Investigation of K^+-meson production in pp and pA collisions with ANKE[1]

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Abstract. The production of K^+-mesons in proton-nucleus collisions has been measured with the ANKE spectrometer at COSY-Jülich. The kaons, produced on internal C, Cu and Au targets and emitted under forward angles $\vartheta_K \sim 0°$, were separated from the circulating COSY beam and momentum analyzed with the help of a chicane-like magnetic system. Double differential spectra were obtained for beam energies $T_p = 1.0 \ldots 2.3$ GeV, thus above and far below the free nucleon-nucleon threshold at $T_{NN} = 1.58$ GeV. The data taken at $T_p = 1.0$ GeV reflect a high degree of collectivity of the target nucleus. For $T_p \geq 1.2$ GeV the invariant cross sections obtained from ANKE as well as from other experiments show a uniform behaviour when plotted as a function of the four-momentum transfer t between the beam proton and the produced kaon. More recent ANKE data on K^+-production in elementary proton-proton collisions taken at $T_p = 2.65$ GeV allow to extract information about the production cross sections for $\Lambda(1116)$, $\Sigma(1280)$ and $\Lambda(1405)$-hyperons and indicate a signal from the $\Sigma(1480)$. Furthermore, a clean sample of $pp \to dK^+\overline{K^0}$ events has been obtained which may be assigned to scalar a_0^+-meson production.

SUB- AND NEAR THRESHOLD K^+-PRODUCTION IN NUCLEI

A central topic of hadron physics is the influence of the nuclear medium on elementary processes. This subject can be studied 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. The investigation of K^+-production is particularly well suited for such studies since the meson is rather heavy so that its production requires strong medium effects. Furthermore, K^+ final-state interactions are expected to be small allowing them to carry the information about their production deep inside the target nucleus to the detectors.

The COoler SYnchrotron COSY-Jülich [1], 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 and, simultaneously, high luminosities of more than $L = 10^{32}$ cm^{-2}s^{-1} can be reached. 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 the 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 [3]. Kaons have to be identified in a background of secondary protons and pions which is up to 10^6 times more intense. The detectors and corresponding data-analysis procedures for K^+-identification are described in detail in [4].

The measured double differential cross sections for K^+ production in proton-carbon interactions at the lowest beam energy, $T_p = 1.0$ GeV, are shown in the left spectrum of Fig. 1. In contrast to measurements at higher energies [6, 7, 8, 9, 10], ANKE reveals, for the first time, a *complete* momentum spectrum at deep subthreshold energies.

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[2] For a complete collaboration list see: `http://www.fz-juelich.de/ikp/anke`

