PRODUCTION OF K$^+$-MESONS IN PROTON-NUCLEUS INTERACTIONS

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The production of K^+-mesons in pA (A = C, Cu, Ag, Au) collisions has been investigated at the COoler SYnchrotron COSY-Jülich at beam energies $T_p = 1.0 \ldots 2.3$ GeV using the ANKE spectrometer. ANKE allows to measure double differential cross sections for K^+-production at forward angles $\vartheta < 12^\circ$ in a wide momentum range. The cross sections obtained in these experiments together with those from literature show a uniform behavior as functions of momentum transfer and excitation energy of the residual nucleus. At the lowest measured beam energy, far below the free NN-threshold ($T_{NN} = 1.58$ GeV), the data reveal a high degree of collectivity in the target nucleus. The spectra obtained above threshold should allow one to extract the nuclear K^+-potential with an accuracy of better than ± 3 MeV. Information about the mechanisms leading to K^+-production can be obtained from K^+p and K^+d coincidence measurements.

1. Inclusive K^+-momentum spectra from ANKE

A central topic of hadron physics is to study the influence of the nuclear medium on elementary processes, for example by measuring meson production at projectile energies below the threshold for free NN collisions (so-called subthreshold production). These processes necessarily involve collective effects of the nucleons inside the target nucleus. K^+-production is particularly well suited for such investigations since the meson is rather heavy, as compared to pions, so that its production requires strong medium effects. 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.

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The COoler SYnchrotron COSY-Jülich [1], which provides proton beams in the range $T_p = 0.04 \ldots 2.83$ 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 and, simultaneously, sufficiently high luminosities of more than $L = 10^{32}$ cm^{-2}s^{-1} can be obtained. Subthreshold K^+-production was a prime motivation for building the large-acceptance ANKE spectrometer [2] within one straight section of the COSY ring. It consists of three dipole magnets, which separate forward-emitted reaction products from the circulating proton beam and allow to determine their emission angles and momenta. Depending on the choice of the magnetic field in the spectrometer dipole, K^+-mesons in the momentum range $p_K \approx 150 \ldots 600$ MeV/c can be detected. The layout of the device, including detectors and the data-acquisition system, was optimized [3] to study K^+-spectra down to $T_p \approx 1.0$ 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 [4]. Thus, the kaons have to be identified [3] in a background of secondary protons and pions which is up to 10^6 times more intense.

The measured cross sections for K^+ production in pC interactions are shown in Fig. 1. The cross sections were normalized to known pion-production cross sections [5, 6] measured for similar kinematical conditions [7]. For $T_p = 1.2$ and 2.3 GeV two data sets have been obtained for different settings of the field strength in the spectrometer dipole, $B = 1.3$ T and 1.6 T. These two modes of operation allow to explore slightly different but overlapping regions of the kaon-momentum spectra. At $T_p = 1.0$ GeV ($B = 1.3$ T), ANKE for the first time allows to measure the full momentum spectrum of the produced kaons at deep-subthreshold energies [8]. The geometry of the experimental setup as well as the analysis procedures are identical for both field values. Fig. 1 shows that there are discrepancies between the two data sets for $p_K \leq 400$ MeV/c at $T_p = 2.3$ GeV, whereas at $T_p = 1.2$ GeV they coincide. We conclude that there is an as yet unknown source of systematic errors, which may yield an additional uncertainty of up to 30% at the higher beam energies. It should be noted that these uncertainties vanish when one calculates the cross-section *ratios* for different target nuclei [9]. Thus, these ratios are used for the discussion of reaction mechanisms and final-state interaction effects in Sects. 4 and 5.

