Measurement of Subthreshold K^+-Production in pA Collisions with ANKE *

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The magnetic spectrometer ANKE has been put into operation in spring 1998 at the cooler synchrotron COSY-Jülich. ANKE allows to momentum analyze ejectiles emitted from an internal target at forward angles $\vartheta \approx 0°$ with high angular acceptance $\Delta\Omega \approx 50$ msr. A primary goal of the physics program with ANKE is the investigation of K^+-production in proton-nucleus collisions at energies around and far below the free nucleon-nucleon threshold at $T = 1.58$ GeV. The measurements have been performed with C, Cu and Au targets at various energies in the range $T = 1.0 \ldots 2.3$ GeV. The major experimental challenge is that the kaon-to-background ratio is as low as $\sim 10^{-6}$ at the lowest energy. Data on the target-mass dependence of the production cross sections for kaon momenta $p_{K^+} = 150 \ldots 510$ MeV/c at beam energies of $T = 1.0$ and 2.3 GeV are presented.

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1. The ANKE spectrometer

In ANKE [2, 3, 4] forward-emitted products from proton-induced reactions are separated from the circulating beam of COSY [5] and their emission angles and momenta are determined. Three dipole magnets guide the beam out of its nominal path in a straight section of the race-track shaped accelerator ring towards the target and back into the standard orbit. The central magnet D2, see Fig.1, has a gap of 20 cm height, thus providing a large solid angle for measurements at low cross sections. The detection system for the K^+-identification is sketched in Fig.1. It provides a horizontal (vertical) angular acceptance of $\vartheta \sim -12° \ldots +12°$ ($|\varphi| < 3.5 \ldots 5.5°$).

The detectors consist of: *i)* 23 Start counters close to the Al vacuum window at the side of D2. *ii)* 15 telescopes [3, 6] which are placed at the D2 focal surface to detect positively charged ejectiles in the momentum range from 110 to 525 MeV/c (at $B = 1.3$ T in D2). Each of the range telescopes (see Fig. 1) is composed of Stop, ΔE, Veto scintillation counters and two degraders made of copper. Telescopes #9–15 contain also lucite Cherenkov counters. *iii)* 2 multi-wire proportional chambers (MWPC1 and MWPC2) which are used to reconstruct ejectile trajectories. Each of them has three anode planes with vertically and $\pm 30°$ inclined tungsten wires.

For the K^+-identification the following information from the detection system is utilized — see [3, 4] for a more detailed description of the data analysis:
i) The ejectile momenta are within $\sim 10\%$ defined by the 10 cm wide telescopes at the focal surface of D2. They were kept constant for all beam

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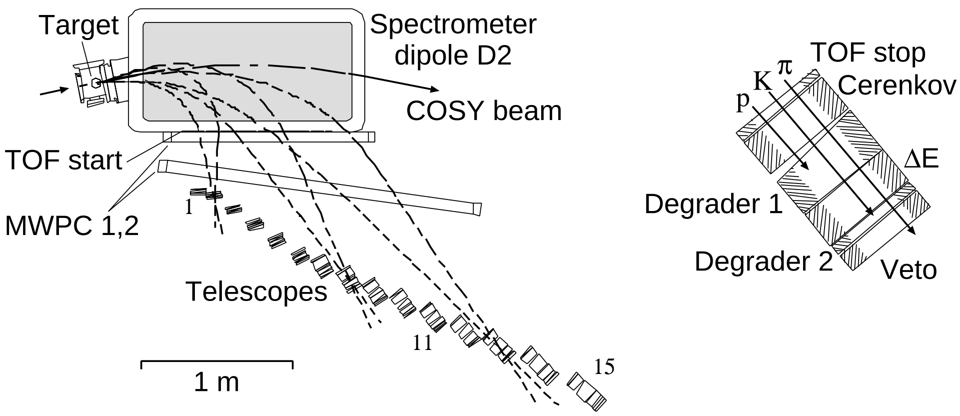

