COSY Proposal + Beam Request

For Lab. use

Exp. No.:	Session No.

Title of Experiment: **Investigation of Subthreshold K^+−Production Processes by Measuring K^+p and K^+d correlations**

Collaborators:	Institute:
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Is support from the LSF program of the EC requested?
No

Date: Oct. 28, 2002

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Total number of particles and type of beam (p,d,polarization)	Momentum range (MeV/c)	Intensity or internal reaction rate (particles per second) minimum needed	Intensity or internal reaction rate (particles per second) maximum useful
Unpolarized p $n>3\cdot10^{10}$	1921	$L=3\cdot10^{10}$	
Type of target	**Safety aspects (if any)**	**Earliest date of installation**	**Total beam time (weeks)**
Internal foil C, Au		End of June 2003	4+6

What equipment, floorspace etc. is expected from Forschungszentrum Jülich/IKP?

Summary of experiment (do not exceed this space):

We review the results of the (finalized) ANKE experimental program on inclusive K^+–meson production in pA collisions. It is shown that ANKE allows to study such processes at very small cross sections down to a beam energy of T_p=1000 MeV, thus far below the free nucleon–nucleon threshold. From the inclusive data information about the K^+ final–state interaction (FSI) in the nuclear medium, in particular about the nuclear K^+ potential can be obtained. In order to learn about the different processes leading to kaon production, measurements of K^+p and K^+d correlations are motivated. Following the decision of PAC #22, corresponding test measurements were performed at ANKE in 2001 which show the feasibility of such studies. We now ask for a total beam time of 10 weeks to finalize the coincidence measurements and, thus, the ANKE experimental program on K^+–meson production in nuclei.

Attach scientific justification and a description of the experiment providing the following information:
For proposals:
Total beam time (or number of particles) needed; specification of all necessary resources
For beam requests:
Remaining beam time (allocations minus time already taken)

Scientific justification:

What are you trying to learn?
What is the relation to theory?
Why is this experiment unique?

Details of experiment:

Description of apparatus.
What is the status of the apparatus?
What targets will be used and who will supply them?
What parameters are to be measured and how are they measured?
Estimates of solid angle, counting rate, background, etc., and assumptions used to make these estimates.
Details which determine the time requested.
How will the analysis be performed and where?

General information:

Status of data taken in previous studies.
What makes COSY suitable for the experiment?
Other considerations relevant to the review of the proposal by the PAC.

EC–Support:

The European Commission supports access of new users from member and associated states to COSY. Travel and subsistence costs can be granted in the frame of the program Access to Large Scale Facilities (LSF).

Status report for COSY experiment #70.1
"Forward K^+ Production in Subthreshold pA Collisions
and
Proposal/Beam-time request
"Investigation of Subthreshold K^+-Production Processes
by Measuring K^+p and K^+d correlations"

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October 28, 2002

Abstract

We review the results of the (finalized) ANKE experimental program on inclusive K^+-meson production in pA collisions. It is shown that ANKE allows to study such processes at very small cross sections down to a beam energy of $T_p = 1000$ MeV, thus far below the free nucleon-nucleon threshold. From the inclusive data information about the K^+ final-state interaction (FSI) in the nuclear medium, in particular about the nuclear K^+ potential can be obtained. In order to learn about the different processes leading to kaon production, measurements of K^+p and K^+d correlations are motivated. Following the decision of PAC #22, corresponding test measurements were performed at ANKE in 2001 which show the feasibility of such studies. We now ask for a total beam time of 10 weeks to finalize the coincidence measurements and, thus, the ANKE experimental program on K^+-meson production in nuclei.

1 Introduction and motivation

K^+-meson production in proton-nucleus (pA) collisions at energies below the elementary $pN \to K^+ N\Lambda$ reaction threshold at $T_p = 1580$ MeV has attracted considerable interest for a long time. Irrespective of the large amount of data [1, 2, 3, 4, 5, 6, 7, 8, 9], which has been collected since the first measurements in 1988 [1], the kaon-production mechanisms are far from being understood. Data on inclusive K^+ production can be equally well reproduced by different models that involve either multi-step processes [1, 10, 11, 12], cooperation between several target nucleons [13, 14], or high momentum components of the nuclear wave function [1, 7, 12, 15, 16]. Experience shows that all mechanisms must be taken into account and their relative contribution strongly depends on the reaction kinematics [9]. It is not easy and may even turn out to be impossible to deduce the values of these weights from the conventional normalization to measured inclusive cross sections. Thus, new types of experiments, selectively exploring features of one or the other mechanism are mandatory, for example the measurement of (K^+d) correlations. Detection of such correlated kaon-deuteron pairs could be a clear signature for the two-step mechanism. In the first step, pions are produced in $pN_1 \to NN\pi$ reactions on one of the target nucleons with typical pion energies of more than 500 MeV, and in a second step these energetic pions produce K^+ mesons via $\pi N_2 \to K^+\Lambda$ or $\pi N_2 \to K^+\Sigma$ reactions on a second nucleon. This mechanism was proposed for the first time in Ref. [1] to describe the energy behavior of the total cross section for K^+-meson production in proton-nuclear interactions below 1000 MeV. The authors indicated that at such low energies the two body reaction $pN \to d\pi$ in the first step contributes significantly ($\approx 25\%$). This was confirmed by subsequent model calculations [10, 11, 12], which showed that – while being present at any energy – the two-step mechanism dominates below 1300 MeV. The role of the $pN \to d\pi$ reaction has been studied theoretically in detail by Sibirtsev et al. [11]. They predicted that the $pN \to d\pi$ reaction (as the first step in two-step production $pN_1 \to d\pi$, $\pi N_2 \to K^+\Lambda$) provides only a small part of the total cross sections at high energies (less than 1% above 2000 MeV), but increases up to 13% at 1200 MeV and reaches 30% at 1000 MeV. They also showed that (K^+d) correlations can be observed in spite of distortions due to final state interactions that the deuteron experiences on its way out of the nucleus. A rather flat background of coalescent deuterons should not be a problem below 1300 MeV, since two-step deuterons are expected to be strongly forward peaked with an average momentum corresponding to the kinematics of the $pN \to d\pi$ reaction and a typical width of about 200–250 MeV/c. In spite of these theoretical studies indicating the possibility to investigate the two-step K^+ production mechanism in nuclei, not a single experiment on (K^+d) correlations has been performed up to now, most probably because of the experimental challenges. The requirements for such measurements are: *i)* high luminosity, since the involved cross sections are small, *ii)* large angular acceptance in forward direction in order to achieve reasonably large counting rates, and *iii)* large momentum acceptance, since the kaon and deuteron momenta are rather different.