2. Systematics of available data

Table 1 shows the available data on K^+-production in pA collisions. The different data sets were obtained for non-overlapping kinematical parameters (i.e. beam energies, kaon emission angles and momenta) which

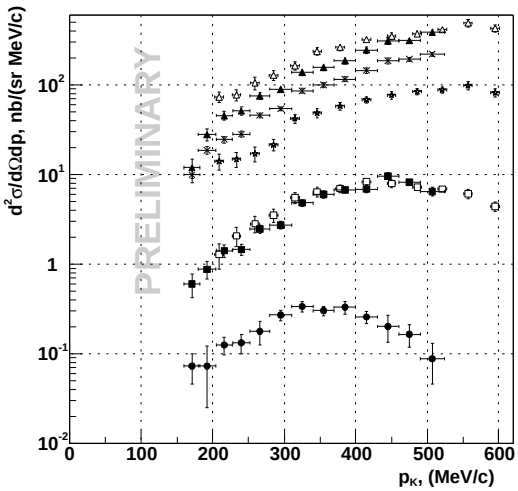

Fig. 1. Double differential $p^{12}C \to K^+X$ cross sections measured at ANKE. Black circles denote the cross sections measured at $T_p = 1.0$ GeV [8], squares at $T_p = 1.2$ GeV, stars at $T_p = 1.5$ GeV, crosses at $T_p = 2.0$ GeV and triangles at $T_p = 2.3$ GeV. All closed symbols correspond to measurements with $B = 1.3$ T and $\vartheta < 12°$, open symbols to $B = 1.6$ T and $\vartheta_{\rm vert.} < 3.5°$, $\vartheta_{\rm hor.} < 6°$. The error bars are purely statistical.

prevents a direct comparison with the data from ANKE and a test of the overall normalizations.

Table 1. Data on K^+-production in pA collisions (ordered by the year of publication) at various beam energies T_p, kaon momenta p_K and emission angles ϑ_K.

T_p (GeV)	Targets	p_K (MeV/c)	ϑ_K (°)	Measured at
0.842...0.99	Be...Pb	*total cross sections*		PNPI [4]
2.1	NaF, Pb	350–750	15–80	LBL [10]
1.2, 1.5, 2.5	C, Pb	500–700	40	SATURNE [11]
1.2	C	165–255	90	CELSIUS [12]
1.7...2.91	Be	1280	10.5	ITEP [13]
2.9	Be	545	17	ITEP [14]
1.0	C, Cu, Au	171–507	≤ 12	**ANKE** [8]
2.5, 3.5	C, Au	300–1050	40	KAOS, [15]
1.2, 1.5, 2.0, 2.3	C,Cu,Ag,Au	171–595	≤ 12	**ANKE**, *prelim.*

In a recent publication [16] we showed that the measured invariant cross sections $E\,\mathrm{d}^3\sigma/\mathrm{d}^3p$ follow an exponential scaling behavior when plotted as

a function of the four-momentum transfer t, which is illustrated in Fig.2 (l.h.s.).

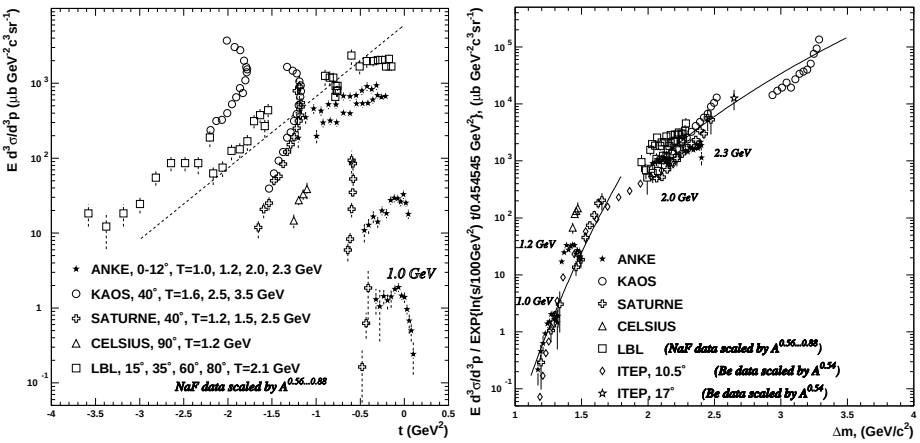

Fig. 2. Left figure: Invariant $p^{12}C \to K^+X$ cross sections as a function of the four-momentum transfer t between the beam proton and the outgoing kaon. Right figure: Scaled invariant $p^{12}C \to K^+X$ cross sections as a function of the excitation energy Δm of the target nucleus. The data from LBL [10] and ITEP [13, 14] were measured with NaF (Be) targets and have been corrected for the target-mass dependence according to Ref.[16]. The beam energies of the ANKE data sets (filled stars) are indicated; for $T_p = 2.3$ GeV the data obtained at $B = 1.3$ T (closed triangles in Fig. 1) were used.

