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Observation of K$^+$d correlations from pA collisions

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Abstract. Results of a first experiment on (K^+p) and (K^+d) correlations from proton-carbon (pC) and proton-deuteron (pd) interactions at beam energies above and much below the threshold for elementary kaon production in nucleon-nucleon reactions (T_{NN} = 1580 MeV) are discussed. These data, obtained with the ANKE spectrometer at COSY-Jülich, provide first direct evidence for K^+ production via the two-step mechanism and an indication for a cluster mechanism. It is shown that both processes contribute significantly in pC collisions at 1200 MeV, while they are strongly suppressed at 2300 MeV and also in pd-interactions at 1344 MeV. It is emphasized that the underlying kinematics can be exploited to distinguish between these reaction mechanisms.

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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 [1–9], which has been collected since the first measurements in 1988 [1], the nuclear kaon-production mechanism is far from being understood. Data on inclusive K^+ production can be equally well reproduced by different models that involve either multi-step processes [1,10–12], 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 contributions strongly depend on the reaction kinematics. 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 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 provides a clear signature for the two-step mechanism; in the first step, pions with typical energies of more than 500 MeV are produced in $pN_1 \to NN\pi$ reactions on one of the target nucleons, 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 another nucleon. It can be expected that such two-step reactions dominate at energies far below threshold, since the intrinsic nucleon momentum can be utilized twice. This mechanism was applied for the first time in ref. [1] to describe the energy behavior of the total K^+-production cross-sections in pA interactions below 1000 MeV. The authors also indicated that, at such low energies, the two-body reaction $pN_1 \to d\pi$ contributes significantly in the first step ($\approx$ 25%). This was confirmed by subsequent model calculations [10–12], 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 provides 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

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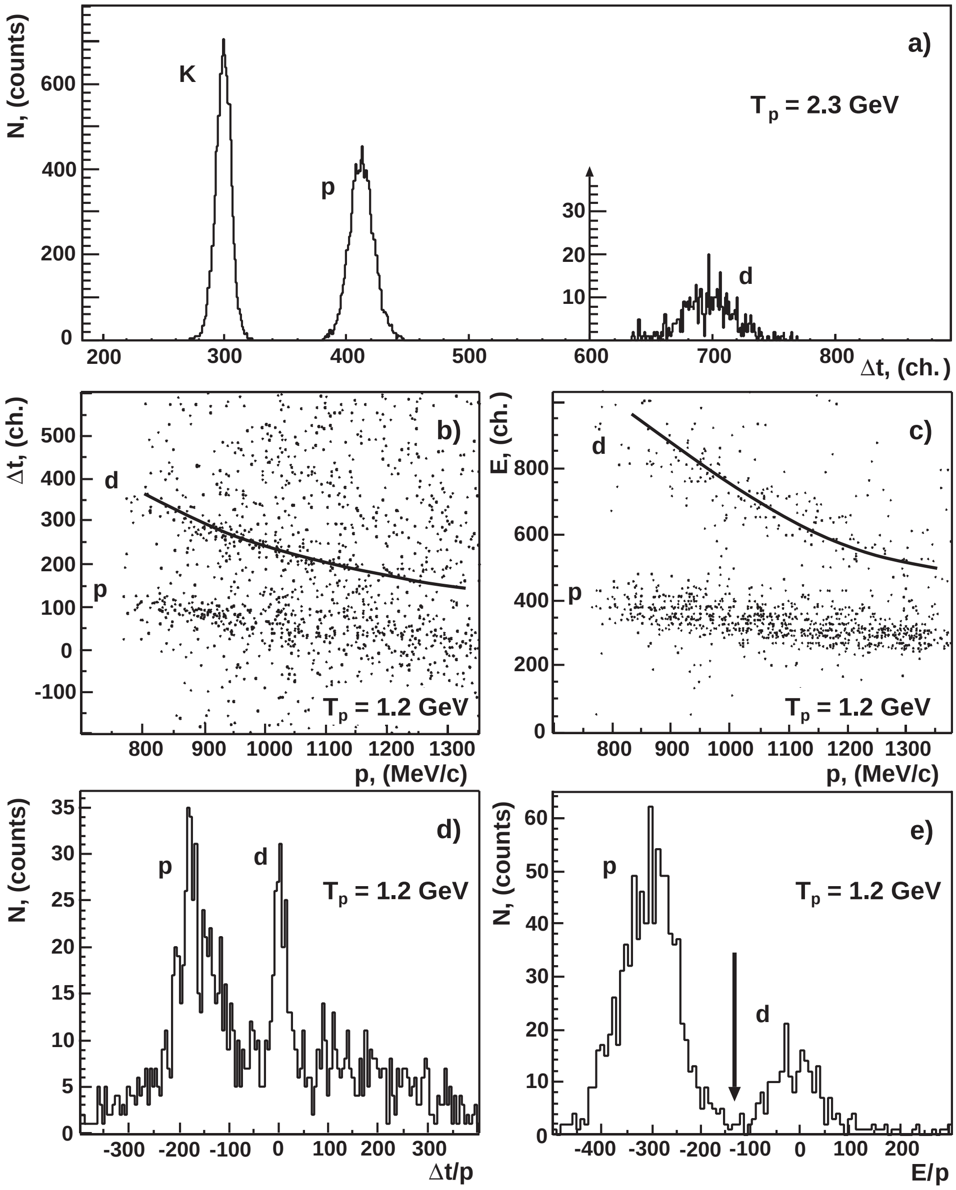