Fig. 1. Top view of the ANKE spectrometer and telescope #14 in the K^+-detection system.

energies by fixing the D2-field strength and the relative target-D2-detector geometry. *ii)* For a given momentum pions, kaons and protons have different ranges. The thicknesses of the scintillators and of the degraders were chosen such that protons from the target are stopped before they reach the ΔE counters. Kaons are stopped in the second degraders or in the far end of the ΔE counters whereas pions and scattered protons with the same velocity as kaons traverse all counters of the telescopes if they do not undergo a nuclear reaction. The degraders installed in front of the ΔE counters are tapered to compensate for the momentum spread across each telescope. *iii)* Fast hardware coincidences between the Start and Stop counters allow to select particles with the same momentum but different emission angles and to set narrow gates on the TOF spectra for kaons. *iv)* The decay of kaons with a mean lifetime of 12.4 ns is a strong criterion for the selection of K^+ candidates. Only events have been accepted with signals in the Veto counters delayed by more than 1.3 ns with respect to prompt particles detected in the same telescope. A combination of criteria *i)* – *iv)* together with an off-line analysis of the MWPC information and of energy losses in all scintillation counters permits to identify kaons even at $T = 1.0$ GeV. The measurements with the different targets were carried out under identical settings of the spectrometer dipole D2 and the detection system. Thus, the detection efficiencies for kaons (and pions) produced in the different targets are equal.

2. Target-mass dependence of the K$^+$-production cross sections

In order to extract absolute double differential cross sections from the number of identified kaons, one has to correct for kaon decay-in-flight between target and telescopes, the angular-momentum acceptances, the detection efficiencies in the scintillators, MWPC inefficiencies and dead-time effects. These analyses are in progress now. However, already at the current stage of the analysis one can extract the cross section ratios for the different targets (and thus the mass dependence of the K$^+$-production cross section) using the formula:

$$\frac{\sigma_A^{\mathrm{K}^+}}{\sigma_{\mathrm{C}}^{\mathrm{K}^+}}(p_{K^+}) = \left[\frac{n_A^{\mathrm{K}^+}}{n_{\mathrm{C}}^{\mathrm{K}^+}}\right]_{\mathrm{tel.}(i)} \cdot \frac{\mathcal{L}_{\mathrm{C}}}{\mathcal{L}_A} \,. \qquad (1)$$

Here the index "A" stands for the copper and gold targets, respectively, while "C" refers to carbon. n^{K^+} is the number of identified kaons in each telescope i normalized to the proton-beam flux. Monitoring of the proton beam interacting with the target was done with an accuracy of 2% using telescopes #2–5 in 4-fold coincidence and thus selecting ejectiles from the target which pass by the spectrometer dipole D2 (see Fig. 1). $\mathcal{L}$ stands for the integrated luminosity during data taking for the particular target. The luminosity ratio can be deduced from the ratio of pion rates, measured under identical experimental conditions for each target during calibration runs using an on-line trigger optimized for π^+ detection:

$$\frac{\mathcal{L}_{\mathrm{C}}}{\mathcal{L}_A} = \left[\frac{n_{\mathrm{C}}^{\pi^+}}{n_A^{\pi^+}}\right]_{\mathrm{tel.}\#15} \cdot \left[\frac{\sigma_A^{\pi^+}}{\sigma_{\mathrm{C}}^{\pi^+}}\right]_{p=500\ \mathrm{MeV/c}} \,. \qquad (2)$$

In Eq.(2) n^{π^+} is the number of pions detected by telescope #15 with momenta of 490...525 MeV/c, normalized to the proton-beam flux (see above). For a momentum of 500 MeV/c the ratio of the pion-production cross sections σ^{π^+} can be extracted from experimental data [7, 8, 9] taken in the energy range $T = 0.73 \ldots 4.2$ GeV at emission angles of 0°, 2.5° and 15°. Figure 2 shows the cross-section ratios for Cu/C and Pb/C calculated from those data.

