Evidence of kaon nuclear and Coulomb potential effects on soft K^+ production from nuclei.

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Abstract

The ratio of forward K^+ production on copper, silver and gold targets to that on carbon has been measured at proton beam energies between 1.5 and 2.3 GeV as a function of the kaon momentum p_K using the ANKE spectrometer at COSY-Jülich. The strong suppression in the ratios observed for $p_K <$ 200–250 MeV/c may be ascribed to a combination of Coulomb and nuclear repulsion in the K^+A system. This opens a new way to investigate the interaction of K^+-mesons in the nuclear medium. Our data are consistent with a K^+A nuclear potential of $V_K^0 \approx 20\,\text{MeV}$ at low kaon momenta and normal nuclear density. Given the sensitivity of the data to the kaon potential, the current experimental precision might allow one to determine V_K^0 to better than $3\,\text{MeV}$.

Key words: Kaon production, Coulomb suppression

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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.

Several groups have made experimental and theoretical studies of total and doubly-differential K^+-production cross sections over a wide range of proton beam energies [1–12]. These studies show that a two-step reaction mechanism, involving the production of an intermediate Δ or π, dominates below the threshold of the elementary $pN \to K^+\Lambda N$ reaction ($T_p = 1.58$ GeV). A strong target mass dependence of the production rate may be a good indicator for the dominance of such secondary mechanisms. At higher energies the role of the secondary effects decreases, especially in the high momentum part of the kaon spectra, where direct production dominates [13].

It is, however, clear that the repulsive Coulomb potential in the target nucleus will distort the soft part of the momentum spectrum. Furthermore, since the K^+ nuclear potential, though small, is also repulsive [14], with a strength rather similar to that of the Coulomb for a heavy nucleus, this distortion will be reinforced. For this reason there have been several publications which have stressed the importance of including the effects of Coulomb and nuclear potentials on the propagation of mesons in the nuclear medium [14–16]. Such effects can change the interpretation of the shape of the K^+ spectrum as well as of the mass dependence of the cross sections; therefore they have to be taken into account in the interpretation of the experimental results.

The influence of final state rescattering effects in meson production can be investigated experimentally for high momentum mesons by measuring two-body reactions, *e.g.* $pA \to (A+1)^* \pi^+$ for pions or $pA \to {}_{\Lambda}(A+1)^* K^+$ for kaons, using high precision spectrometers. However, just as for $\beta^{\pm}$-decay, much stronger Coulomb effects are expected in the very low momentum part of the meson spectrum, but there have as yet been no direct experimental tests, at least for kaons. A reliable way of studying this phenomenon is by measuring directly ratios of cross sections for different nuclei, since many of the possible systematic errors cancel out. Measurements of cross section ratios for mesons of different charges, *e.g.* π^+/π^- or K^+/K^- are, as a rule, clouded by the differences in reaction mechanisms. Since most of the measurements were carried out for high pion and kaon momenta, the existing experimental data [17–20] are not very informative regarding both Coulomb and kaon potentials. This is changing with the commissioning of the ANKE spectrometer, which is currently the only device that is able to measure K^+ mesons with momenta down to ≈ 150 MeV/c.

Measurements of K^+ momentum spectra resulting from proton-nucleus collisions have been performed with the ANKE spectrometer [21] at the COoler SYnchrotron COSY-Jülich. A detailed description of the kaon detection system is given in Ref. [22]. The criteria for the kaon identification and the procedure of measurements are briefly described as follows: The COSY proton beam, with an intensity of $(2-4)\times 10^{10}$ protons and a cycle time of $\sim 60\,\mathrm{s}$, was accelerated to the desired energy in the range $T_p = 1.5 - 2.3$ GeV on an orbit below the target. The targets were thin strips of C, Cu, Ag or Au with a thickness of (40–1500) μg/cm^2. Over a period of $\sim 50\,\mathrm{s}$, the beam was slowly brought up to the target by steerers, keeping the trigger rate in the detectors nearly constant at (1000–1500) s^{-1}, a level that could be handled by the data acquisition system with a dead time of less than 25%. Ejectiles with horizontal angles in the range $\pm 12°$, vertical angles up to $\pm 7°$, and momenta between 150 and 600 MeV/c, were deflected by the ANKE dipole magnet, passed one of 23 plastic scintillation counters and 6 planes of 2.5 mm wire-step MWPCs. They were then focussed onto one of the 15 kaon range telescopes, each consisting of three plastic scintillator counters (stop, ΔE and veto) and two degraders. The 10 cm wide telescopes, placed at the focal surface of the ANKE spectrometer, defined $\sim 10\%$ momentum bites in ejectile momenta. The momentum ranges covered by each telescope were kept constant for the different beam energies by operating ANKE at constant magnetic field strength and maintaining the relative target-dipole-detector geometry. The thicknesses of the scintillators and degraders in the telescopes were chosen so as to stop kaons in the degrader in front of the veto counters. The kaons subsequently decay with a mean life time of ≈ 12.4 ns and the products of this decay (pions or muons) are detected by the veto counters with a delay of more than 1.3 ns with respect to the signals from the corresponding stop counters. The combination of the time-of-flight between the start and stop counters, energy losses in all the scintillators, delayed particle signals, and information from MWPCs resulted in clean kaon spectra, with a background of less than 10% for all beam energies of 1.5 GeV and above. The MWPC track reconstruction allowed us also to vary the angular and momentum acceptances of the individual telescopes.