Fig. 1. a) TOF spectrum of particles in the low-momentum part (K^+ in telescopes; p, d in SW) of the spectrometer, measured in the full angular acceptance at $T_p = 2300$ MeV. b) and c) Momentum dependence of the TOF and energy loss of particles in the high-momentum part of the spectrometer measured at $T_p = 1200$ MeV. d) and e) Event distributions of the distances perpendicular to the lines in b) and c).

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.

Since the idea for a (K^+d) measurement has already been discussed in the design phase of the ANKE facility at the internal beam of COSY [17], the spectrometer and its detectors have been optimized for K^+-meson detection. The detection system for positively charged particles consists of a low- and a high-momentum part. The low-momentum part covers a momentum range between 150 and 900 MeV/c. Two three-plane multi-wire proportional chambers (MWPCs) are used for tracking [18]. Scintillation counters are arranged as start counters, range telescopes (with stop counters) and a side wall (SW) hodoscope to provide time-of-flight (TOF) measurements and kaon identification. In the momentum range 150–610 MeV/c, covered by the range telescopes, it is possible to measure double differential K^+-production cross-sections as low as about $10^{-35}\,\mathrm{cm}^2/(\mathrm{sr\ MeV}/c)$ [8,18, 19]. Particles with momenta 610–900 MeV/c can be detected in the SW counters. The effectiveness of the low-momentum part for correlation measurements has been demonstrated in a first experiment on pn final-state interaction studies in $pp \to pn\pi^+$ reactions [20]. In this case it was sufficient to exploit the TOF between start and stop or SW counters to separate particles with different masses. The high-momentum detectors for momenta between 800 and 3200 MeV/c comprise a forward hodoscope, made of plastic scintillation counters (FD), and three two-plane MWPCs [19].

The experiment was performed with carbon (foil) and deuterium (cluster-jet) targets at proton beam energies of $T_p = 1200$ (C), 1344 (d) and 2300 MeV (C). For the two lower 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 (SW). 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 particles in the angular range $\pm 12°$ horizontally and $\pm(4$–$7)°$ vertically. The procedure of how to identify kaons with ANKE has been described in ref. [18] and is not discussed here any further.