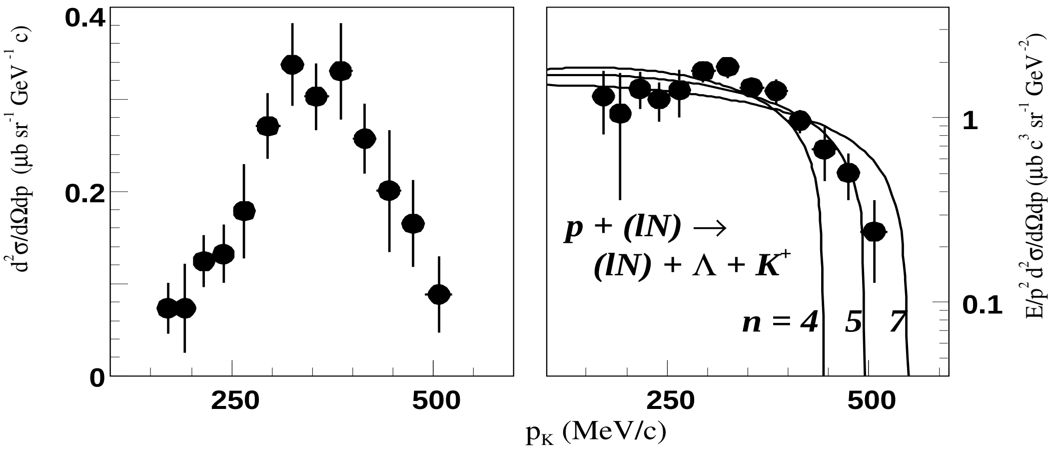

FIGURE 1. Double differential K^+-production cross section for the $p(1.0\text{ GeV})^{12}C \rightarrow K^+(\vartheta \leq 12°)X$ reaction as a function of the K^+-momentum (left histogram). Same data plotted as invariant cross section (right). The solid lines describe the behavior of the invariant cross section within a phase-space approximation (Eq. (1)). The figure has been taken from Ref. [5].

The *low-momentum* part of the K^+-spectrum in Fig. 1 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 target-nucleus system. Such distributions had been assumed to deduce total cross sections from earlier measurements within limited momentum intervals [6, 7, 8, 10].

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 one, see Ref. [5] and references therein. The *high-momentum* part of the kaon spectrum is particularly sensitive to such collective nuclear effects. For example, if the kaons are produced in a single collision of the beam proton with one nucleon, internal momenta of at least $p_N \sim 550$ MeV/c will be needed in order to produce kaons in the forward direction with momenta of $p_K \sim 500$ MeV/c. Such high momentum components above $p_N \sim 500$ MeV/c are essentially due to many-body correlations in the nucleus. 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

$$\frac{E}{p^2}\frac{d^2\sigma}{dp\,d\Omega} \propto \frac{\sqrt{(s_l - m_\Lambda^2 - l^2 m_N^2)^2 - 4m_\Lambda^2 l^2 m_N^2}}{s_l} \tag{1}$$

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

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

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 CM energy of the incident proton and the l target nucleons. The solid lines in Fig. 1 show the momentum dependence of the invariant cross section from Eq. (1) 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 only be understood in terms of cooperative effects with the effective number of nucleons involved in the interaction being $\sim 5-6$. It has been suggested [3, 11, 12, 13, 14] that such effects can be described in terms of multi-step mechanisms or high-momentum components in the nuclear wave function.

It has been shown in Ref. [15] that the invariant cross sections for K^+-production in pA collisions basically scale like $E/p^2\, d^2\sigma/dpd\Omega = c_0 \exp[b_0 t]$ for $t \lesssim -0.5$ GeV^2 where t denotes the four-momentum transfer between the beam proton and the outgoing kaon. c_0 and b_0 are constants which were extracted from fits to published data [6, 7, 8] in the beam-energy range $T_p = 1.2 \ldots 2.5$ GeV. As an example, Fig. 2 (l.h.s) shows the cross sections for the reaction $p(NaF) \rightarrow K^+X$ measured at $T_p = 2.1$ GeV [6]. The dashed line shows a global fit, with $b_0 = 1.5$ GeV^{-2}, to the data in the range $t < -0.6$ GeV^2. Within a factor ~ 2 all data points coincide with the fitted exponential function. At values of t close to zero the invariant cross sections level off and can be approximated by a straight line. The LBL data were obtained in the angular range $\vartheta_K = 15 \ldots 80°$ whereas ANKE covers the forward cone $\vartheta_K \leq 12°$. It is of interest to check whether the overall exponential behaviour suggested in Ref. [15] can also be found at forward kaon-emission angles. The right-hand side of Fig. 2 shows that, in fact, also the ANKE data follow the same exponential behaviour for $t \lesssim -0.3$ GeV^2. Within error bars the fitted slope $b_0 = 1.4$ GeV^{-2} for the 2.0 and 2.3 GeV data coincides with the value for the LBL data. It can be concluded that the "recipe" proposed in Ref. [15] for a comparison of the different data sets can be used. Thus the absolute normalization of the ANKE K^+ data as well as those from other groups can be tested, a corresponding publication is in preparation.