2 Status report: Results of the inclusive K^+-meson studies

2.1 K^+ measurements with ANKE

Since the idea for a (K^+d) measurement has been discussed ever since the first plans for building the ANKE spectrometer [17], the design of ANKE and its detector systems (see Fig. 1) has been optimized for K^+-meson detection — making it possible to measure double differential cross sections as low as about $10^{-35}\,\mathrm{cm}^2/(\mathrm{MeV/c} * \mathrm{sr})$ (see [8, 19, 20]) — and identification of fast forward going particles close to the primary proton beam. The ANKE detectors for positively charged particles consist of two components; a low momentum part, which covers the momentum range between 150 and 900 MeV/c, comprising start counters, so called telescopes with stop counters, a side wall hodoscope (SW) and two three-plane multi-wire proportional chambers (MWPCs) for tracking. The effectiveness of this part of

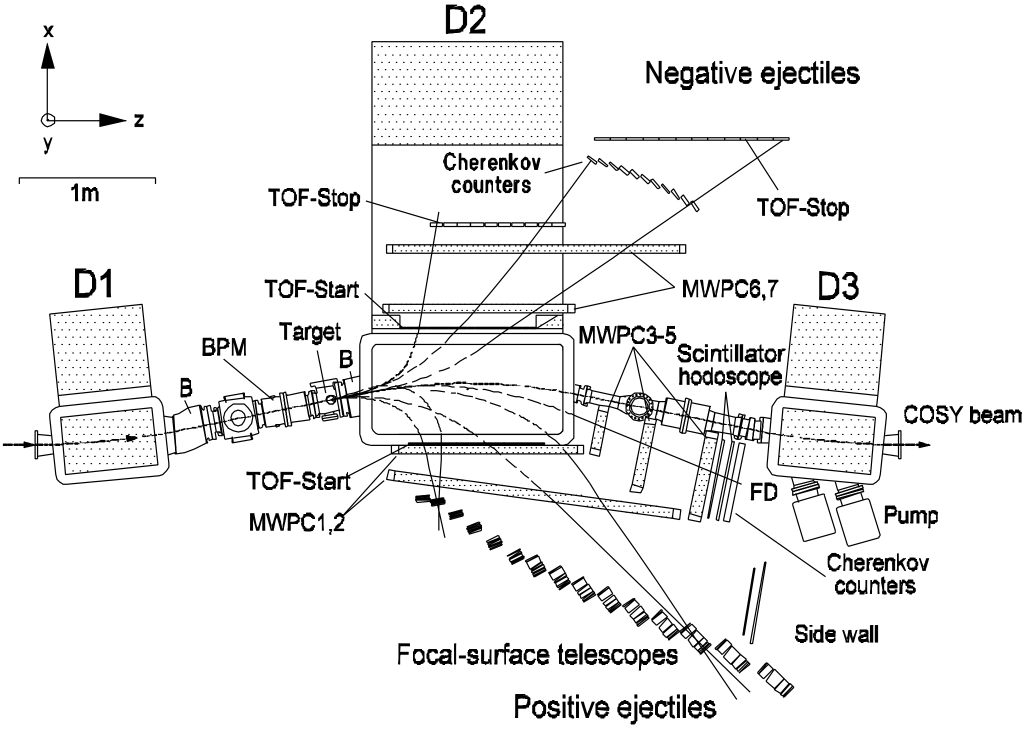

Fig. 1: Top view of ANKE.

the spectrometer to measure correlations has been demonstrated in a first correlation experiment on pn final-state interaction studies in $pp \to pn\pi^+$ [21]. In this case it was sufficient to exploit the time-of-flight (TOF) between start and stop- or SW-counters to separate particles with different masses. The high momentum part for momenta between 800 and 3200 MeV/c consists of a forward hodoscope, made of plastic scintillation counters, and three two-plane MWPCs.

The COSY proton beam, with an intensity of $(2–4)\times10^{10}$ protons and a cycle time of $\sim$ 60 s, was accelerated to the desired energy in the range $T_p = 1.0 - 2.3$ GeV on an orbit below the target. The targets were thin strips of C, Cu, Ag or Au with a thickness of 40–1500 μg/cm^2. Over a period of $\sim$ 50 s, the beam was slowly brought up to the target by steerers, keeping the trigger rate in the detectors nearly constant at 1000–1500 s^{-1}, a level that could be handled by the data acquisition system with losses due to a dead time of less than 25%. Ejectiles with horizontal angles in the range $\pm12°$, vertical angles up to $\pm7°$, and momenta between 150 and 600 MeV/c were deflected by the ANKE dipole magnet D2, passed one of 23 plastic scintillation counters and 6 planes of 2.5 mm wire-step MWPCs. They were then focussed onto one of the 15 kaon range telescopes, each consisting of three plastic scintillator counters (stop, ΔE and veto) and two degraders.