In fig. 1 we display the experimental results for kaon and deuteron identification at $T_p = 2300$ MeV (panel a)) and 1200 MeV (panels b)-e)). The TOF distribution in fig. 1a) has been obtained for events with two particles in the low-momentum part, one of which is a kaon. Kaons, protons and deuterons are very well separated with almost no background, if as an additional criterion the energy loss of particles in start, stop and SW counters is used. In order to identify deuterons at the lower beam energies in the FD, we use two-dimensional spectra with TOF (relative to kaons in the telescopes) *versus* momentum (fig. 1b)) and energy loss in the hodoscope (fig. 1c)). In both spectra two bands corresponding to protons and deuterons are clearly visible. Projections perpendicular to the indicated lines result in figs. 1d) and e), again with well-separated proton and deuteron peaks.

In fig. 2a) the projected TOF spectrum similar to fig. 1d) 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. 1e)). For 1200 MeV an almost background-free deuteron identification is achieved, the accidental background is less than 5%. The corresponding procedure for $T_p = 2300$ MeV results in fig. 2b); 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 pd interactions at 1344 MeV, because only one event remained after the cuts.

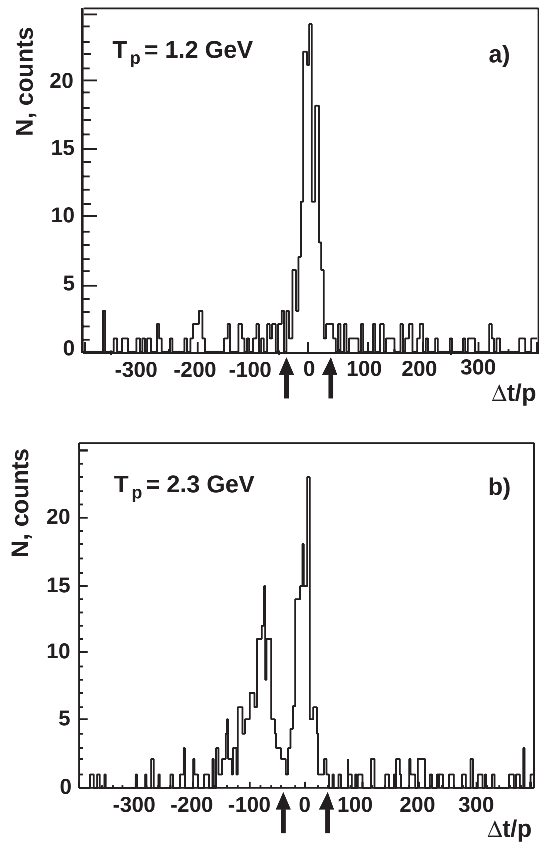

Fig. 2. Projections of the TOF *versus* momentum distributions along the deuteron line as shown in fig. 1. A cut on the energy loss is applied as indicated in fig. 1e).

We have performed an analogous analysis by requesting fast forward-going protons in coincidence with kaons. The total numbers of coincident events are 383 (pC, 1200 MeV), 141 (pd, 1344 MeV), and 6175 (pC, 2300 MeV), respectively. These numbers are used in the following for the normalization of the (K^+d) data.

The deuteron momentum spectra are shown in fig. 3. The total numbers of coincident events are 321 (pC, 1200 MeV) and 212 (pC, 2300 MeV). The single event for pd at 1344 MeV corresponds to less than 1% of the protons detected in the same solid angle and may give an upper limit for the coherent $pd \to dK^+\Lambda$ process. In fig. 3a) 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 (dash-dotted line). Such a shape is most probably attributed to coalescence processes, see, *e.g.*, ref. [21]. 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 here, an upper limit for the contribution of the two-step process leading to kaon production is 25 events, or less than 1% of the total K^+ yield. Choosing a different momentum dependence of the background might result in obtaining

