Subthreshold $K^+$ production in deuteron and alpha induced nuclear reactions

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Abstract

Double differential cross sections $d^2\sigma/dp\,d\Omega$ have been measured for $\pi^+$ and $K^+$ emitted around midrapidity in $d+A$ and $\alpha+A$ collisions at a beam kinetic energy of 1.15 GeV/nucleon. The total $\pi^+$ yield increases by a factor of about 2 when using an alpha projectile instead of a deuteron whereas the $K^+$ yield increases by a factor of about 4. According to transport calculations, the $K^+$ enhancement depends both on the number of hadron-hadron collisions and on the energy available in those collisions: their center-of-mass energy increases with increasing number of projectile nucleons.
Meson production in nucleus-nucleus collisions has become an important tool to study the dynamics of nuclear matter far from its ground state \[1\]. In particular K\(^+\) mesons are regarded as sensitive probes of the hot and dense reaction zone due to their long mean free path \[2-4\]. The sensitivity of kaon production to medium properties is enhanced for bombarding energies below and near the K\(^+\) threshold which is 1.58 GeV for free nucleon-nucleon collisions (NN→K\(^+\)ΛN). Indeed, it has been found experimentally in Au+Au collisions at 1 GeV/nucleon that K\(^+\) mesons originate predominantly from central collisions \[5\]. According to transport calculations, kaons are created at baryonic densities above 2 \(\rho_o\) and their enhanced production cross section is regarded as an experimental evidence for a soft nuclear equation of state \[4,6\]. However, in order to extract information on the properties of dense and hot baryonic matter from kaon data one has to understand the mechanism of subthreshold kaon production and its ingredients: the elementary processes and their cross sections, the internal momentum distribution of nucleons, the role of baryonic resonances and modifications of the hadron masses in the nuclear medium \[7,8\].

It is hardly possible to disentangle experimentally medium effects on kaon production by studying nucleus-nucleus collisions only. A more transparent situation arises in collisions of protons or very light projectiles with nuclear targets: in this case the K\(^+\) mesons are produced in the nuclear medium at normal density. Up to now angle integrated cross sections for K\(^+\) production have been measured in proton-nucleus collisions at beam energies between 0.8 and 1 GeV \[9\]. These data can be explained by model calculations which assume secondary processes \(\pi N \rightarrow K^+\Lambda\) to be the most important K\(^+\) production channel \[10,11\]. Double differential K\(^+\) cross sections have been studied with proton and deuteron beams on nuclear targets at 2.1 GeV/nucleon \[12\]. At this bombarding energy - which is above the K\(^+\) threshold - kaons are produced predominantly in first chance nucleon-nucleon collisions.

In a recent experiment double differential K\(^+\) cross sections have been measured in proton-nucleus collisions at subthreshold beam energies \[13\]. Only about 10% of the measured kaon yield can be explained by first chance collisions \(NN \rightarrow K^+YN\) (\(Y = \Lambda, \Sigma\)). A similar situation exists in nucleus-nucleus collisions where transport models have to assume
secondary collisions like $\Delta N \rightarrow K^+YN$ in order to reproduce the measured data [2, 4]. According to microscopic calculations, multiple hadronic collisions involving baryonic resonances or pions are the main source of subthreshold kaon production. Such effects can be investigated by experiments which use projectiles consisting of very few nucleons and different nuclear targets. This Letter reports on a simultaneous measurement of $K^+$ and $\pi^+$ mesons in $d$ and $\alpha$ induced reactions on carbon and lead targets at a beam energy of 1.15 GeV/nucleon.

The challenge of an experiment on subthreshold kaon production in nuclear collisions is to handle the huge counting rates of protons and pions. It requires a selective and efficient kaon trigger and techniques to unambiguously identify the kaons in spite of the large background produced by rescattered protons. The experiment was performed with the magnetic dipole spectrometer SPES 3 at the synchrotron Saturne in Saclay [13, 14]. The spectrometer covered a large solid angle of 10 msr and a broad momentum range of $p_{\text{max}}/p_{\text{min}}=2.3$ (for one magnetic field setting) up to $p_{\text{max}}=1.4$ GeV/c. The kaon trigger was based on a time-of-flight measurement of momentum selected particles. The simultaneous determination of time-of-flight and trajectory was performed by 4 plastic-scintillator arrays located behind the focal plane of the spectrometer. Each of the large-area detector walls consisted of 20 vertical paddles. A small plastic scintillator positioned in front of the spectrometer provided an additional timing signal. This detector allowed a redundant time-of-flight measurement which was used offline to effectively suppress the background from rescattered protons. Three drift chambers were used for particle tracking which results in a momentum resolution of $\delta p/p=10^{-3}$ and in further rejection of background events. Because of the large flight path of about 10 m from the target to the last scintillator wall the counting statistics of low-energy kaons is limited due to their decay in flight. The experimental setup and the data analysis have been reported elsewhere [13].

