COSY Proposal and Beam Request

The separation of spin-singlet and triplet Λp amplitudes and final state interactions through the measurement of the spin correlation in the $\vec{p}\vec{p} \to K^+\Lambda p$ reaction at ANKE

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Abstract

Although there have been many measurements of hyperon production in the $pp \to K^+\Lambda p$ reaction by different groups at COSY, there has been no attempt to identify separately the production of spin-singlet and -triplet Λp final states. This leaves too much ambiguity in the theoretical modelling. One cannot, for example, hope to describe reliably the cusp structure seen in the $pp \to K^+\Lambda p$ data at the ΣN threshold without knowing what fraction of the "normal" production is in the spin-singlet state.

On the other hand, the level structure of the ${}^4_\Lambda$He hypernucleus suggests that the spin-singlet S-wave ΛN interaction is stronger than the singlet but no direct measurements exist to check this directly in the two-nucleon sector.

Both of these problems can be investigated through the determination of the transverse spin-correlation parameter C_{NN} in the $\vec{p}\vec{p} \to K^+\Lambda p$ reaction. The spin dependence of the production ratio is fixed mainly by the average value of C_{NN} but an investigation of the spin dependence of the ΛN force requires a more careful study of this parameter as a function of the K^+ momentum in the region of the Λp final state interaction peak.

A measurement of C_{NN} is possible at ANKE by using a combination of the polarised proton beam and the polarised hydrogen gas cell target, fed from the atomic beam source. The collaboration has considerable experience in detecting K^+ mesons by looking at K^+p correlations originating from a "point" target. It is important to note here that below the threshold for Σ production the observation of a kaon must be associated with Λ production.

However, the expected counting rates are only "modest" and the thickness of the polarised cell target must be maximised and the background arising mainly from the cell walls minimised in order to achieve a satisfactory result. This is possible if the beam profile is tightly controlled and a reliable but narrow "openable" gas cell is used as the target.

Although the total time required to obtain the requisite data may be of the order of ten weeks, one week is requested here to carry out storage cell optimisation studies and investigate the backgrounds in order to identify the best experimental conditions and demonstrate the feasibility of the full C_{NN} measurements.

1 Introduction

The mere existence of hypernuclei shows that the S-wave interaction between a Λ and a nucleon must be attractive but not sufficiently attractive so as to bind the Λp system. Much information on the ΛN force has been obtained through the study of binding energies of hypernuclei [1]. In particular, the ≈ 1.1 MeV separation between the 0^+ and 1^+ states in $^4_\Lambda$H [2, 3] suggests that the spin-singlet force is more attractive than the triplet. More direct information can be derived from measurements of the low energy Λp total elastic cross section [4] though these are, of course, spin-averaged data.

An alternative approach is to study the Λp system through a final state interaction (FSI) and a clear example of this was the measurement of the $K^-d \to \pi^-(\Lambda p)$ reaction with stopping kaons [5]. The initial state is $J^p = 1^-$ and parity and angular momentum forbid this to be coupled to a final 0^-0^+ pair, no matter what the relative angular momentum is between the π^- and (Λp) system. The data are therefore sensitive to the Λp S-wave spin-triplet FSI. One possible concern though is that the produced pion is strongly interacting and this could distort the simple FSI picture.

This distortion concern should be far less marked for the $pp \to K^+\Lambda p$ reaction because the interaction of the kaon with the proton is quite weak, though the $K^+\Lambda$ system seems to be closely related to certain nucleon isobars, in particular the $S_{11}(1670)$ [6]. The effects of the Λp final state interactions were studied in this reaction at Saclay [7] and more recently by the HIRES collaboration working at COSY [8]. By using the Big Karl spectrograph, very good resolution was obtained on the momentum of the K^+ emerging in the forward direction and this translated into one on the excitation energy in the unobserved Λp system. By fitting together all the available data on Λp elastic scattering and the final state effects in both the $K^-d \to \pi^-(\Lambda p)$ and $pp \to K^+\Lambda p$ reactions, it was claimed that the FSI could be separated in the spin-singlet and -triplet Λp states [8]. They found that the positions of the poles were at energies $\varepsilon_s = 3.6$ MeV and $\varepsilon_t = 5.4$ MeV. Since the Λp system is not bound, these are the positions of virtual states (like that of the singlet pp system rather than the bound deuteron). This means that the singlet is closer to being bound than the triplet and so this agrees well with the sign of the difference in binding energies between the ground and first excited state of $^4_\Lambda$He [2, 3].