The procedure of how to identify kaons with ANKE has been presented in Ref. [20] and is briefly described as follows: The 10 cm wide telescopes, placed at the focal surface of the ANKE spectrometer, defined $\sim$ 10% momentum bites in ejectile momenta. The momentum ranges covered by each telescope were kept constant for the different beam energies by operating ANKE at constant magnetic field strength and maintaining the relative target-dipole-detector geometry. The thicknesses of the scintillators and degraders in the telescopes were chosen so as to stop kaons in the degrader in front of the veto counters. The kaons subsequently decay with a mean life time of $\approx$ 12.4 ns and the products of this decay (pions or muons) are detected by the veto counters with a delay of more than 1.3 ns with respect to the signals from the corresponding stop counters. The combination of the time of flight between the start and stop counters, energy losses in all the scintillators, delayed particle signals, and information from MWPCs resulted in clean kaon spectra, with a background of less than 20% for the lowest (1000 MeV) beam energy. The MWPC track reconstruction allowed us also to vary the angular and momentum acceptances of the individual telescopes. Kaon detection efficiencies for individual telescopes were measured in a special experiment with an accuracy of 10%. Relative monitoring of the luminosity was done with an accuracy of 2% by means of 4-fold coincidences of telescopes 2–5, looking directly to the target.

2.2 Target-mass dependence of the K^+ cross sections

We started our measurements with the study of the target-mass dependence (A-dependence) of the double differential cross sections. If secondary interactions of K^+ mesons with the nuclear matter were small, the total cross sections would be proportional to $A^{2/3}$ for the one-step (like quasifree $pN \to K^+ N\Lambda$) mechanism and roughly proportional to A in case of the multi-step production [9]. Some of the experimental results — ratios of the forward K^+ production cross sections on copper, silver and gold targets to that on carbon as a function of kaon momentum p_K — are presented in Fig. 2. The result is surprising: in contrast to total cross sections, the A-dependence of double differential cross sections does not reveal the expected dependences on the reaction mechanism. It could be shown [22] that they exhibit a strong dependence on secondary interactions of the produced kaons with the nuclear environment.

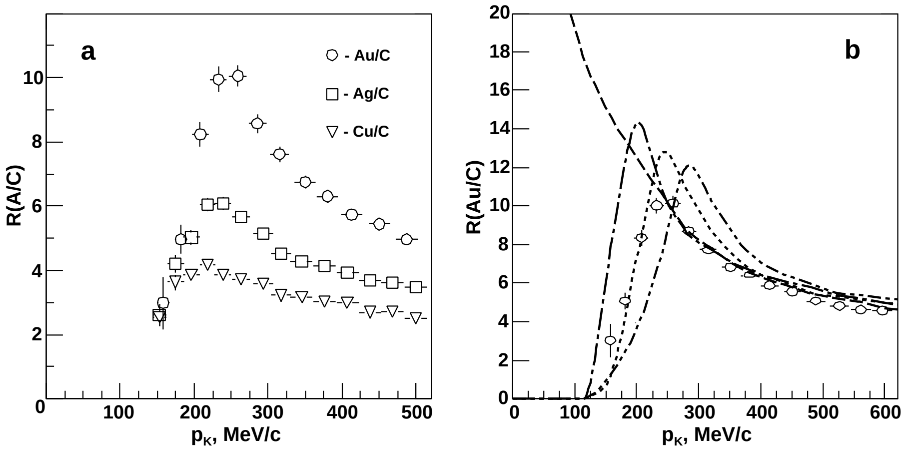

Fig. 2: **a)** Ratios of the K^+ production cross sections on Cu, Ag, and Au measured at $T_p = 2.3\,\mathrm{GeV}$ as a function of the laboratory kaon momentum [22]. **b)** Ratios of the K^+ production cross sections for Au/C at $T_p = 2.3\,\mathrm{GeV}$ as a function of the kaon momentum. The open circles are the experimental data. The broken line is obtained from transport calculations with K^+ rescattering in the nucleus taken into account and simulated without Coulomb and nuclear kaon potentials. The dash-dotted line corresponds to calculations with the Coulomb potential added, the dotted line additionally takes into account the kaon potential of 20 MeV at normal nuclear density, whereas the dashed-double-dotted line shows the result where the kaon nuclear potential of 40 MeV has been used

Fig. 2a) shows that the position of the maximum in $R(A/\mathrm{C})$ increases with A. The situation has a parallel in the well known suppression of β^+ emission in heavy nuclei at low positron momenta arising from the repulsive Coulomb field. Thus, a K^+ produced at rest at some radius R in the nucleus would, in the absence of all other interactions, acquire a momentum of $p_{\min} = \sqrt{2m_K V_C(R)}$. Taking R to be the nuclear edge, this purely classical argument leads to a minimum K^+ momentum for Au of $p_{\min} \approx 130\,\mathrm{MeV/c}$. Moreover, it is known from K^+ elastic scattering experiments at higher energies that the K^+A potential is mildly repulsive, and this is in an accordance with one-body optical potentials based upon low-energy K^+N scattering parameters. At normal nuclear density, $\rho_0 \approx 0.16$ fm^{-3}, the predicted repulsive K^+A potential of strength $V_K^0 \approx$20–25 MeV would shift $p_{\rm min}$ to higher values. In order to see whether the observed low momentum suppression is compatible with such a combination of Coulomb and nuclear repulsion, we performed calculations in the framework of the coupled channel transport model [23]. In this approach the different mechanisms for the kaon production and the influence of average Coulomb and nuclear potentials, as well as hadron rescattering effects which can cause a sudden change of the kaon trajectory when kaon comes close to a nucleon, can be taken into account using realistic density distributions. Results of the calculations for the Au/C-ratio are shown in Fig. 2b. Without including the Coulomb and kaon potentials (dashed line) the ratio exhibits a smooth momentum dependence with a steady increase towards low momenta resulting from the stronger K^+ rescattering processes for the Au target. For kaons the pure Coulomb interaction leads to a distortion of the momentum spectrum and provides a maximum at $p_K \approx 200\,$MeV/c (dashed-dotted line). It has been checked that a 10% change in the charge radius would move the maximum by less than $\pm 2\,$MeV/c. A much larger change is observed in the calculations when a repulsive kaon nuclear potential is also considered, giving a 40 and 80 MeV/c shift with a potential strength of 20 and 40 MeV, respectively. When a kaon potential of $V_K^0 = 20\,$MeV is used in the calculations, a reasonable agreement with the experiment is achieved, with a maximum close to the experimental value of $245 \pm 5\,$MeV/c. After taking into account the absorption of the incident proton by including a baryon potential into the calculations (not shown in Fig. 2b), the agreement with the experimental data is even better.