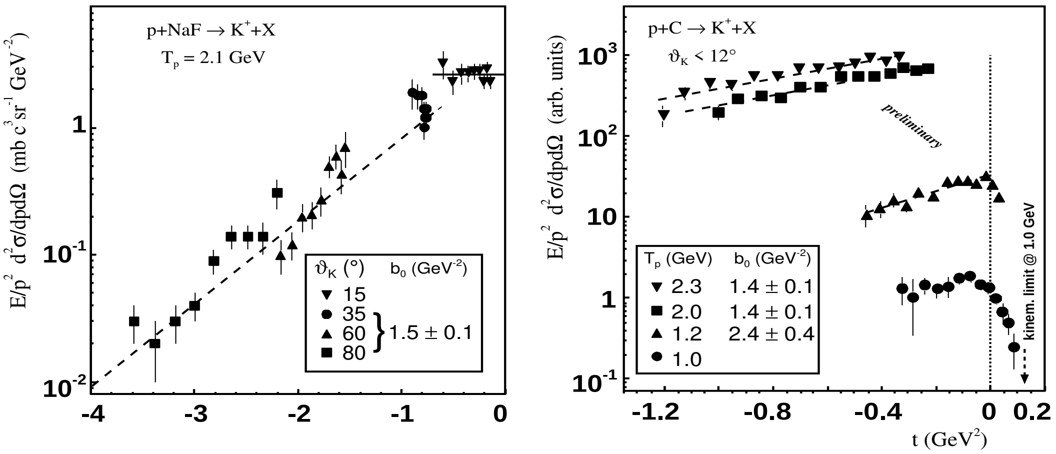

FIGURE 2. Invariant cross sections for the reaction $p(2.1\,GeV)NaF \to K^+X$ measured at LBL for different kaon emission angles [6] (left) and for $p^{12}C \to K^+(\vartheta \leq 12°)X$ measured with ANKE at different beam energies (right). The dashed lines show fitted functions $E/p^2 d^2\sigma/dpd\Omega = c_0 \exp[b_0 t]$.

From Fig. 2 it can also be seen that the only spectra covering the range of positive t are the cross sections obtained at ANKE for $T_p = 1.0$ and 1.2 GeV. In fact, only at forward laboratory angles this t region can be exploited [15] and it corresponds to kinematically extreme conditions which should be most sensitive to collective nuclear effects. For example, the kinematical limit shown in the figure corresponds to the case of hypernucleus formation (neglecting the Λ binding energy).

OPEN STRANGENESS PRODUCTION IN PROTON-PROTON COLLISIONS

The production of K^+-mesons in elementary proton-proton collisions at a beam energy of $T_p = 2.65$ GeV has recently been studied with ANKE. The kaons, produced in reactions $pp \to pK^+Y$ and $pp \to dK^+X$, were measured in coincidence with protons and deuterons. The excellent kaon-vs.-background discrimination (which is mandatory for the subthreshold studies described above) allows to unambiguously identify events with K^+-mesons in the exit channel.

Figure 3 shows the missing-mass distributions for the case of kaon-proton coincidences. Two peaks at $m_Y \sim 1.12$ and ~ 1.20 GeV/c^2 can clearly be seen. The left-hand spectrum in Fig. 3 shows the result of a simulation calculation for the production of $\Lambda(1116)$ and $\Sigma(1193)$-hyperons and the detection of their decay products with ANKE. A cross section ratio of $\sigma_\Lambda/\sigma_\Sigma = 6.6$ yields the best agreement between simulation and data. This cross-section ratio is in good agreement with results from other measurements at comparable energies [17].