The seemingly satisfactory result might be called into question because the combined fit requires the Λp final state in the $pp \to K^+\Lambda p$ reaction to be purely singlet! This seems to be unlikely in a single (non-strange) meson exchange model and so one is tempted to look for other methods to investigate this interesting problem. It has been shown that the variation of the analysing power in the $\vec{p}p \to K^+\Lambda p$ reaction at $\theta_K^{cm} = 90^\circ$ as a function of the Λp invariant mass is sensitive to the spin-triplet FSI [9] and such an approach has been proposed at COSY [10]. Unfortunately, the analysing power in the reaction seems to be quite low at COSY energies and so it is doubtful whether this approach could achieve the necessary counting rates.

The situation might be more promising for double-polarised experiments, where the $\vec{p}\vec{p} \to K^+\Lambda p$ contains useful spin-dependent information even for purely S-wave final states [11, 12]. In the low energy region the ratio of the production of spin-singlet and -triplet Λp pairs is determined completely by a measurement of C_{NN}. [At higher energies the spin-triplet Λp system can be isolated purely through a measurement of the transverse spin correlation for forward-going K^+.] The advantage of this approach is that the two spin states are looked at in the same reaction rather than through a comparison of three or more different reactions. Systematic uncertainties are therefore much reduced.

2 Physics motivation

In the near-threshold region it is plausible to assume that final S-waves dominate the $pN \to K^+\Lambda N$ reaction and this seems to be consistent with the bulk of the data measured in pp collisions. The most general structure of the isospin triplet and singlet amplitudes in this limit has already been derived [13]:

$$\mathcal{M}_1 = \left[W_{1,s}\,\eta_f^\dagger\,\hat{\boldsymbol{p}}\cdot\boldsymbol{\epsilon}_i + iW_{1,t}\,\hat{\boldsymbol{p}}\cdot(\boldsymbol{\epsilon}_i\times\boldsymbol{\epsilon}_f^\dagger)\right]\boldsymbol{\chi}_f^\dagger\cdot\boldsymbol{\chi}_i\,,$$
$$\mathcal{M}_0 = W_{0,t}\,\hat{\boldsymbol{p}}\cdot\boldsymbol{\epsilon}_f^\dagger\,\eta_i\,\phi_f^\dagger\,\phi_i\,, \tag{2.1}$$

where $\boldsymbol{p}$ is the incident cm beam momentum. The initial (final) baryons couple to spin-1 or spin-0, represented by $\boldsymbol{\epsilon}_i$ ($\boldsymbol{\epsilon}_f$) and η_i (η_f) respectively. Similarly, the $\boldsymbol{\chi}_i$ ($\boldsymbol{\chi}_f$) and ϕ_i (ϕ_f) describe the isospin-1 and isospin-0 combinations of the initial NN (final KN) states.

The unpolarised intensities are given by

$$I_{pp} = I(pp\to K^+\Lambda p) = \tfrac{1}{4}\left(|\,W_{1,s}\,|^2 + 2\,|\,W_{1,t}\,|^2\right), \tag{2.2}$$

$$I_{pn} = I(pn\to K^+\Lambda n) = I(pn\to pK^0\Lambda) = \tfrac{1}{16}\left(|\,W_{1,s}\,|^2 + 2\,|\,W_{1,t}\,|^2 + |\,W_{0,t}\,|^2\right). \tag{2.3}$$

Close to threshold, the amplitudes $W_{i,s/t}$ should vary little, except for the different ΛN final-state interactions in the spin-singlet (s) and -triplet (t) systems, which are explicitly accounted for through the introduction of a final state interaction factor $\mathcal{Z}$. In this case the corresponding pp total cross section becomes

$$\sigma(pp\to K^+\Lambda p) = \frac{1}{64\pi^2 ps}\frac{(m_p m_\Lambda m_K)^{1/2}}{(m_p+m_\Lambda+m_K)^{1/2}}Q^2\,I(pp\to K^+\Lambda p)\,\mathcal{Z}(Q,\varepsilon)\,, \tag{2.4}$$

and similarly for the pn reaction. Here the m_i are the masses in the final state, p is the incident proton cm momentum, $\sqrt{s}$ the total cm energy, and $Q = \sqrt{s} - \sum m_i$, the excess energy.