From Fig. 2 one can deduce the π^+-production ratios for Cu/C and Au/C at $T = 1.0$ GeV and 2.3 GeV: for Cu/C values of 1.81 ± 0.05 at $T = 1.0$ GeV and 1.88 ± 0.18 at $T = 2.3$ GeV are obtained. For Pb/C the cross section ratios from Fig. 2 are 2.34 ± 0.07 at $T = 1.0$ GeV and 2.80 ± 0.29 at $T = 2.3$ GeV. These values agree within 10% with ratios scaling as $A^{1/3}$ ($= 2.58$). Thus, assuming an $A^{1/3}$ dependence, it is possible to calculate from the ratios Pb/C those for Au/C. We use for the ratio Au/C values of

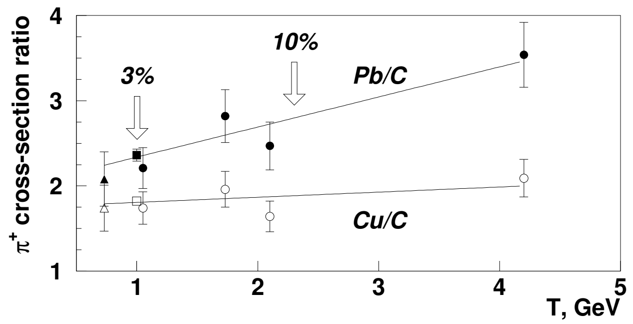

Fig. 2. Ratios of the π^+-production cross sections for Cu/C and Pb/C at $p_\pi = 500$ MeV/c as a function of the projectile energy T. The data were taken from [7] (triangles, $T = 0.73$ GeV, $\vartheta_\pi = 15°$), [8] (squares, $T = 1.0$ GeV, $\vartheta_\pi = 0°$) and [9] (circles, $T = 1.05 \ldots 4.2$ GeV, $\vartheta_\pi = 2.5°$). The lines are linear fits to the data points. The arrows indicate the energies measured at ANKE; the uncertainties of the ratios at these energies are indicated.

2.29 ± 0.07 at $T = 1.0$ GeV and 2.73 ± 0.27 at $T = 2.3$ GeV. Note that the analysis of our π^+-data shows that the cross section ratios (within 2%) are independent of the π^+-emission angle within the ANKE angular acceptance $|\vartheta_\pi| < 12°$.

Figure 3 shows the deduced K$^+$ cross-section ratios at $T = 2.3$ GeV using Eqs.(1),(2) and the π^+-ratios given above. The error bars include only the statistical uncertainties of the kaon data. From the normalization by the pion ratios, an additional overall uncertainty of $\sim 10\%$ has to be added. It can be seen from Fig. 3 that for Cu/C the ratio decreases slowly with increasing kaon momenta. For Au/C there is a pronounced maximum at $p \sim 250$ MeV/c. First theoretical analyses indicate that this behaviour can be due to rescattering of the produced kaons in the nuclear environment [10]. These processes tend to slow down the produced kaons and lead to emission angles out of the ANKE angular acceptance.

The momentum-integrated cross-section ratios for the highest energy measured at ANKE has been deduced from the data in Fig. 3 for Cu/C:

$$\left\langle \frac{\sigma^{\mathrm{K}^+}_{\mathrm{Cu}}}{\sigma^{\mathrm{K}^+}_{\mathrm{C}}} \right\rangle_{p=150...510 \ \mathrm{MeV/c}} = 3.6 \pm 0.4 \qquad (T = 2.3 \ \mathrm{GeV}) \ , \tag{3}$$

and for the ratio Au/C:

$$\left\langle \frac{\sigma^{\mathrm{K}^+}_{\mathrm{Au}}}{\sigma^{\mathrm{K}^+}_{\mathrm{C}}} \right\rangle_{p=150...510 \ \mathrm{MeV/c}} = 6.6 \pm 0.7 \qquad (T = 2.3 \ \mathrm{GeV}) \ . \tag{4}$$

