Investigation of K$^+$-meson production in pA collisions with ANKE

M. Nekipelov[1,2], V. Koptev [2] for the ANKE collaboration

Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany

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Abstract

In a series of measurements with the ANKE spectrometer at COSY-Jülich, the production of K^+-mesons in pA (A=C, Cu, Ag and Au) collisions in a wide range of beam energies, $T_p = 1.0 \ldots 2.3\,\mathrm{GeV}$, has been investigated. Double differential cross sections $d^2\sigma/d\Omega dp$ have been evaluated. The strong suppression in the ratios of K^+ production on copper, silver and gold targets to that on carbon observed for $p_K < 200$–250 MeV/c may be ascribed to a combination of Coulomb and nuclear repulsion in the K^+A system. Our data are consistent with a K^+A nuclear potential of $V_K^0 \approx 20\,\mathrm{MeV}$ at low kaon momenta and normal nuclear density. First momentum spectra of protons and deuterons measured in coincidence with the K^+-mesons have been obtained at $T_p = 1.2\,\mathrm{GeV}$. These data supply direct evidence for the two-step reaction mechanism, with formation of intermediate pions, leading to kaon production.

Final state interactions of K^+ mesons in nuclei are generally considered to be rather small, due to their strangeness of S=+1. As a consequence, the production of K$^+$-mesons in proton-nucleus collisions is of great importance to learn about either cooperative nuclear phenomena or high momentum components in the nuclear many-body wave function. This is particularly the case since the production of kaons, being relatively heavy as compared to pions, requires strong medium effects.

Measurements of K^+ momentum spectra resulting from proton-nucleus collisions at T_p = 1.0, 1.2, 1.5, 2.0 and 2.3 GeV have been performed with the ANKE spectrometer [1] at the COoler SYnchrotron COSY-Jülich. The spectrometer, including its detectors and the data-acquisition system (DAQ), is optimized to measure K^+ spectra under forward angles $\vartheta_K < 12°$ at different beam energies. The main experimental challenge is that at low energies the background (of mostly pions and protons) is approximately a factor of 10^6 more intense than the signal (kaons). The detection system of ANKE allows to suppress this huge background and to detect rare K^+-mesons in the momentum range $p \approx 150 \ldots 600$ MeV/c. Combining hardware and software criteria such as time-of-flight, information from the wire chambers and delayed signals from the K^+-decay gives us a unique possibility to identify kaons. A detailed description of the kaon detection system is given in Ref. [2].

The double differential cross sections for K^+ production in pC interactions from ANKE are shown in Fig. 1. The cross sections were normalized to known pion-production cross sections measured in similar kinematical conditions [3, 4, 5]. For the lowest incident proton energy it is the first measurement of a complete momentum spectrum at deep subthreshold energies [6].

For some beam energies two sets of measurements were performed, one at a lower magnetic field of the spectrometer magnet ($B = 1.3\,\mathrm{T}$), the second at higher field ($B = 1.6\,\mathrm{T}$). These two modes of the spectrometer allow to explore different regions of the momentum spectra. The first mode with lower field is optimal for the deep subthreshold measurements. In both cases the geometry of the experiment is kept constant, and the telescopes are positioned in the focal surface of the spectrometer magnet. The analysis procedures are identical in both cases, thus allowing to understand possible systematic uncertainties. It is seen in Fig. 1 that in some cases there are discrepancies between different data sets. At $T_p = 1.2\,\mathrm{GeV}$ one can observe perfect agreement, whereas the measurements at $T_p = 2.3\,\mathrm{GeV}$ differ for kaon momenta below 400 MeV/c. Therefore, we have to conclude that there is a yet unknown source of systematic error, which may yield an additional uncertainty up to 30% at the higher beam energies. It should be noted here that these uncertainties vanish when one calculates the cross-section ratios for different target nuclei [7].

[1]E-mail address: m.nekipelov@fz-juelich.de

[2]High Energy Physics Department, Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia

