ and $p\Lambda$ pairs and hence, in principle, to different FSI effects.

Figure 2a) presents estimations of the probability to have sufficient energy to produce the $K^+n\Lambda$ system in the final state for a proton beam energy of $T_p = 1.775$ GeV. The energy/angular acceptance of the spectator detection system is shown in Fig. 2b) as a black rectangle and indicated in Fig. 2a) by blue and grey areas. The energy of the measurements is chosen so as to have optimal acceptance for spectator particles in a region of relatively high Λ production cross section.

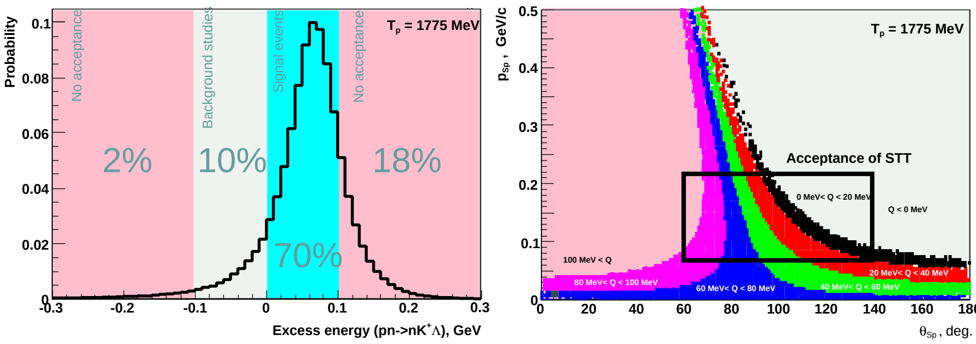

Figure 2: Simulations for the excess energy distributions of the $pn \to K^+n\Lambda$ reaction in pd interactions at a proton beam energy of $T_p = 1.775$ GeV. (a) Probability distribution for having a particular excess energy in quasi-free pn interaction. Regions of ANKE spectator detector acceptance are shown by grey and blue areas. (b) Spectator momentum *versus* spectator angle $\theta_{\rm sp}$. The ANKE spectator acceptance is shown by the black rectangle. Regions associated with different Q bins for the $nK\Lambda$ final state are shown by different colours.

Only a small fraction of $K^+n\Lambda$ events cannot be detected in such a configuration of the system. Events associated with negative Q, which comprise 12% of the total distribution, will be used for background studies. The distribution of a possible spectator momentum $p_{\rm sp}$ as a function of its angle $\theta_{\rm sp}$ in Fig. 2b) shows that little improvement in spectator acceptance could be achieved by changing the detector position. In any case it is hardly possible to move spectator detector further into the forward hemisphere owing to the extremely high count rates from pd elastic scattering in this region of acceptance.

Detection of K^+ in the ANKE range telescopes places some limitations on the total $pn \to K^+n\Lambda$ phase space that can be covered, as shown in Fig. 3. However, the aim of our measurements is the study of Λ production close to threshold, where the ANKE acceptance from the two detection systems (indicated by rectangles in Fig. 3) is relatively high. In Fig. 3a) and b) the angular and momentum acceptances for the ANKE detection systems are shown as functions of Q. The values of the total acceptance, calculated using the ANKE model, efficiencies and luminosity, lead to the expected number of counts from three

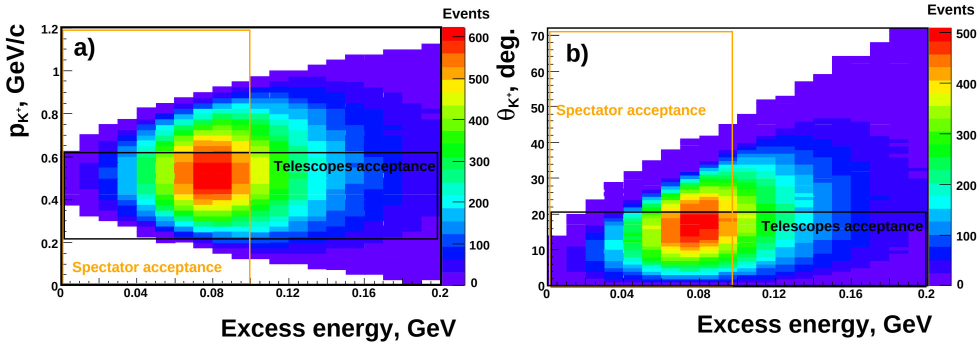

Figure 3: Phase-space simulations for the $pn \to K^+ n\Lambda$ reaction as a function of excess energy Q. Shown are (a) the kaon momentum p_{K^+}, and (b) its angle θ_{K^+}. Regions covered by range telescopes (black rectangle) and spectator detector (yellow rectangle) are indicated.

weeks of measurements at 1.775 GeV shown in Fig. 4.