The right-hand histogram in Fig. 3 shows the K^+-p missing-mass distribution if the coincidence with an additional π^+-meson is demanded. Thus events of the type $pp \to pK^+Y_1(\to \pi^+Y_2)$ can be selected. The remaining distribution shows two peaks around $m_Y \sim 1.40$ and ~ 1.44 GeV/c^2. According to our simulations the broader peak can be attributed to the production of $\Sigma(1385)$ and $\Lambda(1405)$-hyperons. The best agreement between the simulations and the measured distribution can be achieved for cross-section ratios of $\sigma_\Sigma(1385) = \sigma_\Lambda(1116)/35$ and $\sigma_\Lambda(1405) = \sigma_\Lambda(1116)/55$. The second, narrower, peak may be an indication for the production of $\Sigma(1480)$-hyperons. Since the maximum mass which can be produced at a beam energy of $T_p = 2.65$ GeV is $m_Y \sim 1.48$ GeV/c^2, only the low-mass tail of the distribution can be seen in the data. In order to obtain more information about the $\Sigma(1480)$ further measurements at increased beam energy are in preparation.

Figure 4 shows the missing-mass distributions for $p(2.65\,GeV)p \to dK^+X$ events. Due to charge and strangeness conservation, at this beam energy the remaining particle X must be a $\overline{K^0}$. As expected for such $pp \to dK^+\overline{K^0}$ events,

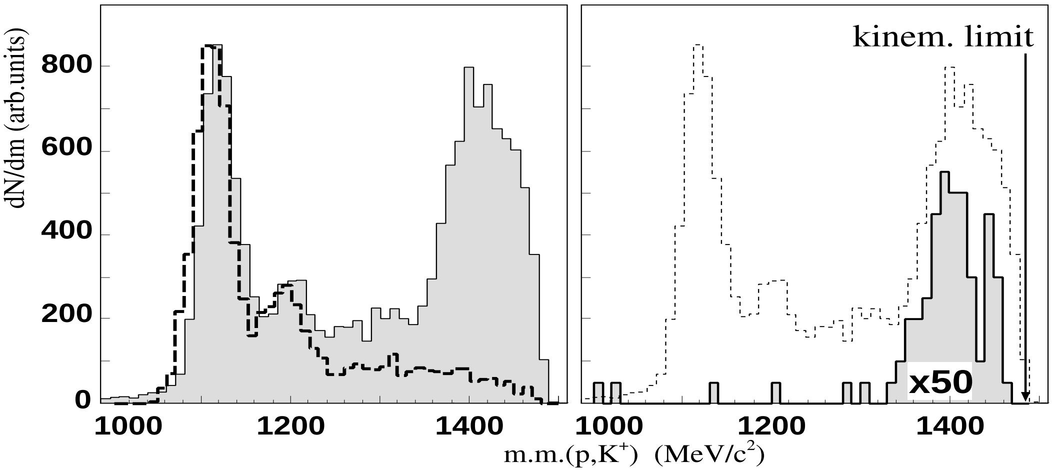

FIGURE 3. K^+-p missing-mass spectra for the reaction $p(2.65\,GeV)p \to pK^+Y$. The left-hand side shows the measured distribution (shaded) in comparison with a simulation for reactions with $Y = \Lambda(1116), \Sigma(1193)$ scaled by an arbitray factor but with $\sigma_\Lambda/\sigma_\Sigma = 6.6$. For the (shaded) histogram on the right-hand side a coincidence with an additional π^+-meson has been demanded. The slight shift between the simulated and measured peak positions is due a preliminary momentum calibration of the spectrometer. More details about the analysis and the simulation calculations can be found in Ref. [16].

the measured d-K^+ missing-mass distribution peaks at $m = m_{K^0} = 498$ MeV/c^2. The main goal of this measurement with ANKE is to extract from the data information about possible resonant $K^+\overline{K^0}$-production, i.e. via the scalar meson $a_0^+(980)$ [19]. The mass distribution of the two kaons (i.e. deuteron missing mass) is shown on the right-hand side of Fig. 4. At $T_p = 2.65$ GeV the available phase space extends from $m_{\min} = m_{K^+} + m_{K^0} = 992$ MeV/c^2 to $m_{\max} = 1035$ MeV/c^2 which is small compared to the expected width of the a_0^+, $\Gamma_a \sim 50 - 100$ MeV/c^2 [20]. This makes the interpretation of the observed events as $K^+\overline{K^0}$ decay of the a_0^+ rather difficult since the shape of the mass distributions is almost identical for resonant and non-resonant $K^+\overline{K^0}$ production [21].