In a very simple approximation [14], the final state interaction factor is given by

$$\mathcal{Z}(Q,\varepsilon) = \frac{4}{\left(1+\sqrt{1+Q/\varepsilon}\right)^2}\,, \tag{2.5}$$

where the energy factor ε can be different for the spin-triplet and singlet final states.

The pp transverse spin correlation, which is only non-zero for the spin-singlet final Λp state, is given by

$$I(pp\to K^+\Lambda p)\, C_{NN}(pp\to K^+\Lambda p) = \tfrac{1}{4}\,|W_{1,s}|^2\ . \tag{2.6}$$

It is important to note that

$$4I(pn\to K^+\Lambda n)\left[1+C_{NN}(pn\to K^+\Lambda n)\right] = I(pp\to K^+\Lambda p)\left[1+C_{NN}(pp\to K^+\Lambda p)\right], \tag{2.7}$$

so that, in the near-threshold region, the additional measurement of the spin correlation in np collisions would afford no further information over that given by measurements of the differential cross sections in pp and pn collisions and the spin correlation in the pp case.

The ratio of spin-triplet to -singlet production strengths is fixed completely by the value of the spin-correlation parameter:

$$\frac{[1-C_{NN}(pp\to K^+\Lambda p)]}{2C_{NN}(pp\to K^+\Lambda p)} = \frac{|\,W_{1,t}\,|^2}{|\,W_{1,s}\,|^2}\frac{\mathcal{Z}(Q,\varepsilon_t)}{\mathcal{Z}(Q,\varepsilon_s)}, \tag{2.8}$$

where, once again, we have made the FSI factors explicit. The energy dependence of this factor is therefore sensitive to the relative sizes of the ε_s and ε_t parameters. Measuring the unpolarised cross sections and the transverse spin correlation would allow us to determine uniquely the contributions of spin-triplet and -singlet Λp states to the $pp\to K^+\Lambda p$ total cross section.

Although the formulae above are only given for the total cross section, in the S-wave limit they are also valid for the differential cross sections. Hence $[1-C_{NN}]\,d\sigma(pp\to K^+\Lambda p)$ is sensitive to the spin-triplet FSI and $C_{NN}d\sigma(pp\to K^+\Lambda p)$ to the spin-singlet. If the two scattering lengths are different, this would be reflected in the variation of the cross section with the Λp invariant mass or, equivalently, with the K^+ momentum in the forward direction.

The model-dependence of the formulae given here is quite weak but, in order to get crude estimates of the effects to be expected, let us assume that the production goes through the exchange of the non-strange mesons π and ρ. In this case, the three elementary amplitudes are of the form

$$\begin{aligned} W_{1,s} &= 2\mathcal{D}_\rho - \mathcal{D}_\pi\ , \\ W_{1,t} &= \mathcal{D}_\pi\ , \\ W_{0,t} &= 6\mathcal{D}_\rho + 3\mathcal{D}_\pi\ , \end{aligned} \tag{2.9}$$

where $\mathcal{D}_\pi$ is the amplitude for π exchange and $\mathcal{D}_\rho$ the dominant vector-meson exchange term [13].

The comparison of inclusive K^+ production in proton-proton and proton-deuteron collisions [15] suggests that the cross section in the pn channel is weaker than in pp, mainly because the $I=0$ rate involves also K^0 production. It was found there that

$$\sigma_{pn}^{K^+}/\sigma_{pp}^{K^+} = 0.5\pm 0.2\,. \tag{2.10}$$

More detailed information on this ratio will be obtained when the final analysis of low energy $pd \to p_{\rm sp}K^+X$ data [16], where the spectator proton $p_{\rm sp}$ is detected in one of the Silicon Tracking Telescopes. However, the available data seem to be consistent with the theoretical estimate of $\mathcal{D}_\pi/\mathcal{D}_\rho \approx -0.9$ [13, 17]. This would, in turn, suggest that the total spin-singlet production in pp collisions is about five times stronger than that of the spin-triplet and that $C_{NN} \approx 0.84$. These are, however, very model-dependent estimates.