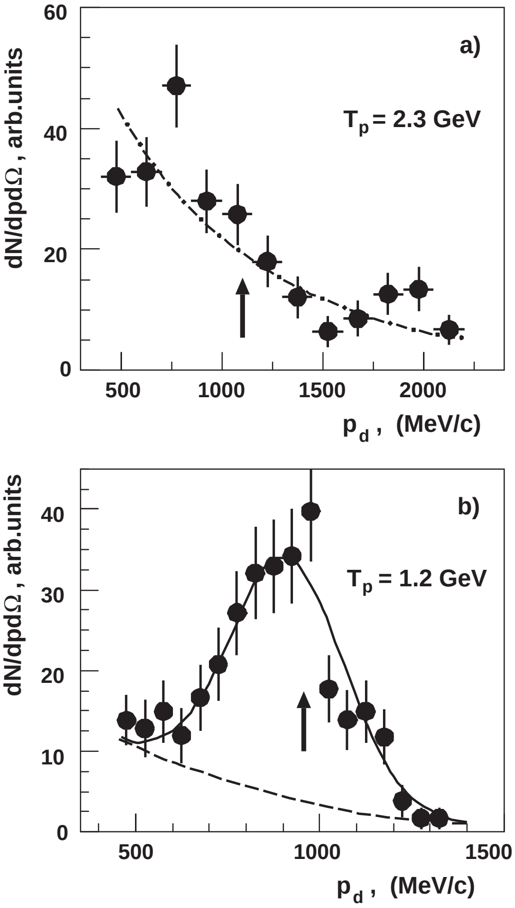

Fig. 3. Deuteron momentum spectra measured for the reaction $p\mathrm{C} \to K^+dX$. The arrows indicate the momenta of deuterons from the $pN \to d\pi$ reaction.

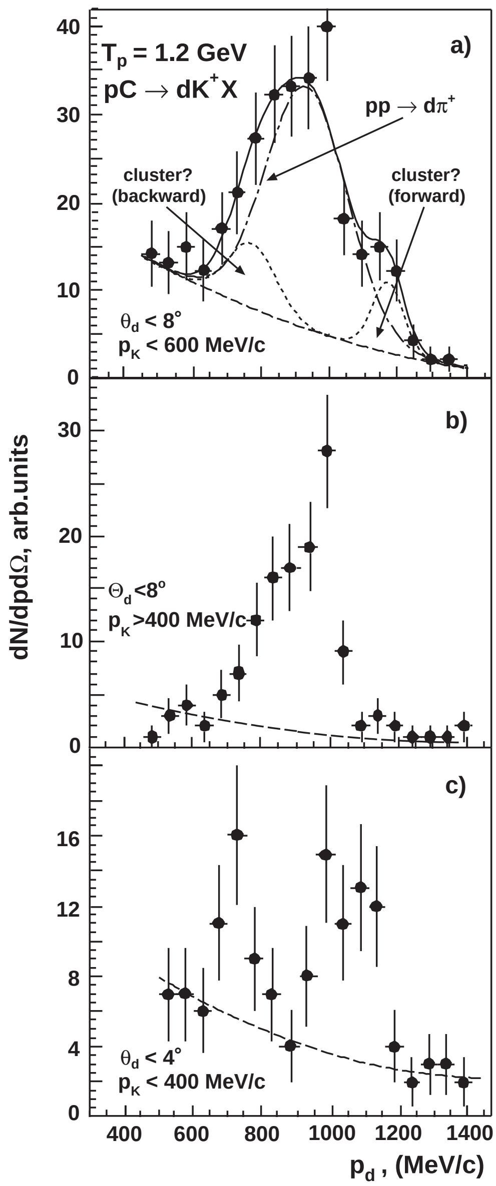

Fig. 4. Deuteron momentum spectra for pC collisions at 1200 MeV and different cuts on the deuteron emission angles and kaon momenta. The dashed lines indicate the fitted background distribution.

a larger two-step contribution, which, however, will not exceed a level of a few per cent. Qualitatively, the results of our measurement are in agreement with the predictions of ref. [11] and are in line with the well-known fact that quasi-free $pN \to NK^+\Lambda$ production is the main source of K^+-mesons in pA collisions at 2300 MeV.