2.3 Double differential cross sections

The absolute values of the double differential cross sections are obtained from the numbers of kaons identified by each telescope, after correction for luminosities, detection efficiencies in the scintillators and MWPCs, kaon decay between the target and the telescopes, and angle-momentum acceptances. Data were obtained for pA interactions at proton beam energies of 1000, 1200, 1500, 2000 and 2300 MeV [24]. In Fig. 3 we present K^+-cross sections for pC interactions at beam energies 1000 and 1200 MeV, measured far below the threshold of the elementary $pN \to K^+N\Lambda$ reaction ($T_p = 1580$ MeV).

Just after our data were published, two groups made calculations in the framework of two different approaches: the transport (CBUU) model [25] and the folding model [26]. Both models gave results coinciding within 20% with each other. In Fig. 3 we present a comparison of our data with the transport model which illustrates several interesting details of the calculations. First of all, from the model calculations the importance of the kaon-nuclear potential is seen. Its implementation reduces the cross sections by a factor of three (solid lines in comparison to dashed lines) if a kaon-nuclear potential of 20 MeV, obtained from our cross-section ratios, is used. About 90% of the kaons are produced via the two-step mechanism (shaded areas in comparison to the solid lines). Note that the transport calculations do not take into account $pN \to d\pi$ reactions as a part of the first stage of the two-step mechanism and do not consider at all cluster mechanisms like $p(2N) \to dK^+\Lambda$.

Preliminary model calculations have also been performed using the Rossendorf Collision (ROC) model [27]. Within this model the cross sections for the interaction of the projectile with the target nucleons are calculated on the basis of a probabilistic interpretation of Glauber theory. A reasonable description of the 1.0 GeV spectrum could so far only be obtained if high-momentum components in the nuclear wave function of the target nucleus are introduced. Then the cross sections measured at higher beam energies are strongly overestimated. This is an indication that at low beam energies strong collective nuclear effects — which are not expected to be correctly treated by this statistical approach — contribute to subthreshold kaon production.

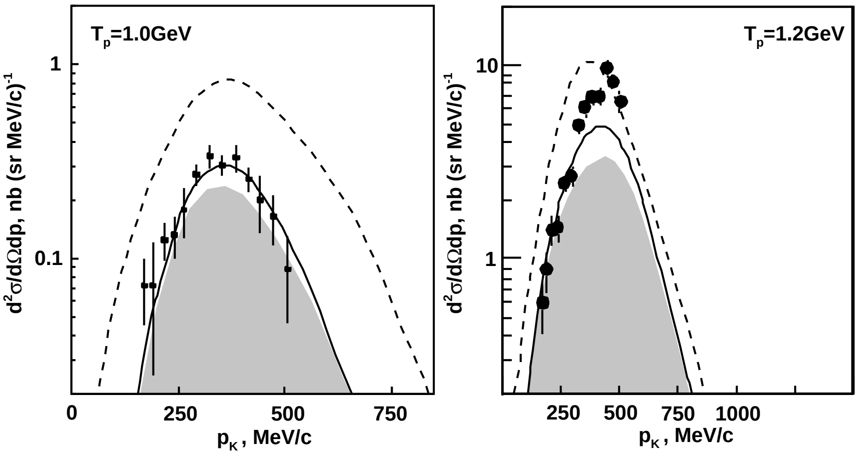

Fig. 3: Double differential cross sections from ANKE for K^+-meson production in pC interaction at 1.0 and 1.2 GeV. The experimental data are compared with the results of the transport-model calculations. The dashed lines correspond to calculations without kaon-nuclear and baryon potentials. The solid lines are calculated with all potentials taken into account. The shaded areas show the contribution of the two-step mechanism.

It is rather difficult, if not impossible, to draw unambiguous conclusions about the importance of, e.g. two-step reactions with deuteron formation in the first step or kaon production on two-nucleon ($2N$) clusters if using inclusive K^+-production data only. For example, the 30–40% difference in the absolute values of the experiment and the transport calculations at 1200 MeV (Fig. 3) seems to indicate that some additional mechanisms have to be added in the calculations, whereas the good agreement at 1000 MeV leaves no room for "unconventional" contributions. This is particularly puzzling since at lower energies collective effects are expected to be more pronounced [8].

The proposed K^+p and K^+d coincidence measurements aim at unambiguous experimental information on the different reaction mechanisms, in particular two-step reactions with deuteron formation and kaon production on ($2N$) clusters. It is quite probable that at 1000 MeV the role of the ($2N$) cluster mechanism will be more important than at 1200 MeV where we performed our first test measurements. Even the K^+ production on three-nucleon clusters may be significant since the beam energy of 1000 MeV is close to the threshold of the $p(3N)\to K^+\Lambda(3N)$ reaction.