3 Experiment

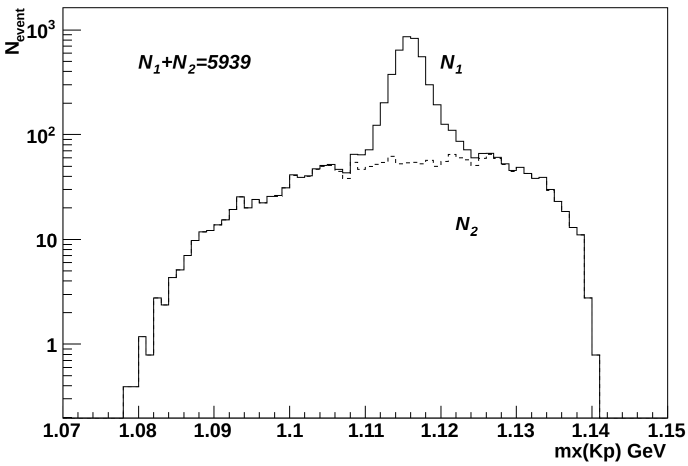

Figure 1: Simulation of the expected K^+p missing-mass spectrum for the $pp \to K^+p\Lambda$ reaction at 2.425 GeV/c for the sum of all polarisation states after ten weeks of beam time. The peak in the distribution at the Λ mass corresponds to the detection of the direct proton from the reaction (N_1), while the smooth distribution underneath arises from the Λ decay proton (N_2) detected in coincidence with the K^+ in the positive detector.

In order that the detection of a K^+ identifies uniquely the $pp \to K^+\Lambda p$ reaction, the experiment must be carried out below the threshold for Σ production. The ANKE magnetic spectrometer is in fact especially well suited for measurements close to threshold. Using a polarised proton beam from COSY in combination with the Polarised Internal gas Target (PIT), it is possible to identify completely the polarisations in the initial state and hence measure C_{NN}.

The total cross section for the $pp \to K^+\Lambda p$ reaction close to threshold is not very high ($\sim 1.7\ \mu$b), and the expected count rates will be only *moderate*. This experiment is therefore very demanding on the quality of the beam and target. In order to have reasonable count rates it is extremely important to store at least 5×10^9 polarised protons in the ring and use an openable storage cell, where it is possible to reach target thickness of the 3×10^{13} atoms/cm^2. However, it is equally

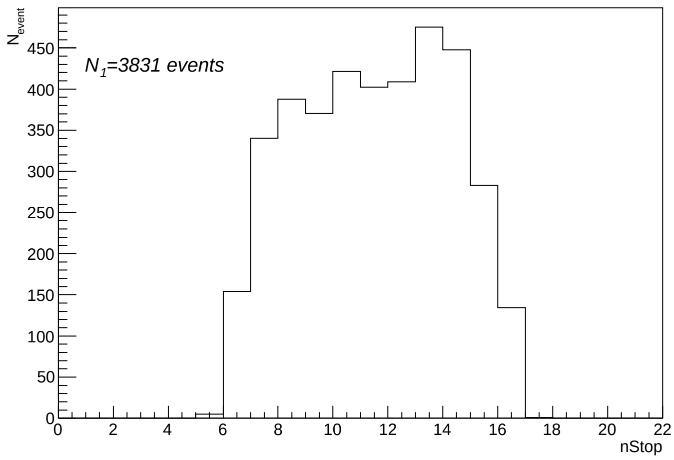

Figure 2: Expected numbers of counts for the $pp \to K^+p\Lambda$ reaction at 2.425 GeV/c for the sum of all polarisation states as a function of the stop counter number after ten weeks of beam time.

important to have stable beam conditions and high degrees of polarisation of the beam ($> 70\%$) and target ($> 80\%$) throughout the beam time.

