Forward K^+ Production in Subthreshold pA Collisions at 1.0 GeV

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K^+-meson production in pA ($A = C, Cu, Au$) collisions has been studied using the ANKE spectrometer at an internal target position of the COSY-Jülich accelerator. The complete momentum spectrum of kaons emitted at forward angles, $\vartheta \leq 12°$, has been measured for a beam energy of $T_p = 1.0$ GeV, far below the free NN threshold of 1.58 GeV. The spectrum does not follow a thermal distribution at low kaon momenta and the larger momenta reflect a high degree of collectivity in the target nucleus.

A central topic of hadron physics is the influence of the nuclear medium on elementary processes. This question can be studied by measuring the production of mesons in nuclei using projectiles with energies below the threshold for free NN collisions (so-called subthreshold production). These processes necessarily involve cooperative effects of the nucleons inside the target nucleus. The investigation of K^+ production is particularly well suited for this purpose since the meson is relatively heavy so that its production requires strong medium effects. Furthermore, the K^+ scatters little in nuclear matter so that its final-state interactions are expected to be small.

Proton-induced K^+ production at subthreshold energies has been studied at several accelerators. Total cross sections have been measured at the Petersburg Nuclear Physics Institute (PNPI) synchrocyclotron for targets between Be and Pb and projectile energies T_p from 0.8 to 1.0 GeV [1]. The results were discussed in terms of different models [1–5], in particular, of single- or two-step reactions involving the creation of an intermediate pion. It was concluded that additional experimental data were needed for an unambiguous determination of the reaction mechanism and the extraction of the information on nuclear-medium effects. Inclusive differential cross sections for pA interactions have been studied at BEVALAC [6], SATURNE [7], and CELSIUS [8]. Partial momentum spectra have been obtained at laboratory emission angles of 10°, 15°, 35°, 40°, 60°, 80°, and 90°, at projectile

energies down to 1.2 GeV, and evidence for the dominance of the two-step processes has been observed at the lowest T_p. Subthreshold production has also been studied at the Institute of Theoretical and Experimental Physics (Moscow, Russia) synchrotron [9], where kaons with high momenta were identified at projectile proton energies of 1.75 to 2.6 GeV, and in heavy-ion reactions at GANIL [10] and GSI [11].

The COoler SYnchrotron COSY-Jülich [12], which provides proton beams in the range $T_p = 0.04–2.65$ GeV, is well suited for the study of K^+ production. In measurements with very thin windowless internal targets, secondary processes of the produced mesons can be neglected. Subthreshold K^+ production was a prime motivation for building the ANKE spectrometer [13,14] within one straight section of the COSY ring. It consists of three dipole magnets $D1–D3$, see Fig. 1, which separate forward-emitted reaction products from the circulating proton beam and allow a determination of their emission angles and momenta. The layout of the device, including detectors and the data-acquisition (DAQ) system, was optimized for the study of K^+ spectra down to $T_p = 1.0$ GeV. This is a very demanding task because of the small K^+ production cross sections, e.g., 39 nb for pC collisions at 1.0 GeV [1]. Kaons have to be identified in a background of secondary protons and pions which is up to 10^6 times more intense. K^+ identification is described in detail in [15,16]; only basic features of the procedures are summarized here.

The COSY ring was filled with $2–4 \times 10^{10}$ protons per cycle and cycle times were typically 30 s. The protons were accelerated to 1.0 GeV on an orbit below the target and then raised by steerers such that the rate in the ANKE detectors was kept constant and on a level that could be handled by the DAQ system. Thin strip targets of C (polycrystalline diamond), Cu, and Au with thicknesses of $40–1500$ μg/cm^2 were used. Reaction products were detected with an array of 15 range telescopes posi-

FIG. 1. Top view of the ANKE spectrometer in the COSY ring and detectors used for K^+ identification. The inset shows the components of one of the range telescopes. Typical kaon trajectories are indicated. Details can be found in [13–16].