The ratio $R(\mathrm{A/C})_{p_K}$ of the kaon production cross sections from heavy (A) to carbon (C) targets for a given kaon momentum p_K can be calculated from the observed number of kaons $n(K^+)$ in the individual telescopes as:

$$R(\mathrm{A/C})_{p_K} = \left[\frac{n_A(K^+)}{n_C(K^+)}\right]_{p_K} \times \frac{L_C}{L_A} \quad . \tag{1}$$

L_C and L_A denote the integrated luminosities during data taking with a particular target. The luminosity ratio could be obtained from the number $n(\pi^+)$ of 500 MeV/c pions, measured during pion calibration runs for every energy and for each target.

$$\frac{L_C}{L_A} = \left[\frac{\mathrm{A}}{\mathrm{C}}\right]^{1/3} \times \left[\frac{n_C(\pi^+)}{n_A(\pi^+)}\right]_{p_\pi=500\,\mathrm{MeV/c}} . \qquad (2)$$

All numbers of detected pions and kaons in Eq. (1) and Eq. (2), n_C and n_A, were individually normalised to the relative luminosities during the corresponding runs. This relative normalisation was obtained by monitoring the interaction of the proton beam with the target to an accuracy of 2% using stop counters 2–5 in four-fold coincidence directly looking at the target [22], thereby selecting ejectiles, produced in the target by hadronic interactions, which bypassed the spectrometer dipole. Pion production cross sections in proton-nucleus reactions have been measured by several groups in the forward direction in the 0.73–4.2 GeV energy range [18,19,23]. The combined analysis of these data showed that, to within 10%, the ratios of the pion production cross sections can be scaled with the target mass number as $\mathrm{A}^{1/3}$ [24], which is used in Eq.(2).

The absolute values of the doubly-differential cross sections can be obtained from the numbers of kaons $n(K^+)$ identified by each telescope, after correction for luminosities, detection efficiencies in the scintillators and MWPCs, kaon decay between the target and the telescopes, and angle-momentum acceptances. For the cross section ratios, used in our present analysis, absolute values are not needed and many uncertainties of the efficiency corrections cancel out. The presentation of normalised cross sections is deferred until a later publication.

The gold/carbon ratio is shown in Fig. 1a for proton beam energies of 2.3, 1.75, and 1.5 GeV. This ratio has a broadly similar shape at all three energies, with clear maxima for $p_{\max} \approx 245\,\mathrm{MeV/c}$ coinciding within 2 MeV/c. For higher kaon momenta the ratios decrease monotonically with p_K and in this region the K^+ production in gold is relatively stronger at 2.3 GeV than at lower energies, reflecting changes in the production mechanism with bombarding energy. For low kaon momenta one sees a dramatic fall in the ratio $R(\mathrm{Au/C})$. To ensure that this phenomenon is not an artefact of the ANKE detection system, the 2.3 GeV run was repeated with a reduced dipole magnetic field, resulting in a change in the values of the momenta that are focussed onto individual range telescopes. The low p_K suppression remained unchanged. Identical ratios were also obtained when the polar K^+ emission angles in data analysis were restricted to lie below $\vartheta_K = 3^\circ$ with the help of the MWPC information (see Fig.1b).