Apart from the data taken with ANKE at $T_p = 1.0$ and 1.2 GeV all spectra cover the range of negative t. The sharp fall-off of the cross sections from ANKE towards positive values of t was explained [16] by the fact that the data were taken very close to the kinematical limit for hyper-nucleus formation at $t = 0.145$ GeV^2 ($T_p = 1.0$ GeV) which is expected to be accompanied by very small cross sections. For $t < 0$ the different data follow an exponential dependence of:

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3p} = c_0 \exp\left[b_0 t\right] , \tag{2.1}$$

with parameters c_0 and b_0 given in Ref.[16]. It has been speculated [16] that deviations from the exponential behavior (see, e.g., the data from KAOS [15] in Fig. 2) reflect a dependence on the available squared CM energy s and the excitation energy of the target nucleus, $\Delta m = m_X - m_A$ (m_X and m_A denote the mass of the target nucleus before and after the reaction process, respectively). Based on Regge phenomenology the following formula has

been suggested as a parameterization of the invariant cross section:

$$E\,\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3p} \propto f(t, m_X^2)\exp\left[b_0 t \cdot \ln\left(s/s_0\right)\right] . \qquad (2.2)$$

The r.h.s. of Figure 2 shows the invariant cross sections, divided by an average s, t dependence, using $b_0 = 2.2$ GeV^{-2} (indicated by the dashed line on the l.h.s. of Fig.2) and $s_0 = 100$ GeV^2, as a function of the excitation energy Δm. The solid lines in Fig.2 correspond to a parameterization of the invariant cross sections in p^{12}C interactions

$$E\,\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3p} = \sigma_0 \cdot \Delta m^{N_0} \cdot \exp\left[b_0 t \cdot \ln\left(s/s_0\right)\right] = \sigma_0 \cdot \Delta m^{N_0} \cdot \left(s/s_0\right)^{b_0 t} , \qquad (2.3)$$

with the following fitted parameter sets:

Table 2. Parameters obtained from a fit with Eq. (2.3)

Beam energy (GeV)	σ_0 (nb GeV^{-2}c^{3}sr^{-1})	N_0 (n)	b_0 (GeV^{-2})	s_0 (GeV^2)
< 1.58	25	17 (13)	2.2	100
> 1.58	1000	9.5 (8)		

The term Δm^{N_0} reflects a phase space behavior $\sigma \propto \Delta m^{N_0} = \Delta m^{(3n-5)/2}$ with n particles in the final state. As can be seen from Fig.2, the parameterization from Eq. (2.3) can describe all available data on K^+-production in pA reactions obtained in largely different angular-momentum intervals within a factor $\sim 2-3$. This parameterization is based on Lorentz invariant variables and, thus, is independent of the choice of the reference system, pp or pA.

3. Kinematical considerations

The parameterization given by Eq. (2.3) not only supplies a useful description of all available data, but Fig. 2 (r.h.s.) also reveals that

1. The data from ANKE at $T_p = 1.0$ GeV were obtained down to $\Delta m = 1.173$ GeV/c^2, i.e. very close to the kinematical limit at $\Delta m_{\mathrm{min}} = m_\Lambda = 1.116$ GeV/c^2. At this limit no energy can be transfered which excites the target nucleus or knocks out target nucleons. The target nucleus must take part in the reaction as a whole such that the effective target mass is $12 \cdot m_N$. There are only two particles, K^+-meson and nucleus, in the final state ($n = 2$).