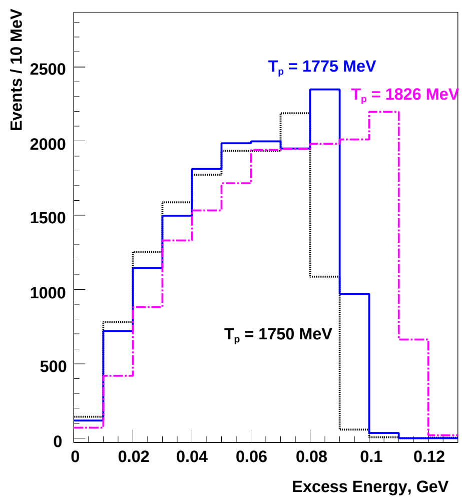

Figure 4: Counts expected after three weeks of measurements at $T_p = 1.750$, 1.775 and 1.826 GeV, as a function of Q.

For comparison, the counts expected at slightly lower and higher energies are shown in same figure. It is clear from these that an increase in the beam energy extends the range of excess energies covered but reduces slightly the numbers of events in the lowest excess energy bins and *vice-versa*. The systematic error in the $pn \to K^+ n\Lambda$ total cross section determination due to the reaction model is estimated to be of the order of 10%. Experimental data accumulated during this beam time should make it possible to control the parameters of the $n\Lambda$ FSI and hopefully to reduce the systematic errors in the Λ total cross section determination.

Figure 5a) shows a simulation for the missing mass of the detected K^+ integrated from 60 to 80 MeV in excess energy. The solid line corresponds to phase

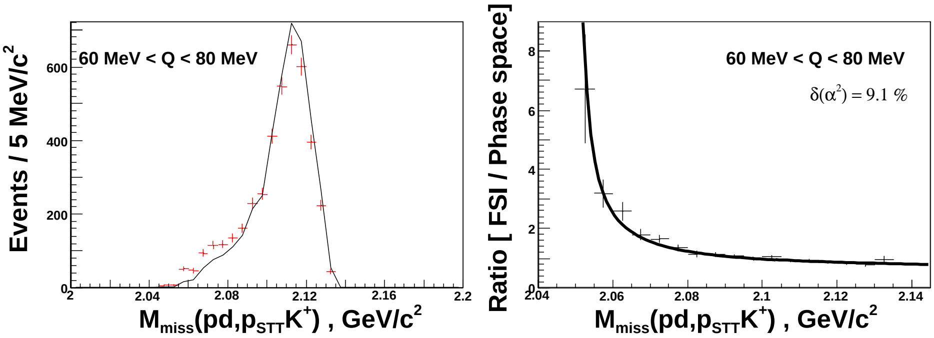

Figure 5: Studies of the $n\Lambda$ final-state interaction using data integrated over the range $60 < Q < 80$ MeV. Error bars on the points indicate the statistical accuracy expected after three weeks of beam time. (a) Missing mass of the K^+ compared to phase space. The parameters of the $n\Lambda$ FSI are taken to be equal to those of $p\Lambda$ FSI. (b) Ratio of phase space to the phase space modified by the $n\Lambda$ FSI for events that fall inside the ANKE acceptance. The error in the determination of the FSI parameter of Eq. (3.1) $\delta(\alpha^2)$ due to the the statistical accuracy is indicated.

simulations while the dots with error bars indicate the statistical precision expected after three weeks of measurements. The ratio of phase-space simulations to the model that takes into account the $n\Lambda$ FSI is shown by dots with error bars in Fig. 5b). The fit of this ratio with the parameterisation of the FSI used leads to a 6% statistical error in the α^2 parameter of Eq. (3.1). The same kind of analysis will be done in every Q bin, thus increasing the statistical accuracy of the α^2 determination.

The systematic error in the α^2 value will mostly depend on the precision in the determination of the range telescope efficiencies. For this reason it is absolutely necessary to perform careful measurements of these efficiencies using a hydrogen target. In one week of beam time, careful adjustment of the delayed-veto trigger has to be done and statistics must be accumulated that are sufficient to study the efficiency across each telescope. Such a very detailed calibration of the telescopes has never been done before and so it is hard to estimate the resulting uncertainties.

K^+p correlations are usually used to measure the telescope efficiency. In this method the efficiency is determined telescope-by-telescope by the ratio of the number of K^+p correlations detected with and without the delayed-veto criterion. When the delayed veto is not used, the signal in the time-of-flight spectrum sits on a 20-30% coincidence background, which is subtracted during the analysis. The efficiency varies with telescope number, changing from ≈ 25 % in telescopes 3-6 to only ≈ 10 % for telescopes 7-15. From Fig. 3 it is clear that it is extremely important to fix well the efficiencies in numbers 7-15 since these telescopes contribute to the errors in the final result for the lowest excess energies, where the results are much less model dependent.