3 Measurements of K^+d correlations

With the measurement of the double differential cross sections for K^+ production from several nuclei in a wide beam-energy range we finished the first stage of the ANKE experimental program on K^+ production in nuclei. This included commissioning of the ANKE spectrometer and the detectors, their calibration, and studies of the critera for kaon selection. We now have the possibility to measure the K^+ cross sections at a level of 10–100 pb/(sr*MeV/c) and to perform measurements of inclusive kaon-momentum spectra.

The second and the last stage of our original proposal [17] was and is the (K^+p), (K^+d) correlation experiment. Since such an experiment has been never made at any energy and it is very ambitious, the PAC recommended in spring 2001 to spend two days for a test measurement. The only goal was to show that this experiment is feasible at ANKE and that the K^+d coincidences can be separated from the backgroud of accidental coincidences. These two days (50 hours for p(1200 MeV)+C) were successfully used in October 2001. Since these studies were requested by PAC, a more detailed description of the measurements will be given in the following. Moreover, during an η-production experiment in summer 2002 we parasitically measured for 5 days (120 hours) K^+d coincidences in proton-deuteron interactions at $T_p = 1344$ MeV.

The experiments were performed at proton beam energies of T_p = 1200 (pC), 1344 (pd) and 2300 MeV (pC). At these energies forward deuterons from free or quasi-free $pN \to d\pi$ reactions have momenta close to 1000 MeV/c. Therefore the expected deuteron peak should be observed in the high momentum part of the spectrometer, but some deuterons will also be seen in the low momentum part. In coincidence, kaons with momenta between 175 and 610 MeV/c have been identified in the telescopes of the low momentum detectors. This is because ANKE was operated in the standard 1.6 T mode, accepting forward emitted particle with $\pm 12°$ horizontally, and 4–7° vertically. In Fig. 4 we display the experimental results for kaon and deuteron identification in the case of 2300 MeV incident proton energy (part a)) and 1200 MeV (parts b) – e)).

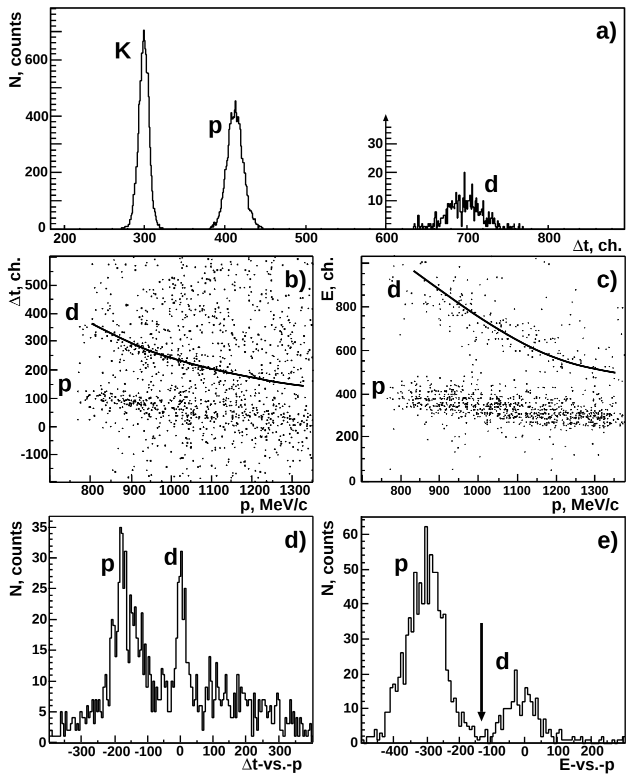

Fig. 4: **a)** Time-of-flight spectrum of particles in the low momentum part of the spectrometer, measured in the full angular acceptance at T_p = 2300 MeV. **b)** and **c)** Momentum dependence of the time-of-flight (**b**) and energy loss (**c**) of particles in the high momentum part of the spectrometer measured at $T_p = 1200$ MeV. **d)** and **e)** Projections of the momentum dependences (**b)** and **c)** respectively) along the indicated lines.

The distribution of events in Fig. 4a) has been obtained for two-particle events in the low momentum part, one of them being a kaon. Kaons, protons and deuterons are very well separated with less than 10% background, if as an additional criterion the energy loss of particles in start, stop and SW counters is used. In order to identify deuterons in the high momentum part, we first plot two-dimensional spectra of time-of flight (relative to kaons in the telescopes) versus momentum (Fig. 4 b)) and energy loss in the hodoscope (Fig. 4 c)); in both spectra two bands corresponding to protons and deuterons are clearly visible. Projections along the indicated lines result in Figs. 4 d) and 4 e), again with well separated proton and deuteron peaks.

In Fig. 5 b) the projected time-of-flight spectrum similar to Fig. 4 d) is shown with the additional cut on deuterons in the energy-loss spectrum (i.e. events on the right hand side of the arrow in Fig. 4 e)).

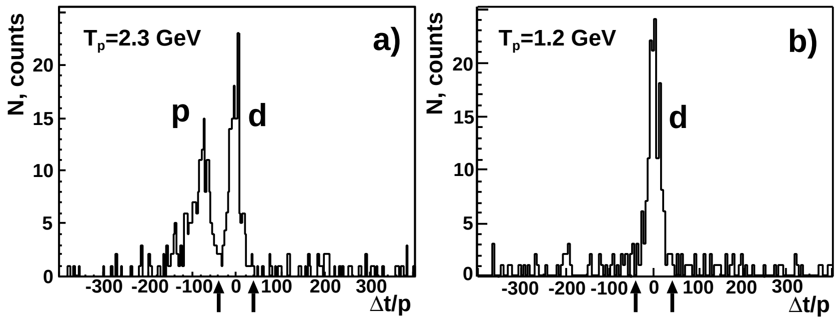

Fig. 5: Projections of the time-of-flight versus momentum distributions along the deuteron line as shown in Fig. 4. A cut on the energy loss is done as indicated in Fig. 4e).