2. Within a phase-space treatment of the final state, the steep rise ($N_0 = 17$, $n = 13$) of the subthreshold data indicates that all 12 nucleons plus the Λ-hyperon carry away energy in the final state. This seems to be in contradiction with the above statement of $n = 2$. However, this might reflect that more and more nucleons in the *initial state* must take part in the kaon-production process when approaching the kinematical limit (see discussion of the 1.0 GeV data below).

3. The different slope parameters N_0 below and above the free NN threshold ($T_{NN} = 1.58$ GeV) indicate a change of the dominant K^+-production mechanism. This has been predicted by various model calculations [17, 18, 19, 20] and is confirmed by recent coincidence measurements with ANKE (see Sect. 4 for details).

The ANKE data for K^+ production at $T_p = 1.0$ GeV are plotted as invariant cross sections in Fig. 3, see also Ref. [8]. As discussed above the high-momentum part of the kaon spectrum (smallest values of Δm) is most sensitive to collective nuclear effects. For example, if the kaons are produced in a collision of the beam proton with a single nucleon, internal momenta of at least $p_N \approx 550$ MeV/c are needed in order to produce kaons in the forward direction with momenta of $p_K \approx 500$ MeV/c. Such high momentum components above $p_N \approx 500$ MeV/c are essentially due to many-body correlations in the nucleus.

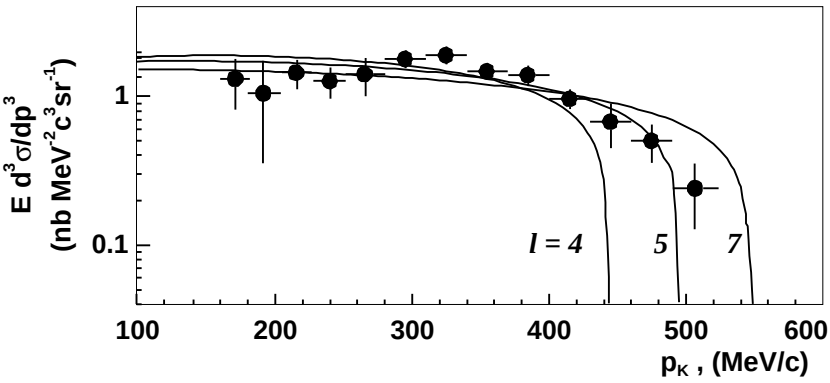

Fig. 3. Invariant K^+-production cross section for $p(1.0\ \mathrm{GeV})^{12}C \to K^+X$ as a function of the K^+-momentum. The solid lines describe the behavior of the invariant cross section within a phase-space approximation (Eq. (3.1)). The figure has been taken from Ref. [8].

To get a *rough estimate* of the number of participating nucleons, one can describe the invariant cross section within a phase-space approximation.

The invariant cross section for the $p+(lN)\rightarrow(lN)+\Lambda+K^+$ reaction is then

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3p} \propto \frac{\sqrt{(s_l - m_\Lambda^2 - l^2m_N^2)^2 - 4m_\Lambda^2 l^2 m_N^2}}{s_l}$$
$$s_l = s+m_K^2-2E_K(T_p+[l+1]m_N)+2p_Kp_pcos\theta_K \ , \qquad (3.1)$$

where s denotes the square of the CM energy of the incident proton and the l target nucleons. The solid lines in Fig. 3 show the invariant cross section calculated with Eq. (3.1) for $l = 4, 5, 7$. Although this approach completely neglects the intrinsic motion of the l target nucleons, it shows that kaon production at $T_p = 1.0$ GeV can only be understood in terms of cooperative effects, where the effective number of nucleons involved in the interaction is $\sim 5-6$. It has been suggested [4, 17, 18, 19, 20] that such effects can be described in terms of multi-step mechanisms (see Sect. 4) or high-momentum components in the nuclear wave function.