tioned along the focal surface. The time of flight (TOF) was measured with 0.5 to 2 mm thick start scintillators (23 detectors of 5 cm width) and 1 cm thick (10 cm wide) stop scintillators which are components of the telescopes; see Fig. 1. Because of the momentum focusing of the dipole $D2$, the telescopes can be used to identify different ejectiles via their ranges: protons are stopped before reaching the ΔE counters, K^+ mesons come to rest before the veto counters, while pions give signals in all detectors. Copper degraders are used to slow down the kaons in front of the ΔE counters (degrader 1) and prevent them from reaching the veto counters (degrader 2). Pions and muons from the decay of stopped kaons are emitted isotropically, and partially detected in the veto counter, with a characteristic delay corresponding to the kaon lifetime $\tau = 12.4$ ns. The multiwire proportional chambers MWPC 1 and 2 allow one to determine the ejectile tracks and hence separate particles originating from the target from scattered background, e.g., from the pole shoes of $D2$. Applying the criteria (i) TOF, (ii) energy losses in the scintillation counters, (iii) delayed signals in the veto counters, and (iv) track origin in the target, it is possible to identify unambigously K^+ mesons [15]. Criteria (i) and (iii) were applied on-line to decrease the amount of data written to tape.

The typical number of identified K^+ mesons, $N^K_{\text{tel}(i)}$, in one telescope i during a four days run on C was 100. Since each telescope covers a given momentum range, the $N^K_{\text{tel}(i)}$ determine directly the momentum distribution. The accepted momentum bites range from 13% at the low-momentum side of the telescope array ($\sim$150 MeV/c) to 7% for high momenta ($\sim$510 MeV/c). The vertical angular acceptance of ANKE varies between $\vartheta_V = \pm 7°$ and $\pm 3.5°$ for the low- and high-momentum telescopes, respectively. In the horizontal direction, ejectiles with emission angles $|\vartheta_H| \leq 12°$ were accepted by the on-line TOF-trigger system [15].

Double differential cross sections for K^+ production were obtained from $N^K_{\text{tel}(i)}$ by comparison with the number of pions $N^\pi_{\text{stop}(i)}$ detected in the stop counters of the same telescope, which were measured in dedicated calibration runs. The ratio of K^+ and π^+ counts was corrected for the different detection efficiencies ϵ and normalized to the corresponding luminosities (deduced from count rates M^π and M^K in monitor counters; see below) and to the cross sections of π^+ production in pC interactions in the forward direction at 1.0 GeV [17–19]. Because of their much larger production cross section, pions can be identified applying only criteria (i) and (iv). The cross section is thus given by

$$\frac{d^2\sigma^K}{d\Omega\,dp} = \frac{d^2\sigma^\pi}{d\Omega\,dp}\frac{N^K_{\text{tel}(i)}}{N^\pi_{\text{stop}(i)}}\frac{M^\pi}{M^K}\frac{1}{\epsilon},$$

$$\epsilon = \frac{\epsilon^K_{\text{tel}(i)}\epsilon^K_{\text{MWPC}(i)}\epsilon^K_{\text{decay}}}{\epsilon^\pi_{\text{stop}(i)}\epsilon^\pi_{\text{MWPC}(i)}\epsilon^\pi_{\text{decay}}},$$

(1)

where $\epsilon^K_{\text{tel}(i)}$ is the K^+-identification efficiency of the ith telescope including the detection probability for the decay
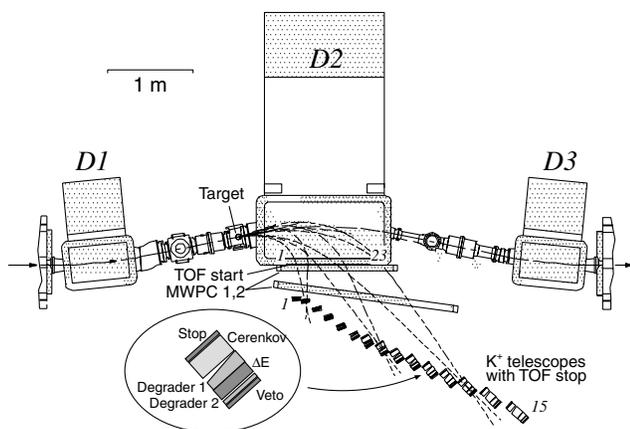
muons and pions. Only events where veto counter signals were delayed by at least 2.5 ns with respect to those of the stopped kaons were considered. The efficiencies, $\epsilon^K_{\text{tel}(i)} \sim$ 0.1–0.3, were obtained from a calibration run at $T_p =$ 2.3 GeV, where K^+ production is significantly larger [15].