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. 3b)) as well as in the deuteron-to-proton ratio. In comparison to 2300 MeV, it increases by a factor of ≈ 25. About 30% of the 321 events in the spectrum form a smooth background of coalescent deuterons, whereas the remaining 220–230 events form the peak structure around 1000 MeV/c. The position and width of the structure depend on the assumptions for the fit. 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. The deduced (peak) deuteron-to-proton ratio is 0.6, *i.e.* much larger than the calculated ratios of the total cross-sections in ref. [11]. However, taking into account that the angular distribution of protons is twice as broad as for deuterons, the ratio reduces to about 0.15. This result is in reasonable agreement with the prediction of ref. [11] if deuteron disintegration in the carbon nucleus is neglected.

The one-peak fit to the experimental data yields a significantly wider distribution than theoretically predicted and is shifted to the low-momentum region. Moreover, the peak structure of fig. 3b) shows a shoulder at the high-momentum tail. A better fit is obtained with three Gaussian peaks (fig. 4a); 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 and

1165 ± 20 MeV/c (≈ 100 MeV/c) for the right one. In this case, the maximum and width of the central peak are closer to the predictions according to ref. [11]. The intensity of the central peak is about four times larger than that of the low- and high-momentum ones together and thus does not change the qualitative statement about the agreement with calculations made before. Taking into account the expected difference in angular distributions of protons and deuterons, the deuteron-to-proton ratio is about 0.11.

As stated above, we assign the central 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 naive phase-space calculations, in which K^+-mesons are produced on ($2N$) clusters inside the nucleus. These might be significantly different from free deuterons, *i.e.* the interparticle separation might be much smaller. The simulations yield two peaks at about 800 MeV/c and 1250 MeV/c (FWHM about 100–150 MeV/c), corresponding 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. Forward-emitted pions have an energy of about 830 MeV (neglecting the intrinsic nucleon momenta), weakly varying with 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 450–500 MeV/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°. Thus, the intensity of the central peak should be proportional to the solid angle covered by the deuteron detector and strongly depend on the part of the kaon momentum spectrum accepted for correlations with deuterons ("2-step cut"). For possible ($2N$) cluster mechanisms, the beam energy of 1200 MeV is less than 60 MeV above the threshold for the $pd \to dK^+\Lambda$ reaction. Since the binding energy of a ($2N$) cluster is at least as large as for two individual nucleons, the excess energy should be even smaller. As a result, the deuterons from the cluster mechanism must have a much narrower, strongly forward-peaked angular distribution ($< 10°$). They correlate with kaons of momenta less than 425 MeV/c, the kinematical upper limit for kaons from the ($2N$) cluster mechanism. A cut on the low-momentum part (< 400 MeV/c) of the kaon spectrum and on correlated deuterons within a reduced angular acceptance (4° instead of 8°) should thus reduce the deuteron peak from the two-step mechanism by a factor of $\sim 2 \times 4$ ("cluster cut"). According to phase-space calculations, no significant changes are expected for the ($2N$) clusters at rest.

The experimental results after applying such cuts are presented in fig. 4b), c) and confirm our naive kinematical considerations. Deuterons, correlated with the most energetic kaons having momenta of 400–610 MeV/c ("2-step cut"), form a 250 MeV/c wide peak (see fig. 4b)) corresponding to the kinematics of the two-step mechanism via the $pN \to d\pi$ reaction. Moreover, even within the moderate statistical accuracy of our experiment two peaks at $p_d \sim 750$ and $\sim$1100 MeV/c are observed (see fig. 4c)) in the deuteron momentum distribution when analysing their correlations with low energetic kaons within a limited angular acceptance ("cluster cut"). It is really surprising that these structures are in reasonable agreement with a phase-space calculation of the $p(2N) \to dK^+\Lambda$ process, taking into account the conditions of the experiment but reducing the mass of two nucleons at rest by 16 MeV. This result is taken as the first indication for a ($2N$) cluster mechanism contributing to subthreshold K^+ production in nuclear targets.