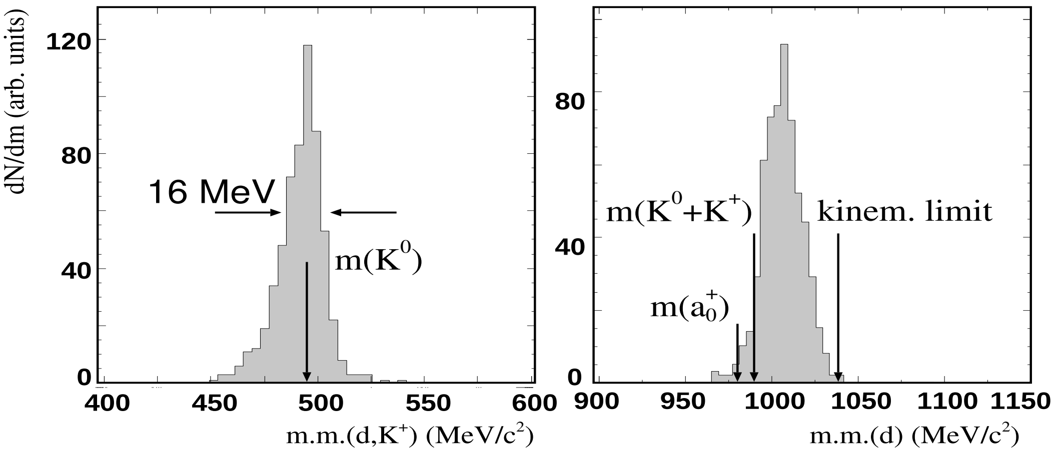

FIGURE 4. Missing-mass spectra for the reaction $p(2.65\,GeV)p \to dK^+X$ [18]. See text for details.

In order to extract more information about resonant a_0^+-events from the experimental data, future analyses will focus on two points. *i)* Acceptance corrected Dalitz plots and angular distributions. Already at the current stage of the analysis it can be stated that the two kaons are dominantly produced in relative s-wave as expected for resonance production [21]. *ii)* In parallel to the $pp \to dK^+X$ events, also d-π^+ coincidences were recorded. The d (d-π^+) missing-mass distribution of these events shows an enhancement around 980 MeV/c^2 (545 MeV/c^2) indicating the production of a_0^+-mesons subsequentially decaying into $\pi^+\eta$. However the analysis of this reaction channel is significantly more diffucult due to much stronger non-resonant and multi-pion background contributions.

FUTURE PLANS FOR STRANGENESS PRODUCTION AT ANKE

Future studies of strangeness production with ANKE will focus on the following measurements:

- Continuation of the inclusive pA program outlined above. The maximum accessible K^+-momenta will be increased from ~ 500 to ~ 1000 MeV/c^2 thus allowing to study the kinematically extreme region of positive t at beam energies $T \geq 1.2$ GeV, c.f. Fig. 2 [22].
- Correlation measurements of $pA \to (K^+p)X$ and $(K^+d)X$ events. It is expected that information about the K^+-production mechanisms can be obtained from these data [22].
- In fall 2001 an additional detection system for K^--mesons will be installed at ANKE. This will allow for studies of a_0^0, f_0, ϕ-mesons in pp, pn, and pA collisions, see e.g. [23, 24, 25].