4. Production mechanisms

The dependence of meson-production cross sections on the target mass A has frequently been used (see Ref. [16] and references therein) to obtain information about production mechanisms. At large beam energies, K^+-mesons are supposed to be dominantly produced in a collision of the beam proton with a single target nucleon ($pN \rightarrow NK^+\Lambda$). In this case one expects that the cross section scales as $A^{2/3}$. Below threshold multi-step production, in particular two-step reactions with the creation of intermediate pions ($pN_1 \rightarrow NN\pi$, $\pi N_2 \rightarrow K^+\Lambda$), should dominate, and the cross sections are then proportional to A^1 [16].

Figure 4 shows the cross section ratios for Au and C nuclei at $T_p = 1.0$ GeV and 2.3 GeV. Surprisingly, at both beam energies the momentum averaged cross-section ratios seem to be in line with $\mathrm{d}\sigma/\mathrm{d}\Omega(A) \propto A^{2/3}$. There is, at least, no increase of the average ratio towards the lower beam energy. The mass dependence of the 1.0 GeV data from ANKE, selecting forward angles $\vartheta < 12^\circ$, is in strong contrast to the observed A^1 dependence ($R(\mathrm{Au/C}) \approx 16$) of the total cross sections at the same beam energy [4]. The authors of Ref. [4] interpreted the latter as an indication for multi-step processes. A qualitative explanation [16] of this discrepancy can be obtained if one assumes that in the subthreshold domain the large angle K^+-production is due to reactions of the projectile protons with more than a single nucleon. The A dependence of the ANKE data at small angles indicates direct production of K^+-mesons through the interaction of incident protons with surface nucleons. We have to conclude, however, that the A

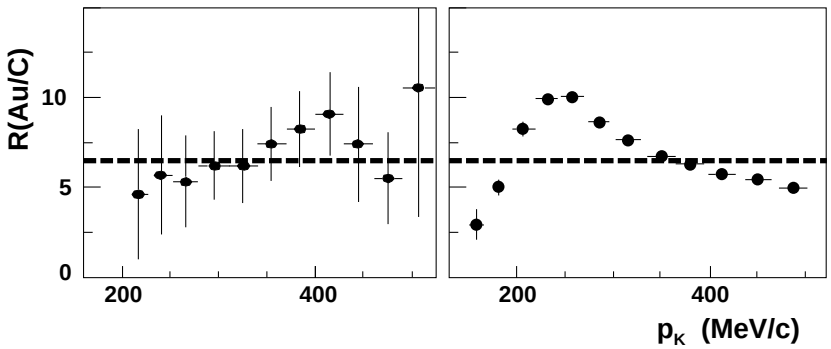

Fig. 4. Ratios of the K^+ production cross sections Au/C measured at $T_p = 1.0$ GeV (l.h.s.) [8] and 2.3 GeV (r.h.s.) [9] as a function of the kaon momentum. The dashed line indicates an $A^{2/3}$ behavior of the cross sections.

dependence of the differential spectra does not reveal the expected change from direct to multi-step kaon production with decreasing beam energy.

According to model calculations, the momentum distributions of protons and deuterons, measured in coincidence with the K^+-mesons, are sensitive to the different production mechanisms [19, 21]. A (K^+d)-pair in the final state can, for example, be observed in case of a particular two-step reaction with deuteron formation in the first step ($pN_1 \to d\pi$, $\pi N_2 \to K^+\Lambda$) [4, 19], while K^+p pairs may come both from the two-step and direct production. On the other hand, the influence of deuteron break-up in the nucleus might be strong, so that one does not observe any coincident deuterons.

First test measurements of K^+p and K^+d coincidences have been performed at $T_p = 1.2$, 1.5 and 2.3 GeV. The amount of detected deuterons is rather large (comparable to the K^+p yield) at $T_p = 1.2$ GeV and decreases towards larger energies. This is in line with the interpretation that the contribution of two-step mechanisms is large at 1.2 GeV and almost negligible at the highest energy. The momentum spectrum of the correlated deuterons at $T_p = 1.2$ GeV is shown in Fig. 5.