For 1200 MeV, an almost background free deuteron identification is achieved and the accidental background is less than 5 %. The corresponding procedure for $T_p = 2300\,\mathrm{MeV}$ results in Fig. 5 a). Although some protons survive, the deuteron peak is well separated with an estimated proton background of less than 15%. For the further deuteron analysis, only events within the gate, indicated by the two arrows, are used. We do not show the corresponding spectrum for proton-deuteron interactions at 1344 MeV, because only one event remained after the cut.

We have also performed an analogous analysis by requesting fast forward going protons in coincidence with kaons. In Fig. 6 the proton-momentum distributions are displayed.

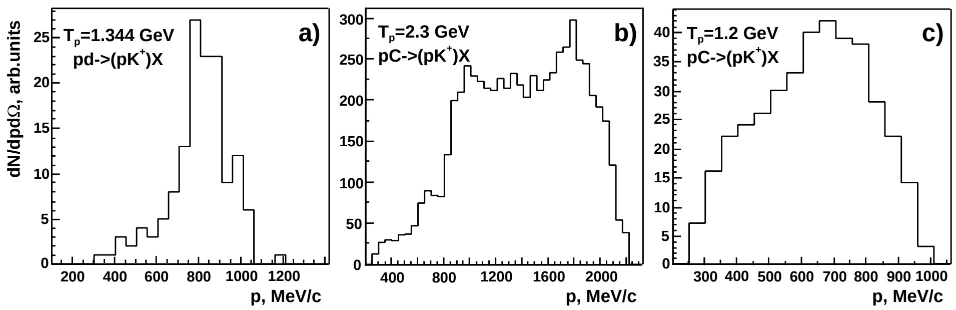

Fig. 6: Proton-momentum spectra measured for the indicated reactions. The distributions also contain protons originating from Λ decay.

Shown are the sums of the corresponding distributions from both detector parts of the spectrometer measured within a scattering angle of $\vartheta = 8^\circ$ and corrected for efficiencies and acceptances. For protons, the total number of coincident events are 383 (pC, 1200 MeV), 141 (pd, 1344 MeV), and 6175 (pC, 2300 MeV), respectively. We have not yet done further investigations of the proton spectra. For example, they still contain both direct protons and protons from Λ decay. This may be the reason for the double structure at 2300 MeV in pC reactions. The distributions are presented here since they serve as a normalization for the (K^+d) correlations. The main emphasis of the further analysis is to understand to which extent the $pN \to d\pi$ process is important as the first stage of the two-step mechanism.

The deuteron-momentum spectra are shown in Fig. 7. Here, the total numbers of coincident events are 321 (pC, 1200 MeV) and 212 (pC, 2300 MeV). The single event for pd at 1344 MeV is not shown, it corresponds to less than 1% of the protons detected in the same solid angle (Fig. 5b)) and gives an upper limit for the coherent $pd \to dK^+\Lambda$ process. In Fig. 7a) the distribution for $T_p = 2300$ MeV is plotted. The spectrum can be described by an exponential distribution $e^{-p/k}$ with a parameter $k = 769$ MeV/c (dashed-dotted line). Such a shape is most probably defined by coalescence processes, see e.g. Ref. [28]. From (on-shell) kinematics of the $pN \to d\pi$ reaction, deuterons are expected around 1100 MeV/c (indicated by the arrow). The experimental distribution does not show a peak there. An upper limit for the contribution of the two-step process leading to kaon production is 25 events. Qualitatively, the results of our measurement are in agreement with the predictions of Ref. [11]. A quantitative comparison is difficult, because in the calculation the fraction of the total cross section is given, whereas the experimental results were obtained for a restricted solid angle ($\leq 8°$). In any case the deuteron-to-proton ratio of less than 1% is in agreement with the well known fact that quasi free $pN \to NK^+\Lambda$ production is the main source for K^+ mesons in pA collisions at 2300 MeV.

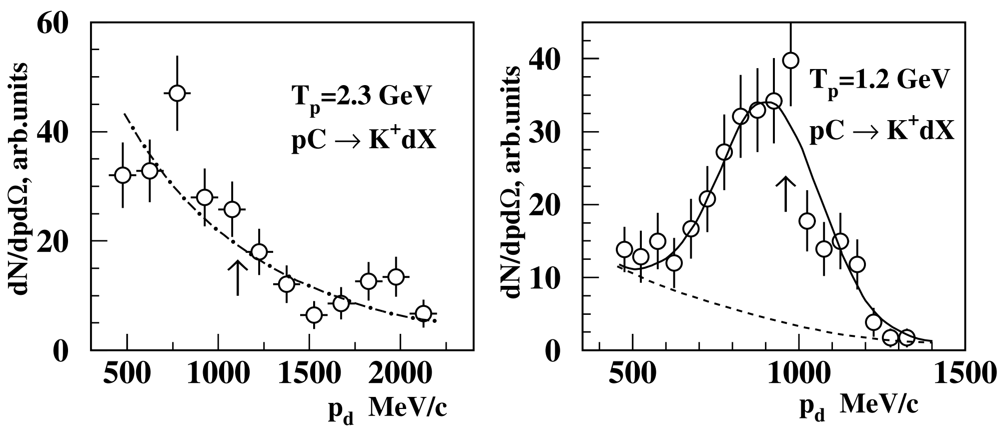

Fig. 7: Deuteron momentum spectra measured in the reactions indicated in the figures. The arrows indicate the momenta of deuterons from the $pN \to d\pi$ reaction.