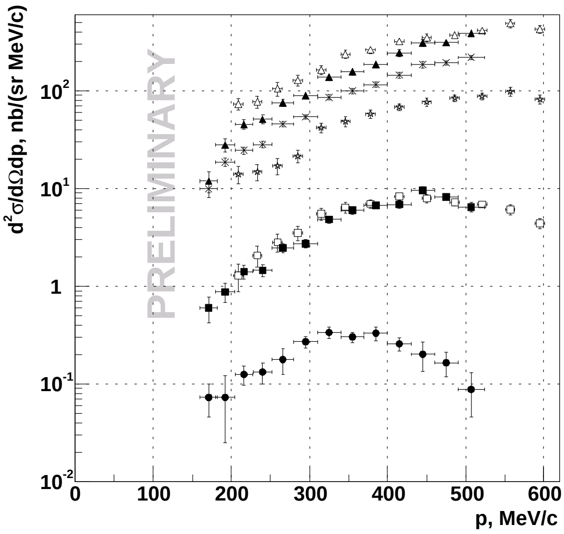

Figure 1: Double differential K^+-production cross sections measured at ANKE. Black circles denote the cross sections measured at $T_p = 1.0\,\mathrm{GeV}$ [6], squares at $T_p = 1.2\,\mathrm{GeV}$, stars at $T_p = 1.5\,\mathrm{GeV}$, crosses at $T_p = 2.0\,\mathrm{GeV}$ and triangles at $T_p = 2.3\,\mathrm{GeV}$. All closed symbols correspond to the measurements with $B = 1.3\,\mathrm{T}$ and $\vartheta < 12°$, while open symbols to $B = 1.6\,\mathrm{T}$ and $\vartheta_v < 3.5°$, $\vartheta_h < 6°$. The error bars are purely statistical.

In addition to the direct production on a single target nucleon the K^+ mesons can also be produced in two-step processes with intermediate pion production, i.e a $pN_1 \to \pi X$ reaction, followed by $\pi N_2 \to K^+X$ on a second target nucleon. Depending on the beam energy, K^+-production may be due to both the direct and two-step reaction mechanisms. At low beam energies

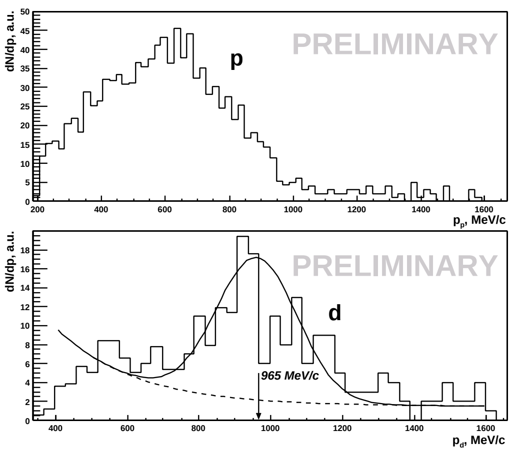

Figure 2: Coincident proton and deuteron momentum spectra at $T_p = 1.2\,\mathrm{GeV}$. The solid line shows the result of a fit to the data. The arrow indicates the position of the peak maximum.

the two-step process is energetically favorable since the intrinsic nucleon motion can be utilized twice.

If one takes a closer look to the first chance collision of the two-step production mechanism, it becomes clear that there are two possible scenarios: $pN \to NN\pi$ and $pN \to d\pi$. It has been suggested that at an incident proton beam energy of $T_p = 1.0\,\mathrm{GeV}$ the pions from the $d\pi^+$ process can contribute as much as about 25% to further kaon production [8, 9]. Especially favorable are processes in which the deuteron is emitted backward in the $d\pi$ CMS, since this leads to production of high-momentum pions. On the other hand the influence of deuteron break-up in the nucleus might be so important, that one can not observe any coincident deuterons.

Though the results of the calculations performed in the framework of the coupled channel transport model [10, 11] agree rather well with the experimental data at $T_p = 1.0\,\mathrm{GeV}$ and at $T_p = 2.3\,\mathrm{GeV}$ [10], a strong underestimate of the data is observed at $T_p = 1.2\,\mathrm{GeV}$. This may be due to the fact that the contribution of $pN \to d\pi$ and of kaons produced on few-nucleon clusters are not taken into account in the calculations. If this is the reason for the discrepancy, it may also affect the calculations of the cross sections at $T_p = 1.0$ GeV.

Since the analysis of the K^+ production cross sections as well as their target mass dependence does not yet allow an unambiguous conclusion about the underlying reaction mechanism [6, 12], it was proposed [13] to investigate the production of K^+ mesons correlated with protons [14] and deuterons [9] from one-step or two-step production mechanisms. The K^+d final state can only be observed in case of the two-step reaction, while K^+p pairs come both from the two-step and direct production.