The openable storage cell that is currently being prepared for use at ANKE is optimised for an experiment at 353 MeV [19], where the beam size will be different from that at the energy planned for this experiment, $T_p = 1.662$ GeV. It is known that the target thickness in experiments with the PIT depends strongly on the cell diameter and length. At the energy of this experiment, the beam is expected to be narrower and so it is possible to use a storage cell with a 10 mm diameter instead of the 12 mm agreed for proposal #213 [19]. This would increase the target thickness by a factor of two but such an improvement is only possible when there is real information on the beam size at the higher energy.

It is planned to use COSY stochastic cooling in order to keep the beam size under the control during the cycle and fix the momentum spread. This should allow one to avoid beam losses on the cell walls due to the beam heating caused by beam-target interactions. However, this will require additional time for setting up of COSY during the machine development.

The EDDA internal polarimeter can be used for beam polarimetry during the experiment. This will allow the measurement of the beam polarisation with a precision of better than 5%, with negligible statistical uncertainty [18]. However, a dedicated cycle with beam extraction on the EDDA solid state target would have to be prepared.

Proton-proton elastic scattering, detected in coincidence in the ANKE STT and Fd detectors, can be used for the target polarimetry. Due to the relatively low quality of the double polarised data a dedicated runs with unpolarised proton beam for determination of target polarisation should be performed during the experiment. Data on the analysing power for the pp elastic scattering for angles $4-10^\circ$ is available from the SAID data base and can be used for the polarimetry. It is therefore possible to perform target polarimetry with this method with a precision of better than 10%. However, a dedicated test run is needed in order to estimate this uncertainty more precisely and hence more reliably estimate possible systematic error in C_{NN} measurement.

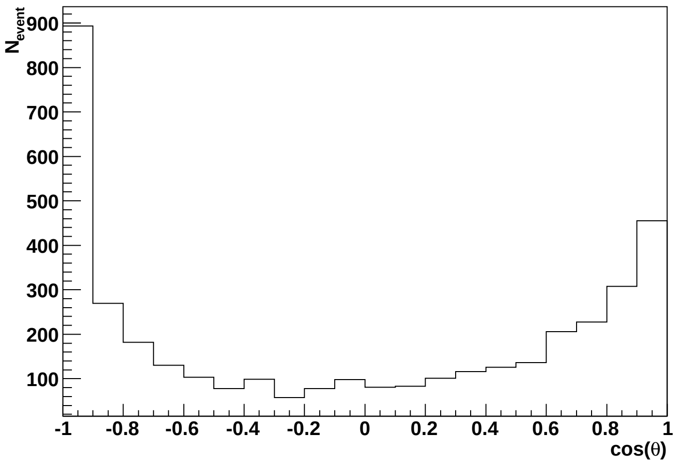

Figure 3: Expected numbers of counts for the $pp \to K^+p\Lambda$ reaction at 2.425 GeV/c for the sum of all polarisation states as a function of $\cos\theta_K$ after ten weeks of beam time.

The K^+ identification at ANKE can be done using K^+p correlations, with the detection of the kaon in the positive side detector (Pd) and the proton in the forward detector (Fd). From experiments with the cluster target, where the luminosities are a factor thirty higher, it is known that the background in the kaon time-of-flight spectra is approximately 20-30% when only two particle are detected. This background can be further reduced using cuts on the amplitudes in the counters and in the K^+p missing mass. However, it is hard to predict the amount of background in the K^+ time-of-flight and missing mass spectra coming from the storage-cell walls. We can therefore only assume at the moment that the background in every stop counter is known with a precision of $\sim 10\%$. More reliable estimates for the possible background conditions in the time-of-flight spectra are only possible on the basis of real data accumulated during a dedicated test run.

A simulation for the K^+p missing-mass spectrum expected at ANKE at a beam momentum of 2.425 GeV/c is presented in Fig. 1. In this simulation the gas distribution in the storage cell, the re-scattering effects, and the extended vertex positions are all taken in to account. The same momentum reconstruction algorithm as that to be used during a real experiment allows us to reconstruct a K^+p missing mass spectra with a clean peak from the Λ hyperon (N_1) on top of a moderate physical background (N_2) from the $\Lambda \to p\pi^-$ decay (BR = 64%). Unfortunately, it is not possible to simulate the true background conditions for an experiment with a storage cell target; such effects can only be studied under real experimental conditions.