A peak structure in the deuteron-momentum distribution is observed at $p_d \approx 965$ MeV/c, which is close to the expected value for on-shell two-body kinematics of the reaction $pN \to d\pi$ with backward emission of the deuteron in the $(d\pi)$ CMS. In this collinear geometry, pions with maximum momenta are produced which is energetically favorable for K^+-production in the second step. A similar peak structure has been predicted [19] for the deuteron spectrum at $T_p = 1.0$ GeV and, thus, this spectrum can be considered as first direct experimental evidence of the two-step production below threshold. However, detailed model calculations still have to show whether

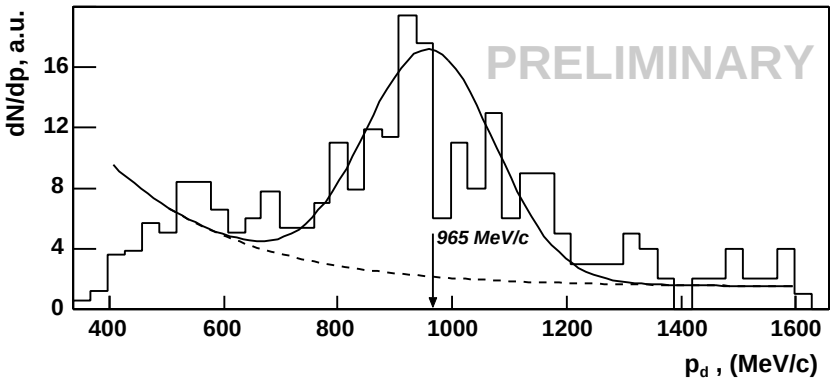

Fig. 5. Coincident deuteron momentum spectra at $T_p = 1.2$ GeV. The deuteron emission angles were restricted to $\vartheta_d < 8°$. The solid line shows the result of a fit to the data, the arrow the fitted peak position.

the observed peak structure cannot be faked by competing processes like coalescence [22] or pick-up reactions. Another source of K^+d pairs might be the kaon production on two- (or multi-) nucleon clusters [4, 18] which is expected to yield deuterons with similar momentum distributions as from the two-step mechanism.

5. Final-state interaction effects

The ratios of kaon-production cross sections for Cu/C, Ag/C and Au/C measured at 2.3 GeV are presented in Fig. 6. All data exhibit similar shapes, rising steadily with decreasing kaon momenta, passing a maximum and falling steeply at low momenta. The position of the maximum varies with the nucleus, a fit to the data gives $p_{\max}(A/\mathrm{C}) = 245 \pm 5$, 232 ± 6, and 211 ± 6 MeV/c for Au, Ag, and Cu, respectively.

The same effect at low p_K has been observed for beam energies down to 1.5 GeV, suggesting that the phenomenon is independent of the K^+-production mechanism and, thus, due to final-state interaction of the K^+ with the residual nucleus. The peak structure seems not to be visible in the ratio Au/C at $T_p = 1.0$ GeV shown on the l.h.s. of Fig. 4. However, at this low beam energy the large background permitted us to extract the cross sections only down to $p_K \approx 220$ MeV/c, which is slightly below the peak positions observerd at $T_p \geq 1.5$ GeV. Taking into account the large error bar of the lowest data point, the apparent constant ratio at $T_p = 1.0$ GeV is not in contradiction with the strong decrease abserved at higher energies.

Fig. 6 shows that the position of the maximum in $R(A/\mathrm{C})$ increases with