Measurement of K^+p and K^+d coincidences has been performed at $T_p = 1.2$, 1.5 and 2.3 GeV. The amount of detected deuterons decreases with increase of T_p, though they are quite abundant at $T_p = 1.2$ GeV. This is in line with the statement, that the contribution of the two-step mecha-

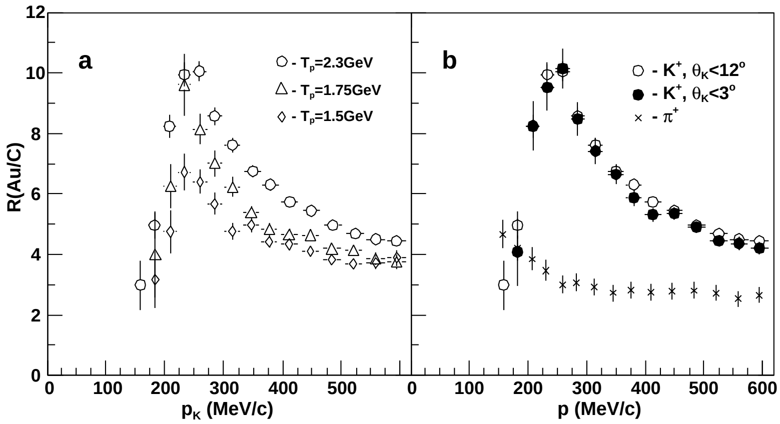

Figure 3: Ratios of K$^+$(π^+) production cross sections for Au and C measured at different beam energies (a) and kinematic conditions (b) as functions of the laboratory meson momentum. a) All the symbols correspond to kaons measured in the full ANKE acceptance ($\vartheta < 12°$). b) The open circles are as in the left figure, whereas the closed circles correspond to kaons measured in the restricted angular interval ($\vartheta < 3°$). The π^+-production cross-section ratios of Au to C at $T_p = 2.3$ GeV are designated by crosses. The figure has been taken from Ref.[7].

nism decreases when approaching the threshold from below and becomes almost negligible at high energies.

The momentum spectra of protons and deuterons correlated with kaons are shown in Fig. 2. The emission angles of those particles were restricted to $\vartheta < 8°$. A peak structure in the momentum distribution of deuterons is clearly seen. The peak position is at $p_d \approx 965$ MeV/c, which is close to the expected value for on-shell two-body kinematics, $pN \to d\pi$, with a backward emitted deuteron in the CMS. This spectrum can be considered as a direct experimental prove of the two-step production below threshold. Additionally, a hint on the enhancement in the region of ~ 400 MeV/c on the proton momentum spectrum may correspond to the region of the final-state interaction of two outgoing nucleons.

Model calculations still have to show whether the observed peak structure cannot be faked by the processes like coalescence and pick-up reactions. According to [9] coalescence deuterons behave as indicated by the dashed line in Fig. 2. In the reactions like $pC \to dK^+\Lambda X$ there are few possible sources for the deuteron formation. In addition to already mentioned ones, the production on the two-nucleon clusters are also possible as well as the production on three- and more-nucleon clusters.

As already stated, the analysis of the target-mass dependence of the cross sections [12] does not allow to fix the underlying production mechanisms, though reveals other interesting aspects of the K^+ production on nuclei related to the final-state interactions effects.

The gold/carbon ratio is shown in Fig. 3a for $T_p = 2.3$, 1.75 and 1.5 GeV. This ratio has a broadly similar shape at all three energies, with clear maxima for $p_{\max} \approx 245$ MeV/c coinciding within 2 MeV/c. For higher kaon momenta the ratios decrease monotonically with p_K. For low kaon momenta one sees a dramatic fall in the ratio R(Au/C). To ensure that this phenomenon is not an artefact of the ANKE detection system, the 2.3 GeV run was carried out in the operations modes of $B = 1.3$ T and 1.6 T. The low p_K suppression remained unchanged. Identical ratios

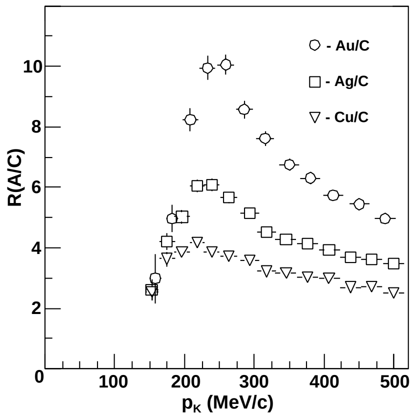

Figure 4: Ratios of the K^+ production cross sections on Cu, Ag, and Au measured at $T_p = 2.3\,\mathrm{GeV}$ as a function of the laboratory kaon momentum. The figure has been taken from Ref.[7].

were also obtained when the polar K$^+$ emission angles in data analysis were restricted to lie below $\vartheta_K = 3°$ (see Fig. 3b).