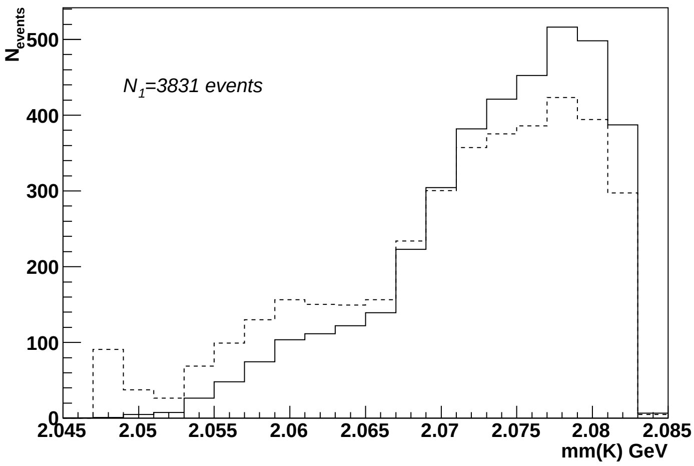

Figure 4: Simulations for the K^+ missing-mass spectrum measured at ANKE for the sum of all polarisation states after ten weeks of the beam time. The solid and dashed lines are obtained assuming phase-space and phase space corrected by the final-state interaction, with parameters taken from Ref. [8], respectively.

The background conditions in this experiment will not allow us to separate in the missing-mass spectra genuine K^+p coincidences, where the proton comes from the Λ decay, from those where the proton is produced in the cell wall. Therefore, only events with direct protons can be used in the subsequent analysis. However, the events in the kaon time-of-flight spectrum will increase the numbers in the peak in the time-of-flight spectra and can help us to understand the background better.

The numbers of counts expected after ten weeks of beam time at a proton beam momentum of 2.425 GeV/c, summed over the all polarisation states, are presented in Fig. 2 as a function of the stop counter number in Pd. The background conditions for the various stop counters and polarisation state will be different. One therefore needs at least a hundred events per stop counter per polarisation state in order to estimate reliably the background under the K^+ peak in the time-of-flight spectrum.

A variety of differential polarisation observable for the $pp \to K^+p\Lambda$ reaction can be reconstructed using data obtained from this experiment. As an example, a simulation for the K^+ angular spectra measured at ANKE after ten weeks of beam time is presented in Fig. 3. Although in this experiment the decay products of the Λ hyperon will not be identified, information about the Λ direction can be reconstructed using the four-momenta of the detected particles.

Good momentum resolution is crucial for this kind of measurement; the D2 magnet has therefore to be operated at the highest possible field strength (1.5675 T). The resolution expected in the invariant mass of the $p\Lambda$ system will be of the order of 3 MeV/c^2. The resolution in the K^+p missing-mass spectrum measured at ANKE is dominated by the resolution of the wire chambers in the positive and forward detector systems. If the background conditions are moderate, it would be possible to perform a kinematic fit, which would allow the resolution in the $p\Lambda$ system to be improved by another factor of two or three.

A simulation of the K^+ missing-mass spectrum measured with the ANKE spectrometer after ten weeks of beam time is presented in Fig. 4. The dashed line represents a phase space distribution corrected by the final state interaction using the parameters from Ref. [8]. The background conditions in individual stop counters are different. Without real experimental data obtained with the storage cell it is therefore impossible to estimate the error in C_{NN} for the every missing-mass bin and hence estimate the possible sensitivity to the relative strengths of the two $p\Lambda$ FSI.

4 Beam Request

The proposed experiment will yield the following results:

- Fix the relative strengths of the singlet and triplet production amplitudes for the $pp \to K^+p\Lambda$ reaction close-to-threshold through the measurement of C_{NN} with a precision of better than 20%.
- Measuring C_{NN} as a function of the K^+ momentum will give information on the relative strengths of the singlet and triplet $p\Lambda$ FSI, on which there is little direct information.

The total beam time needed to perform such an experiment at ANKE is **ten weeks**. However, in order to carry out storage cell optimisation studies and investigate the backgrounds, we request **one week** of beam time within the next allocation period. This test beam time with polarised beam and target should be accompanied by sufficient machine development time in order to set up the COSY stochastic cooling system and get at least 5×10^9 polarised protons through the openable ANKE storage cell.

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