The number of K^+p coincidences expected per day with and without the

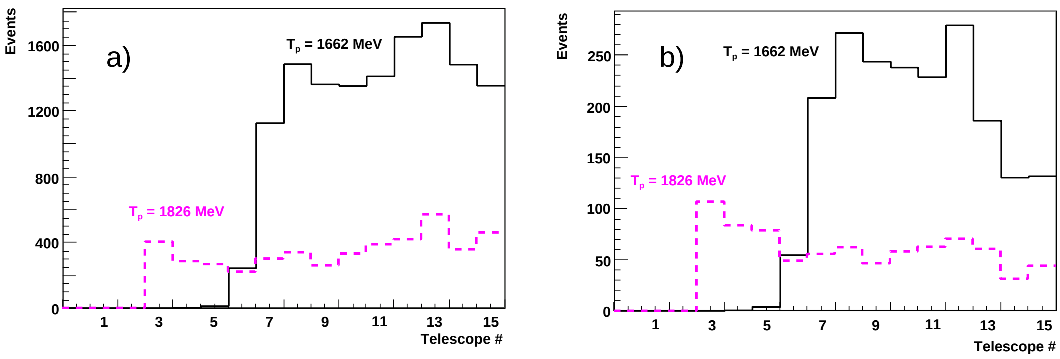

Figure 6: Number of K^+p coincidences per telescope from the $pp \to K^+p\Lambda$ reaction after one day of beam time estimated for $T_p = 1.662$ and 1.826 GeV. The two panels represent (a) simple K^+p correlations, and (b) K^+p correlations including the delayed-veto criterion.

delayed veto and hydrogen target is presented in Fig. 6. For this estimation a luminosity of 1×10^{31}, similar to that available during the Σ^+ production experiment [24], has been used. The rate of K^+p coincidences at 1.662 GeV should be factor 3.5 higher than at 1.826 GeV while, for kinematic reasons, there are no kaons in telescopes 3-6. For this reason we propose to use these two energies for efficiency studies. One week of measurements with a hydrogen target, including one day to change the target from hydrogen to deuterium, should yield a precision in telescope efficiency determination of better then 5%.

4 Beam-time request

In total we request **four weeks** of beam time for studies of $pn \to K^+n\Lambda$ production close to threshold. It comprises of:

- One week with a hydrogen target for telescope efficiency determination, trigger and spectator detectors adjustment.
- Three weeks with a deuterium target for studies of the $pn \to K^+n\Lambda$ reaction.

Spectator detector, which is crucial for the proposed measurements, is very sensitive to the quality of the beam. Since three different COSY beam energies (1.662, 1.775 and 1.826 GeV) need to be prepared for this experiment, it is therefore highly desirable to have a full machine development week before the experiment.

These would be the first measurements of hyperon production on the neutron in the threshold region. The statistics obtained should lead to the determination of the total Λ production cross section with a precision of better than 15%.

References

[1] A. Budzanowski *et al.*, Phys. Lett. B **687** (2010) 31.

[2] P. Kowina *et al.*, Eur. Phys. J. A **22** (2004) 293.

[3] S. Abd El-Samad *et al.*, Phys. Lett. B **688** (2010) 142.

[4] R. E. Ansorge *et al.*, Nucl. Phys. B **60** (1973) 157.

[5] R. E. Ansorge *et al.*, Phys. Rev. D **10** (1974) 32.

[6] D. Berkley and G. B. Collins, Phys. Rev. **112** (1958) 614.

[7] S. Schnetzer *et al.*, Phys. Rev. C **40** (1989) 640.

[8] M. Debowski *et al.*, Z. Phys. A **356** (1996) 313.

[9] M. Buscher *et al.*, Eur. Phys. J. A **22** (2004) 364.

[10] Yu. Valdau *et al.*, in preparation.

[11] S. Barsov and R. Schleihert, COSY Proposal #**175** (2007).

[12] F. Balestra *et al.*, Phys. Rev. Lett. **83** (1999) 1534.

[13] G. Fäldt and C. Wilkin, Eur. Phys. A **24** (2005) 431.

[14] K. Tsushima, A. Sibirtsev, A. W. Thomas and G. Q. Li, Phys. Rev. C **59** (2000) 369.

[15] R. Shyam, Phys. Rev. C **73** (2006) 0035211.

[16] S. Barsov *et al.*, Nucl. Instr. Methods A **462** (2001) 364.

[17] V. Koptev *et al.*, Phys. Rev. Lett. **87** (2001) 022301.

[18] M. Büscher *et al.*, Nucl. Instr. Methods A **481** (2002) 378.

[19] A. Khoukaz *et al.*, Eur. Phys. J. D **5** (1999) 275.

[20] I. Lehmann *et al.*, Nucl. Instr. Methods A **530** (2004) 275.

[21] H. J. Stein *et al.*, Phys. Rev. ST Accel. Beams **11** (2008) 052801.

[22] S. Agostinelli *et al.*, Nucl. Instr. Methods A **506** (2003) 250; http://geant4.web.cern.ch/geant4.

[23] A. Sibirtsev, J. Haidenbauer, H.–W. Hammer and S. Krewald, Eur. Phys. J. A **27** (2006) 269.

[24] Yu. Valdau *et al.*, Phys. Rev. C **81** (2010) 045208.