It was mentioned above that the two-step mechanism is expected to dominate below 1300 MeV. Most probably, this is the reason for the drastic change in the deuteron-momentum spectrum at $T_p = 1200$ MeV (Fig. 7b)) as well as in the deuteron-to-proton ratio. In comparison to 2300 MeV it increases by a factor of $\approx$100. About 30% of the 321 events in the spectrum form a smooth background of coalescent deuterons, whereas the rest (220–230 events) lies within the peak structure around 1000 MeV/c. The position and width of the structure depend on the best fit approach. If one assumes that only one Gaussian peak is present (solid line), the results are (910 ± 15) MeV/c for the maximum and 350 ± 25 MeV/c for the width (FWHM). It is tempting to assign these deuterons to the $pN \to d\pi$ process, which according to the prediction of Ref. [11], should appear at 963 MeV/c with a width of 200–250 MeV/c. At $T_p = 1200$ MeV the deduced deuteron-to-proton ratio is 0.6, i.e. much larger than the calculated ratios of total cross sections in Ref. [11]. However, taking into account that the angular distribution of protons is twice broader for deuterons, the ratio reduces to about 0.15. In the experiment only deuterons can be detected which survived from desintegration in the carbon nucleus (about 50%). Thus the measured part of the $pN \to d\pi$ channel is about 0.30, about twice larger than predicted in Ref. [11] and closer to the predictions given in Ref. [13].

The one-peak fit to the experimental data yields a significantly wider distribution than theoretically

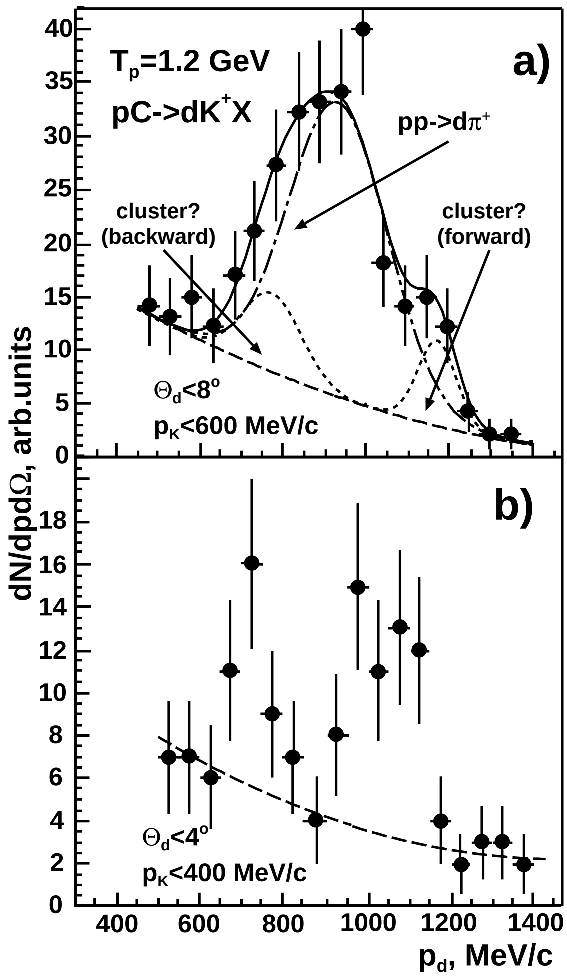

Fig. 8: Deuteron momentum spectra for pC collisions at 1200 MeV and different cuts on the deuteron emission angles and kaon momenta.

predicted and shifted to the low momentum region. Moreover, the peak-structure of Fig. 7b) shows a shoulder at the high momentum side. A better fit is obtained with three Gaussian peaks (Fig. 8a)); the maxima (widths) are: (930 ± 40) MeV/c ($\approx$260 MeV/c) for the central one, (775 ± 25) MeV/c ($\approx$150 MeV/c) for the left one and (1165 ± 20) MeV/c ($\approx$100 MeV/c) for the right one. The maximum and the width of the central peak are closer to the predictions given in Ref. [11]. The intensity of the central peak is about four times larger than of both the low and high momentum ones together and thus does not change the statement about the agreement with calculations made before. Taking into account the difference in angular distributions of protons and deuterons, the deuteron-to-proton ratio is about 0.11.

As stated above, we assign this peak to correlated (K^+d) pairs, created via the two-step mechanism. In order to understand the origin of the two other contributions, we have performed a naive phase space model calculation, in which K^+ mesons are produced on $(2N)$ clusters inside the nucleus, which might be significantly different from a deuteron. The simulations give two peaks at about 800 MeV/c and 1250 MeV/c (FWHM about 100–150 MeV/c each), which corresponds to backward and forward emitted deuterons in the cm-system, in qualitative agreement with our experimental findings.