REFERENCES

1. Maier, R., *Nucl. Instr. Methods Phys. Res., Sect. A* **390**, 1 (1997).
2. Barsov, S. *et al.*, *Nucl. Instr. Methods Phys. Res., Sect. A* **462**, 364 (2001).
3. Koptev, V.P. *et al.*, *JETP* **67**, 2177 (1988).
4. Büscher, M. *et al.*, *Nucl. Instr. Methods Phys. Res., Sect. A* (in print), available via: `http://ikpd15.ikp.kfa-juelich.de:8085/doc/Publications.html`.
5. Koptev, V. *et al.*, *Phys. Rev. Lett.* **87**, 022310 (2001).
6. Schnetzer, S. *et al.*, *Phys. Rev. C* **40**, 640 (1989).
7. Debowski, M. *et al.*, *Z. Phys. A* **356**, 313 (1996).
8. Badalà, A. *et al.*, *Phys. Rev. Lett.* **80**, 4863 (1998).
9. Kiselev, Yu.T. *et al.*, *J. Phys. B* **25**, 381 (1999).
10. Büscher, M. *et al.*, *Z. Phys. A* **355**, 93 (1996).
11. Cassing, W. *et al.*, *Phys. Lett. B* **238**, 25 (1990).
12. Müller, H., and Sistemich, K., *Z. Phys. A* **344**, 197 (1992).
13. Sibirtsev, A.A., and Büscher, M., *Z. Phys. A* **347**, 191 (1994).
14. Paryev, E.Ya., *Eur. Phys. J. A* **5**, 307 (1999).
15. Büscher, M. *et al.*, *submitted to Phys. Rev. C*; nucl-ex 0107011.
16. Kravchenko, P., Proc. 2nd ANKE workshop on *"Strangeness production in pp and pA interactions at ANKE"*, June 21/22 2001, Gatchina, Russia; *Berichte des Forschungszentrums Jülich*, to be published.
17. Sewerin, S. *et al.*, *Phys. Rev. Lett.* **83**, 682 (1999); Kowina, P. *et al.*, Annual report 2000 of the IKP, *Berichte des Forschungszentrums Jülich Jül-3852*, ISSN 0944-2952, p.45 (2001).
18. Kleber, V., Proc. 2nd ANKE workshop on *"Strangeness production in pp and pA interactions at ANKE"*, June 21/22 2001, Gatchina, Russia; *Berichte des Forschungszentrums Jülich*, to be published.
19. Büscher, M. *et al.*, *"Study of a_0^+-mesons at ANKE"*, beam-time request for COSY Proposal #55 (2000); available via `http://ikpd15.ikp.kfa-juelich.de:8085/doc/Proposals.html`.
20. Groom, D.E. *et al.* (Particle Data Group), *Eur. Phys. J. C* **15**, 1 (2000).
21. Chernyshev, V. *et al.*, Proc. 2nd ANKE workshop on *"Strangeness production in pp and pA interactions at ANKE"*, June 21/22 2001, Gatchina, Russia; *Berichte des Forschungszentrums Jülich*, to be published.
22. Koptev, V., and Rudy, Z. *et al.*, *"Forward K^+-production in subthreshold pA collisions"*, beam-time request for COSY Proposal #70 (2001); available via `http://ikpd15.ikp.kfa-juelich.de:8085/doc/Proposals.html`.
23. Büscher, M., and Schleichert, R. *et al.*, *"Study of ω and ϕ-meson production in the reactions $pd \to dV p_{\mathrm{sp}}$ at ANKE"*, COSY Proposal #75 (1998); available via `http://ikpd15.ikp.kfa-juelich.de:8085/doc/Proposals.html`.
24. Büscher, M. *et al.*, *"Investigation of neutral scalar mesons with ANKE"*, COSY Proposal #97 (2001); available via `http://ikpd15.ikp.kfa-juelich.de:8085/doc/Proposals.html`.
25. Hartmann, M., Proc. 2nd ANKE workshop on *"Strangeness production in pp and pA interactions at ANKE"*, June 21/22 2001, Gatchina, Russia; *Berichte des Forschungszentrums Jülich*, to be published.