Ratios of kaon-production cross sections for copper, silver and gold targets measured at 2.3 GeV are presented in Fig. 2. All data exhibit similar shapes, rising steadily with decreasing kaon momenta, passing a maximum and falling

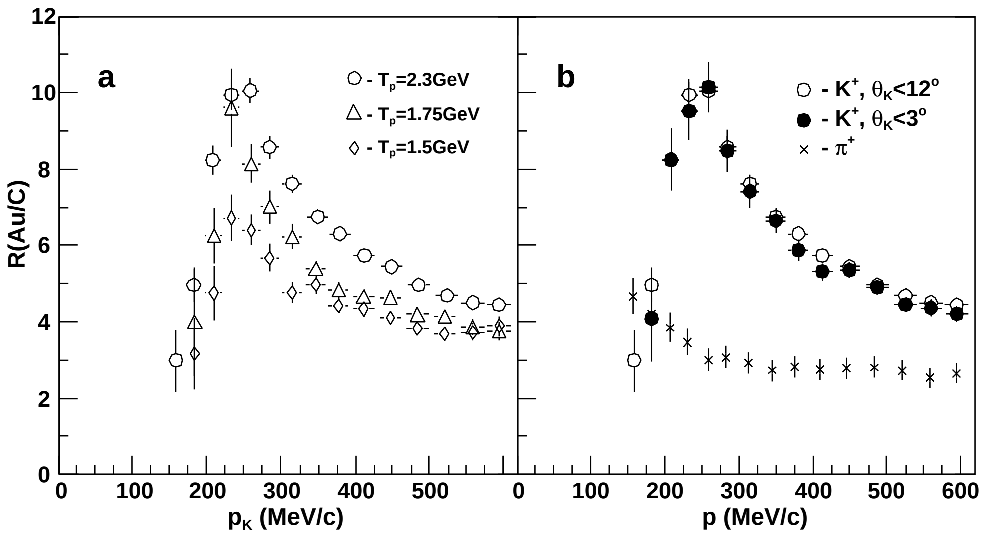

Fig. 1. Ratios of $K^+(\pi^+)$ production cross sections for Au and C measured at different beam energies (left figure) and kinematic conditions (right figure) as functions of the laboratory meson momentum. a) All the symbols correspond to kaons measured in the full ANKE acceptance ($\theta < 12°$). b) The open circles are as in the left figure, whereas the closed circles correspond to kaons measured in the restricted angular interval ($\theta < 3°$). The π^+-production cross-section ratios of Au to C at $T_p = 2.3\,\text{GeV}$ are designated by crosses.

steeply at low momenta. The position of the maximum varies with the nucleus, a fit to the data results in $p_{\max}(\text{A/C}) = 245 \pm 5$, 232 ± 6, and $211 \pm 6\,\text{MeV/c}$ for Au, Ag, and Cu, respectively. The error bars include contributions from a systematic uncertainty of about 1% in the absolute value of momentum as well as the using of different functional forms to fit the points near the maxima.

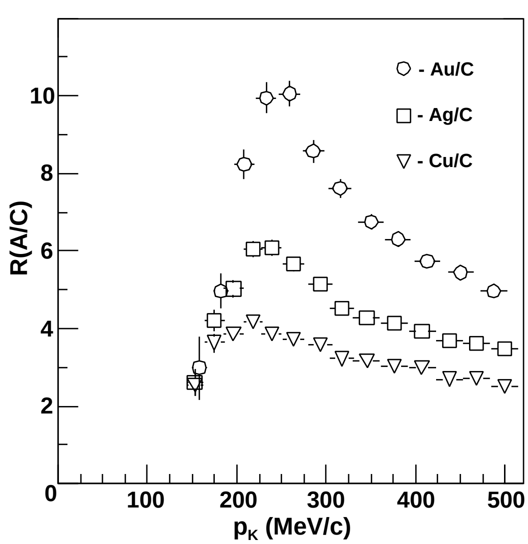

Fig. 2. Ratios of the K^+ production cross sections on Cu, Ag, and Au measured at $T_p = 2.3\,\text{GeV}$ as a function of the laboratory kaon momentum.

It is clear from Fig. 1 that the suppression of R(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. 2 shows that the position of the maximum in R(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. Thus a K^+ produced at rest at some radius R in the nucleus would, in the absence of all other interactions, acquire a momentum of $p_{\min} = \sqrt{2m_K V_C(R)}$. Taking R to be the nuclear edge, this purely classical argument leads to a minimum K^+ momentum for Au of $p_{\min} \approx 130\,\mathrm{MeV/c}$.

It is, moreover, known from K^+ elastic scattering experiments at higher energies [25] 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 [26]. At normal nuclear density, $\rho_0 \approx 0.16\,\mathrm{fm}^{-3}$, the predicted repulsive K^+A potential of strength $V_K^0 \approx 20 - 25\,\mathrm{MeV}$ [14] would shift $p_{\min}$ to higher values.