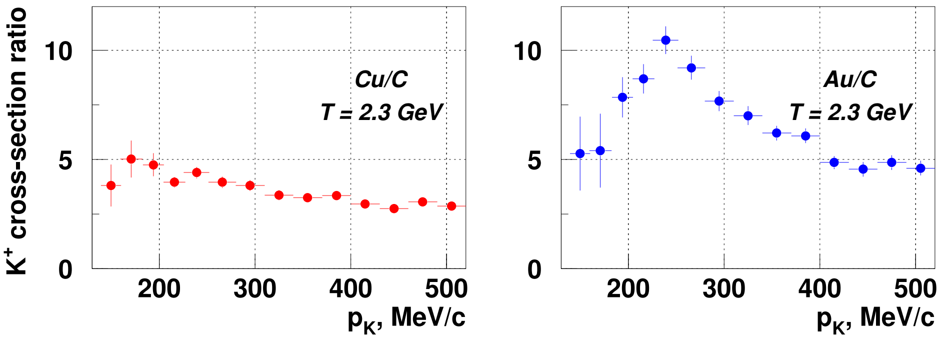

Fig. 3. Ratios of the K$^+$-production cross sections for Cu/C and Au/C as a function of the kaon momenta. Due to large background in telescope #1 the cross-section ratios are only shown for telescopes #2–15. The horizontal error bars indicate the momentum range covered by each telescope.

Note that these ratios are in rather good agreement with an $A^{2/3}$ dependence of the total cross sections, which is expected if the kaons are produced by first-chance proton-nucleon collisions (see e.g. [11, 12, 13, 14]). In this case one would expect total cross-section ratios of ~ 3.0 for Cu/C and ~ 6.5 for Au/C. Thus, our values are in good agreement with expectations from a simple geometrical model for kaon production.

A similar analysis at the lowest beam energy yields for the momentum-integrated ratio of the K$^+$-production cross sections for Cu/C:

$$\left\langle \frac{\sigma_{\rm Cu}^{\rm K^+}}{\sigma_{\rm C}^{\rm K^+}} \right\rangle_{p=150\ldots510\ {\rm MeV/c}} = 5.6 \pm 0.5 \qquad (T = 1.0\ {\rm GeV})\ , \qquad (5)$$

and for the ratio Au/C:

$$\left\langle \frac{\sigma_{\rm Au}^{\rm K^+}}{\sigma_{\rm C}^{\rm K^+}} \right\rangle_{p=150\ldots510\ {\rm MeV/c}} = 9.2 \pm 1.2 \qquad (T = 1.0\ {\rm GeV})\ . \qquad (6)$$

It has been shown [11, 12, 13, 14] that at low beam energies the K$^+$-production proceeds dominantly via two-step mechanisms where in a first proton-nucleon collision an intermediate pion is produced. After a subsequent collision of this pion with a second nucleon the K$^+$-meson is emitted together with a hyperon. For such mechanisms one expects a scaling of the total K$^+$-production cross section roughly like $\sigma \propto A$ [11]. It is interesting to note that for Cu/C the predicted values (5.3 from [11] and 5.7 from [12]) are in good agreement with our data. However, for Au/C one would expect total ratios of ~ 16 [11] (or ~ 14 from [12]) which are much larger than our value of 9.2 ± 1.2 (within the ANKE acceptance). Currently, theoretical analyses are in progress in order to understand the apparently smaller number of produced kaons for the heavy gold target.

Summarizing, differential data on K^+-meson production in proton-nucleus collisions have been obtained above and far below the free nucleon-nucleon threshold for various target nuclei. The mass dependences of the cross sections under forward angles indicate the importance of K^+-rescattering effects. Further analyses, like the extraction of absolute cross sections, are in progress.

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