The average pion detection efficiencies are $\epsilon^\pi_{\text{stop}(i)} =$ 0.98. The MWPC efficiencies ϵ_{MWPC} are in the range 0.97–0.99 both for pions and kaons. $\epsilon^K_{\text{decay}}$ and $\epsilon^\pi_{\text{decay}}$ take into account losses in flight between target and stop counters; they were determined by simulations as 0.30–0.36 for kaons and 0.85–0.88 for pions. Relative monitoring of the proton beam interacting with the target nuclei A (M^K_A and M^π_A) was done with an accuracy of 2% using fourfold coincidences of stop counters 2, 3, 4, and 5, which in this arrangement directly look to the target detecting ejectiles bypassing the spectrometer dipole $D2$.

Our double differential cross section for K^+ production in proton-carbon interactions at $T_p = 1.0$ GeV is shown in Fig. 2(a). In contrast to measurements at higher energies [6–9,20], ANKE reveals, for the first time, a complete momentum spectrum at deep subthreshold energies.

The *low-momentum* part of the K^+ spectrum in Fig. 2(b) cannot be described by a thermal distribution, $E/p^2 d^2\sigma/dp\,d\Omega \propto \exp(-T^\star/T_0)$, where $T^\star$ is the K^+ kinetic energy in the beam-proton nucleus system. Such distributions had been assumed to deduce total cross sections from earlier measurements with limited momentum intervals [6–8,20].

A high degree of collectivity is needed in the target nucleus to allow K^+ production far below the free NN threshold; i.e., the number of target nucleons involved must be significantly larger than 1 [1–5]. Alternatively, high in-

FIG. 2. (a) Double differential K^+-production cross section for the $p(1.0 \text{ GeV})^{12}\text{C} \to K^+(\vartheta \leq 12°)X$ reaction as a function of the K^+ momentum. (b) Same data plotted as invariant cross section. The error bars are purely statistical. The overall normalization uncertainty is estimated to be 10%. The solid lines describe the behavior of the invariant cross section within a phase-space approximation [Eq. (2)].

trinsic momenta of the participating target nucleon(s) are required to supply the missing energy for subthreshold kaon production. This is particularly the case for the *high-momentum* part of the kaon spectrum: internal momenta of a single nucleon of at least $p_N \sim 350(550)$ MeV/c would be needed in order to produce kaons in the forward direction with momenta of $p_K \sim 260(500)$ MeV/c. High momentum components above $\sim$500 MeV/c are essentially due to many-body correlations in the nucleus [21].

To get a rough estimate of the number of participating nucleons, we describe the invariant cross section within a phase-space approximation. This method has previously been applied to K^+-production data [20] in order to compare spectra obtained under different kinematical conditions [6,7,20]. The invariant cross section for the $p + (lN) \to (lN) + \Lambda + K^+$ reaction is then

$$\frac{E}{p^2}\frac{d^2\sigma}{dp\,d\Omega} \propto \frac{\sqrt{(s_l - m_\Lambda^2 - l^2 m_N^2)^2 - 4m_\Lambda^2 l^2 m_N^2}}{s_l}, \quad (2)$$

where m_Λ and m_N are the Λ and nucleon masses, respectively. l is the number of nucleons involved in the interaction and

$$s_l = s + m_K^2 - 2E_K(T_p + [l+1]m_N) + 2p_K p_p \cos\theta_K. \quad (3)$$

m_K, E_K, p_K, and θ_K are the kaon mass, total energy, momentum, and emission angle, respectively, while T_p and p_p denote the beam energy and momentum. s is the square of the center-of-mass energy of the incident proton and the l target nucleons. The solid lines in Fig. 2(b) show the momentum dependence of the invariant cross section from Eq. (2) for $l = 4, 5, 7$. Although this neglects the intrinsic motion of the l target nucleons, it shows that kaon production at $T_p = 1.0$ GeV can be understood only in terms of cooperative effects with the effective number of nucleons involved in the interaction being $\sim$5–6. It has been suggested [1–5] that such cooperative effects can be described in terms of multistep mechanisms or high-momentum components in the nuclear wave function.