Ratios of kaon-production cross sections for copper, silver and gold targets measured at 2.3 GeV are presented in Fig. 4. All data exhibit similar shapes, but the position of the maximum varies with the nucleus, a fit to the data results in $p_{\max}(\mathrm{A/C}) = 245 \pm 5$, 232 ± 6, and $211 \pm 6\,\mathrm{MeV/c}$ for Au, Ag, and Cu, respectively.

It is clear from Fig. 3 that the suppression of $R(\mathrm{Au/C})$ at low p_K is largely independent of beam energy and of the angular acceptance of the spectrometer, suggesting that the phenomenon is principally due to the interaction of the K^+ with the residual nucleus. On the other hand, Fig. 4 shows that the position of the maximum in $R(\mathrm{A/C})$ 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.

It is, moreover, known from K^+ elastic scattering experiments at higher energies [15] that the K^+A potential is mildly repulsive, and this is in accord with one-body optical potentials based upon low-energy K^+N scattering parameters [16]. At normal nuclear density, $\rho_0 \approx 0.16\,\mathrm{fm}^{-3}$, the predicted repulsive K^+A potential of strength $V_K^0 \sim 20\,\mathrm{MeV}$ [17] would shift $p_{\min}$ to higher values.

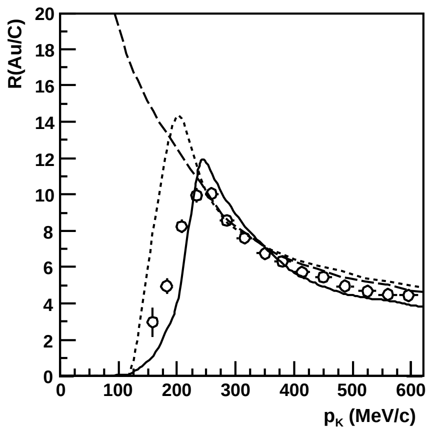

Figure 5: Ratios of K^+ production cross sections for Au/C at $T_p = 2.3\,\mathrm{GeV}$ as a function of the kaon momentum. The open circles are the experimental data. The dotted line is obtained from transport calculations including only the Coulomb potential, the solid line corresponds to calculations with the addition of a kaon potential of 20 MeV at ρ_0 (the baryon potential is also included). The dashed line corresponds to simulations without Coulomb and nuclear kaon potentials. In all cases considered here, K^+ rescattering in the nucleus has been taken into account. The figure has been taken from Ref.[7].

Results of calculations in the framework of the coupled channel transport model [10, 11] for the $R(\mathrm{Au/C})$ ratio are shown in Fig. 5. Without including the Coulomb and kaon potentials (dashed line in Fig. 5) 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. A behavior of this type was observed in π^+ production, which was also measured in a short test experiment (see Fig. 3b). In this case the influence of the Coulomb potential is expected to show up below $p_\pi \approx 80\,\mathrm{MeV/c}$, which was below our acceptance limit. For kaons the pure Coulomb interaction leads to a distortion of the momentum spectrum and provides a maximum at $p_K \approx 200\,\mathrm{MeV/c}$ (dotted line in Fig. 5).

An additional change is observed in the calculations when a repulsive kaon nuclear potential is also considered. When a kaon potential of $V_K^0 = 20\,\mathrm{MeV}$ is used in the calculations, a reasonable agreement with the experiment is achieved, with a maximum close to the experimental value of $245 \pm 5\,\mathrm{MeV/c}$ (solid line in Fig. 5). To take into account the interactions of the incident proton, a baryon potential has also been included. It is expected that after refined model calculations the strength of V_K^0 may be determined to better than 3 MeV [7], which is much better than that from heavy-ion data at $\rho > \rho_0$ [17].

In summary, the double differential cross sections for K^+-production have been obtained at different incident proton beam energies, $T_p = 1.0\ldots 2.3\,\mathrm{GeV}$. Correlated deuterons have been observed together with the kaon. Their amount increases with decreasing energy which indicates that two-step production becomes more important below threshold. The momentum spectrum of deuterons at $T_p = 1.2\,\mathrm{GeV}$ gives an experimental indication for the two-step mechanism and, in particular, of the $pN_1 \to d\pi$ process, followed by $\pi N_2 \to K^+X$ on a second target nucleon. We have observed a strong suppression of the ratio of low-momentum K^+ production on heavy nuclei to that on carbon. The independence of this effect from the beam energy and the variation of the structure with A provides clear evidence for the influence of the K^+ Coulomb and nuclear interaction potentials. The preliminary analysis suggests that the K^+ nuclear potential at normal nuclear matter density is of the order of 20 MeV, which is in line with K^+ elastic scattering experiments [15] and low-energy K^+N scattering parameters [16] and analyses of heavy-ion data [18, 19].

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