To confirm this result and to understand the nature and characteristics of such clusters in more detail, additional experiments with better statistics are necessary, *e.g.* deuteron angular distributions. The latter is expected to be narrower for clusters than for the two-step mechanism. Furthermore, it will be desirable to measure triple coincidences, the third particle being a proton or a π^- from Λ decay. It is also important to perform an experiment at $T_p = 1000$ MeV, where the $pN \to d\pi$ contribution is predicted to be up to 66% of the total production, mostly in forward direction. In this case K^+ production on ($3N$) clusters may become important, since the beam energy of 1000 MeV is close to the threshold of the $p(3N) \to K^+\Lambda(3N)$ reaction. Such measurements will also be performed with ANKE at COSY-Jülich.

In conclusion, the results of a first experiment on (K^+p) and (K^+d) correlations from pC and pd interactions at energies above and much below the threshold of the elementary kaon-production reaction are discussed. First direct experimental evidence for the two-step process ($pN_1 \to d\pi$, $\pi N_2 \to K^+Y$) and an indication for the cluster mechanism ($p(2N) \to K^+\Lambda d$) are presented for K^+-meson production in pC collisions at $T_p = 1200$ MeV. The contribution of the cluster mechanism is at a level of 30% compared to two-step kaon production with deuteron formation in the first step. It is shown that, by exploiting kinematical criteria, it is possible to study these mechanisms independently. In pC collisions at $T_p = 2300$ MeV and in pd interactions at 1344 MeV both mechanisms are strongly suppressed compared to direct kaon production.

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References

1. V.P. Koptev *et al.*, JETP **67**, 2177 (1988).
2. S. Schnetzer *et al.*, Phys. Rev. C **40**, 640 (1989).

3. M. Büscher *et al.*, Z. Phys. A **335**, 93 (1996).
4. M. Debowski *et al.*, Z. Phys. A **356**, 313 (1996).
5. A. Badala *et al.*, Phys. Rev. Lett. **80**, 4863 (1998).
6. Yu. Kiselev *et al.*, J. Phys. G **25**, 381 (1999).
7. A.V. Akindinov *et al.*, JETP Lett. **72**, 100 (2000).
8. V. Koptev *et al.*, Phys. Rev. Lett. **87**, 022301 (2001).
9. M. Büscher *et al.*, Phys. Rev. C **65**, 014605 (2002).
10. W. Cassing *et al.*, Phys. Lett. B **238**, 25 (1990).
11. A.A. Sibirtsev, M. Büscher, Z. Phys. A **347**, 191 (1994).
12. Yu. Paryev, Eur. Phys. J. A **5**, 307 (1999).
13. H. Müller, K. Sistemich, Z. Phys. A **344**, 197 (1992).
14. A. Bonasera, T. Maruyama, Prog. Theor. Phys. **90**, 1155 (1993).
15. A.A. Sibirtsev, Phys. Lett. B **359**, 29 (1995).
16. A.A. Sibirtsev, W. Cassing, U. Mosel, Z. Phys. A **358**, 357 (1997).
17. W. Borgs *et al.*, COSY Proposal no. 18 (1991), unpublished.
18. M. Büscher *et al.*, Nucl. Instrum. Methods A **481**, 378 (2002).
19. S. Barsov *et al.*, Nucl. Instrum. Methods A **462**, 364 (2001).
20. V. Abaev *et al.*, Phys. Lett. B **521**, 158 (2001).
21. M. Büscher *et al.*, Z. Phys. A **350**, 161 (1994).