In order to see whether the observed low momentum suppression is compatible with such a combination of Coulomb and nuclear repulsion, we performed calculations in the framework of the coupled channel transport model [13,27]. In this approach the different mechanisms for the kaon production and the influence of average Coulomb and nuclear potentials, as well as hadron rescattering effects, which can cause a sudden change of the kaon trajectory when kaon comes close to a nucleon, can be taken into account using realistic density distributions. Results of the calculations for the R(Au/C) ratio are shown in Fig. 3. Without including the Coulomb and kaon potentials (dashed line in Fig. 3a) 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 behaviour of this type was observed in π^+ production, which was also measured in a short test experiment (see Fig. 1b). 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 $p_K \approx 200\,\mathrm{MeV/c}$ (dashed-dotted line in Fig. 3a). It has been checked that a 10% change in the charge radius would move the maximum by less than $\pm 2\,\mathrm{MeV/c}$.

A much larger change is observed in the calculations when a repulsive kaon nuclear potential is also considered, giving a 40 and 80 MeV/c shift with a potential strength of 20 and 40 MeV, respectively. 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. 3b). To take into account the absorption of the incident proton, a baryon potential has also been included. The latter does not change the position of the maximum, but makes the agreement with the experimental data better. A precision of 5 MeV/c in the position of the maximum, taken together with the sensitivity of the data to kaon potential shown above, might allow one to determine the strength of V_K^0 to better than 3 MeV.

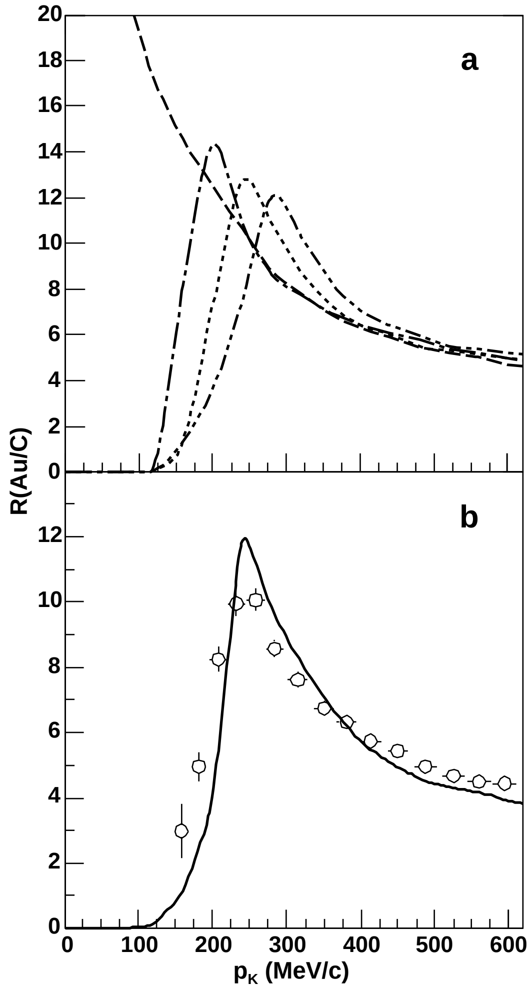

Fig. 3. Ratios of K^+ production cross sections for Au/C at $T_p = 2.3\,\mathrm{GeV}$ as a function of the kaon momentum. a) The dash-dotted line is obtained from transport calculations including only the Coulomb potential, the dotted line corresponds to calculations with the addition of a kaon potential of 20 MeV at ρ_0, whereas the dashed-double-dotted line shows the result where a kaon potential of 40 MeV has been used. The broken 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. b) The open circles are the experimental data. The solid line shows the result of transport calculations starting from the dotted line in the top figure with a baryon potential added.

In summary, we have observed a strong suppression of the ratio of K^+ production by protons on heavy nuclei to that on carbon at low kaon momenta. The independence of this effect from 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 sensitivity found within our model suggests that a careful study of this region will provide a new way to investigate the K^+A optical potential at low momenta. For this to be successful, more extensive transport calculations or other phenomenological descriptions have to be developed. Our 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 [25] and low-energy K^+N scattering parameters [26]. Data on K^+ production from heavy-ion reactions at GSI also point towards K^+ nuclear potentials of about the same strength [28,29]. We hope that the accuracy of our data will stimulate further development of model calculations to provide a better description of the momentum spectra. If this is done we could expect the strength of the kaon potential to be extracted with an accuracy better than 3 MeV.

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