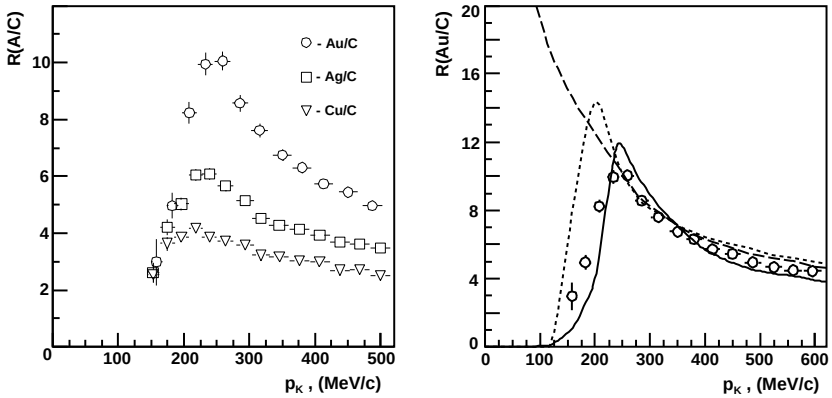

Fig. 6. Left figure: Ratios of the K^+ production cross sections Cu/C, Ag/C, and Au/C measured at $T_p = 2.3$ GeV as a function of the kaon momentum. Right figure: Ratio for Au/C at $T_p = 2.3$ GeV. The dotted line is obtained from transport calculations [26, 27] including only the Coulomb potential, the solid line corresponds to calculations with the addition of a repulsive kaon potential of 20 MeV (as well as baryon potentials). The dashed line corresponds to simulations without Coulomb and nuclear kaon potentials. In all cases K^+ rescattering in the nucleus has been taken into account. The figures have been taken from Ref. [9].

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 potential V_C. Positively charged particles, like K^+-mesons, produced at rest at some radius R in the target nucleus, acquire a momentum $p = \sqrt{2mV_C(R)}$, if other interactions are negligible.

Moreover, it is known from K^+ elastic scattering experiments at higher energies [23] that the nuclear K^+A potential is mildly repulsive, in agreement with one-body optical potentials based upon low-energy K^+N scattering parameters [24]. At normal nuclear density, $\rho_0 \approx 0.16\,\mathrm{fm}^{-3}$, the predicted repulsive K^+A potential of strength $V_K \approx 20$ MeV [25] would shift the kaon momenta to higher values.

Results of calculations in the framework of a coupled channel transport model [26, 27] for R(Au/C) are shown in Fig. 6 (r.h.s.). Without including the Coulomb and nuclear kaon potentials (dashed line) the ratio exhibits a smooth momentum dependence with a steady increase towards low momenta as a result of the stronger K^+ rescattering processes for the Au target. Coulomb interaction leads to a distortion of the momentum spectrum and provides a maximum at $p_K \approx 200$ MeV/c (dotted line). An additional change is observed in the calculations when a repulsive kaon nuclear potential is also considered. Using a kaon potential of $V_K = 20$ MeV

in the calculations, a reasonable agreement with the data is achieved, with a maximum close to the experimental value of 245 MeV/c (solid line). We expect that after refined model calculations the nuclear K^+-potential at normal nuclear density ρ_0 can be determined with an accuracy of better than ± 3 MeV. This is significantly better than the current knowledge from heavy-ion collisions ($\rho > \rho_0$) where the uncertainties are of the order of 15 MeV [25].

6. Outlook

The ANKE experimental program on inclusive production of K^+-mesons in pA reactions has been finalized. First test measurements of K^+p and K^+d coincidences have been performed in 2001 and show the predicted [19, 21] sensitivity to different reaction mechanisms leading to kaon production below and above threshold, see discussion in Sect. 4. It is planned to continue these studies during the year 2003. Similar measurements have already been made with a hydrogen target at $T = 2.65$ and 2.83 GeV. First analyses of these data showed that ANKE allows to study the production of heavy hyperons, up to the $\Lambda(1520)$, in $pp \to pK^+Y$ reactions [28, 29].

In spring 2002 a detection system for negatively charged particles, in particular K^--mesons, has been commissioned at ANKE. It will be used to study the production of K^+K^- pairs in pp [30], pn [31] and pA [32] collisions. From the latter measurements one hopes to obtain information about the production and interaction of K^--mesons in the nuclear medium. The nuclear potential of the K^--mesons is supposed to be strongly attractive, in contrast to K^+-mesons where we found a repulsive potential, or mass shift, of $V_K \approx 20$ MeV. The measurements can be carried out in the end of 2003 or beginning of 2004.

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