To test this conjecture, the kinematical features of both mechanisms were exploited. The beam energy of $T_p = 1200$ MeV is far above the threshold of the $pN \to d\pi$ reaction in the first stage of the two-step mechanism. Forward pions from this reaction have an energy of about 830 MeV (neglecting the intrinsic nucleon momenta) weakly dependent on the emission angle. This pion energy is also well above the threshold of the $\pi N \to K^+\Lambda$ reaction in the second step and produces kaons with momenta of 450–500MeV/c for kaon emission angles less than 15°. Deuterons, produced in the first step have a rather wide angular distribution (more than 35°) and the shape of the deuteron peak weakly depends on the deuteron emission angle within 10–15°. So, the intensity of this peak should be about proportional to the solid angle covered by the deuteron detector and also strongly depends on the part of the kaon momentum spectrum accepted for correlations with deuterons. For the possible $(2N)$ cluster mechanism, the energy of 1200 MeV is only less than 60 MeV above the threshold of a $pd \to dK^+\Lambda$ reaction. Since the binding energy of a $(2N)$ cluster is at least as large as of two individual nucleons the excess energy should be even smaller. As a result, the deuterons from the cluster mechanism must have much narrower, strongly forwarded angular distribution ($< 10°$) and they correlate with kaons of momenta less than 425 MeV/c (kinematical upper limit for kaons from $2N$-clusters mechanism). If in the data analysis only the low momentum part (<400 MeV/c) of the kaon spectrum is used for correlations with deuterons detected within twice reduced angular acceptance (4° instead of 8°), the deuteron peak from the two-step mechanism is expected to be about 10 times reduced. According to phase-space calculations for the $(2N)$ clusters at rest no significant changes are expected for the backward and forward deuteron peak from the clusters mechanism.

The result of the data analysis with the reduced kaon momentum and deuteron angular acceptances is presented in Fig. 8b) and it confirms our naive kinematical considerations. Even with such poor statistics a hint on two peaks is seen. What is really surprising is that the structure of the distribution is in reasonable agreement with a phase-space calculation of the $p(2N) \to dK^+\Lambda$ process taking into account the conditions of the experiment and with a mass of two nucleons at rest reduced by 16 MeV. Taking into account the limited statistics obtained during the test experiment this result seems to be the first indication for a cluster mechanism contributing to subthreshold K^+ production in nuclear targets.

4 Proposal

It is not possible to draw unambiguous conclusions about the reaction mechanisms from the comparison of the measured inclusive double differential cross sections of K^+-meson production in pC interactions at 1000 MeV and 1200 MeV with the conventional transport or folding model calculations. Most probably the mechanisms discussed in the introduction, but never applied for comparisons with data on double differential cross sections, must be used. Before including them into the models, the experimental proof of their relevance must be given. This can only be obtained from a new type of experiments such as K^+p and K^+d correlation measurements.

That is why a first attempt of such measurements has been made at ANKE. This short test experiment on K^+p and K^+d correlations, in pC interactions at an energy much below the threshold for elementary kaon production, showed that these measurements can be successfully performed at ANKE with high statistics and at low background levels. The first direct experimental prove of the two-step mechanism and an indication of the cluster mechanisms could be obtained. Strong evidence for the two-step mechanism, including the two body reaction $pN \to d\pi$ at the first stage, is presented for K^+-meson production at 1200 MeV in pC collisions. The contribution of the cluster mechanism can be on a level of 30% compared to $pN \to d\pi$. It is also shown that, exploiting kinematical criteria, it is possible to study these mechanisms individually.

In spite of the positive answers from the previous studies, they are rather qualitative than quantitative. To confirm the obtained result, to understand the nature and characteristics of a possible cluster mechanism and to allow for a comparison with results of theoretical studies higher statistics is necessary. This will permit detailed studies of the distributions presented in Fig. 8 at $T_p = 1200$

MeV as a function of kaon momenta and of deuteron emission angle with the goal to distinguish the mechanisms more clearly. With higher statistics and stronger $pN \to d\pi$ peak suppression there is a chance to define more precisely the maxima of the forward and backward peaks of the cluster mechanism and to extract from them the mass of the $(2N)$ clusters and, as the result, the binding energy of two nucleons in clusters. Furthermore, we plan to measure not only double but also triple coincidences. The third particle is a proton or a π^- from the Λ decay. That will make the experiment more exclusive. Luminosity, acceptances and count rates achieved at ANKE allow to increase statistics of K^+d and K^+p correlations 10 times during **3 weeks** of beam time.

For further confirmation of the observed mechanisms, it is proposed to do this experiment not only with the light (carbon) target but with a much heavier (gold) target. The strong final-state interaction of deuterons with the heavy residual nuclei will cause deuteron disintegration, so that for the Au-target only about 5% of deuterons should survive. The peaks shown in Fig. 8 should practically disappear and only the background of the coalescent deuterons (distribution similar to that in Fig. 7a)) will be measured. A comparison of the deuteron momentum distributions from light and heavy targets will be further confirmation for the discussed mechanisms. The K^+p, K^+d correlation experiment with the gold target is proposed for $T_p = 1200$ MeV and for that we need **one additional week** of beam time to collect the statistics equal to that presented in Fig. 7.

It is very important to perform this experiment also at a proton beam energy of 1000 MeV. Recent theoretical studies [29] showed excellent agreement with the experimental data at this energy [8]. It is not surprising that calculations reproduce the shape of the experimental spectrum which is mostly defined by kinematics and Coulomb-nuclear potential effects studied at ANKE [22]. Puzzling is the good agreement of absolute values of the calculated and measured cross sections, since these calculations did not take into account the $pN \to d\pi$ channel of the two step mechanism nor the cluster mechanism. It is quite probable that at 1000 MeV the role of the $(2N)$ cluster mechanism will be more important than at 1200 MeV. Moreover, K^+ production on three-nucleon clusters could be important since the energy of 1000 MeV is close to the threshold of the $p(3N) \to K^+\Lambda(3N)$ reaction. Due to the smaller cross sections a beam time of **6 weeks** using a carbon target will be needed.

5 Beam-time request

For the next beam-time period: 3 weeks for measurements of K^+d, K^+p correlations at $T_p = 1200$ MeV with a carbon target plus 1 week for measurements with a gold target, totally **4 weeks**.

Allocation of 6 weeks for the measurements at $T_p = 1000$ MeV with a carbon target will be applied for after analysis of the $T_p = 1200$ MeV data. With these measurements the ANKE experimental program on subthreshold K^+ production will be finished.

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