It has also been pointed out [1–5] that the mechanism of subthreshold K^+ production might be identified from the A dependence of the production cross section. The total cross sections measured at PNPI in the energy range $T_p = 0.8–1.0$ GeV scale as $\sigma_{\text{tot}} \propto A^1$ [1]. This behavior has been interpreted in terms of a two-step mechanism with the formation of an intermediate π meson.

We used targets of widely different masses to determine the A dependence of the differential cross sections. All measurements were carried out with the same geometry and detection system at ANKE and the same proton beam settings. The ratios of the kaon-production cross sections for various nuclei as a function of kaon momentum $\sigma^{K^+}_A/\sigma^{K^+}_C$ are therefore equal to the corresponding ratios of kaon count rates in the individual telescopes, normalized to the pion cross-section ratio at a momentum of

507 ± 17 MeV/c detected in telescope No. 15:

$$\left(\frac{\sigma_A^K}{\sigma_C^K}\right)_{(i)} = \left(\frac{N_A^K}{N_C^K}\right)_{(i)} \frac{M_C^K}{M_A^K} \left(\frac{N_C^\pi}{N_A^\pi}\right)_{(15)} \frac{M_A^\pi}{M_C^\pi} \left(\frac{\sigma_A^\pi}{\sigma_C^\pi}\right)_{(15)}. \quad (4)$$

The cross-section ratios for producing pions with momenta around 500 MeV/c in the forward direction in pA collisions were measured to better than 10% by several groups in the 0.73–4.2 GeV energy range [16–19]. All uncertainties from the efficiency correction ϵ in Eq. (1) cancel out for such ratios. The results for Cu/C and Au/C are shown in Fig. 3.

The ratios are almost independent of the K^+ momentum. The solid lines in Fig. 3 indicate fits with constant values; $R(\mathrm{Cu/C}) = 4.0 \pm 0.3$ and $R(\mathrm{Au/C}) = 6.8 \pm 0.8$. These values should be compared to the expected ratios if the cross sections scaled as A^1: $R(\mathrm{Cu/C}) \sim 5$ and $R(\mathrm{Au/C}) \sim 16$. Our data show a significantly weaker A dependence with an exponent closer to 2/3. This is in contrast to the behavior of the total cross sections at the same beam energy found in [1], where kaon production was described in terms of the two-step mechanism. It is possible that, due to rescattering of the produced kaons in the target nucleus out of the angular acceptance of ANKE, there is a kaon deficiency at high momenta and small angles. Since this effect should be stronger for heavier targets, it might account for the weaker A dependence of the differential cross section.

Summarizing, we have measured small-angle K^+ production at $T_p = 1.0$ GeV, which is far below the free NN threshold. The low-momentum part of the K^+ spectrum does not follow a thermal distribution whereas the high-momentum part reveals a high collectivity of the target nucleus. Within a simple kinematical model, about 5–6 nucleons are needed to allow kaon production with momenta $p_K \sim 500$ MeV/c. Alternatively, intrinsic momenta of at least $p_N \sim 550$ MeV/c are required if such kaons are produced in a collision with a single target nucleon. The target-mass dependence of the differential cross sections shows a scaling significantly weaker than those of the total cross sections [1]. The latter have been interpreted in terms of two-step K^+ production. It remains to be shown by microscopic calculations whether this finding is due to rescattering effects of the kaons in the target nucleus or whether it is a reflection of single-step kaon production with high-momentum components in the nuclear wave function.

FIG. 3. Ratios of the K^+ production cross sections for Cu/C and Au/C as a function of the kaon momentum. The solid horizontal lines indicate a fit by a constant value. The dashed lines illustrate the ratios if the cross sections scale like $A^{2/3}$ (dashed line) and A^1 (dash-dotted line).

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