The experiment was performed with beams of $d$ and $\alpha$ particles at a kinetic energy of 1.15 GeV/nucleon and with an intensity of about $10^9$ particle/sec. The C and Pb targets had a thickness of 0.68 g/cm$^2$ and 1.35 g/cm$^2$, respectively. The spectrometer position and
the magnetic field were chosen such that a polar angular range of $36^\circ < \theta_{\text{lab}} < 44^\circ$ and a momentum bite of $0.35 \text{ GeV/c} < p_{\text{lab}} < 1.15 \text{ GeV/c}$ was covered. These values correspond to acceptances of $0.3 < y/y_{\text{proj}} < 0.6$ ($70^\circ < \Theta_{\text{cm}} < 100^\circ$) for kaons and $0.6 < y/y_{\text{proj}} < 0.7$ ($110^\circ < \Theta_{\text{cm}} < 120^\circ$) for pions with $y/y_{\text{proj}}$ the normalized rapidity and $\Theta_{\text{cm}}$ the polar angle in the nucleon-nucleon center-of-mass system. The numbers of kaons registered within a given measuring time amount to $250 \text{ K}^+$ in $15 \text{ h}$ for $\alpha + \text{Pb}$, $100 \text{ K}^+$ in $12 \text{ h}$ for $\alpha + \text{C}$, $130 \text{ K}^+$ in $25 \text{ h}$ for $d + \text{Pb}$ and $50 \text{ K}^+$ in $20 \text{ h}$ for $d + \text{C}$.

Figure 1 shows the measured inclusive cross sections $d^3\sigma/dp^3$ for the production of $\pi^+$ as a function of their kinetic energy in the nucleon-nucleon center of mass frame ($T_{\text{cm}}$). The statistical errors are smaller than the symbols. The cross sections have a systematic error of $18\%$ due to uncertainties in beam normalization ($15\%$), wire chamber efficiency ($5\%$) and spectrometer acceptance ($10\%$). The spectra are fitted by Maxwell-Boltzmann distributions $d^3\sigma/dp^3 = A_0 \exp(-T_{\text{cm}}/T_0)$. Angle differential cross sections $d\sigma/d\Omega$ are obtained by integrating the fits over momentum. The fit parameters and the resulting values for $d\sigma/d\Omega$ and $\chi^2$ are presented in Table I.

It is interesting to note that the pion spectra presented in Fig.1 are "thermally" distributed even for $d + \text{C}$ collisions where only very few nucleons participate. In contrast, pion spectra measured in collisions between heavy nuclei exhibit an enhancement at low momenta with respect to a Maxwell-Boltzmann distribution. This effect was attributed to the decay kinematics of the delta resonance [15,16].

The $\pi^+$ cross sections as shown in Fig.1 change with the size of the target nucleus and with the projectile. The target nucleus dependence is demonstrated in the upper part of Fig. 2 which shows the pion ratio for the two target nuclei $R_T(\pi^+) = \frac{d^3\sigma}{dp^3}(\text{Pb})/\frac{d^3\sigma}{dp^3}(\text{C})$ as a function of the pion center-of-mass kinetic energy. The ratio $R_T(\pi^+)$ increases from 4 to 6 with increasing pion energy, both for the deuteron and the $\alpha$ projectile. The data obtained with a proton beam are shown for comparison (solid line) [13]. The assumption that the pion yield is proportional to the surface of the target nucleus ($\sigma \propto A_T^{2/3}$) results
in a value of \( R_T = (\frac{208}{12})^{2/3} = 6.7 \). The decrease of the measured ratio \( R_T(\pi^+) \) towards lower \( \pi^+ \) energies indicates an increased absorption of low momentum pions in Pb as compared to the C nucleus. The pion production cross section ratio for different projectiles \( R_P(\pi^+) = \frac{d^3\sigma}{dp^3}(\alpha)/d^3\sigma(dp^3)(d) \) (lower part of Fig. 2) increases with increasing pion energy from 1.8 up to values above 5 for pion kinetic energies of \( T_{cm} > 0.5 \) GeV. A value of \( R_P(\pi^+) = 2 \) is expected from the \( \alpha \) to deuteron mass number ratio. Note, that pions with kinetic energies above \( T_{cm} = 0.32 \) GeV (indicated by an arrow in Fig. 2) cannot be produced in free nucleon-nucleon collision at this bombarding energy.

In the following we will discuss kaon production. In Fig. 3 the measured \( K^+ \) cross sections \( d^3\sigma/dp^3 \) are shown as a function of the kinetic energy in the nucleon-nucleon center-of-mass frame. The kaon error bars are due to statistics. The overall systematic error of 23% is larger than the one quoted for pions due to the uncertainty of the kaon identification. The angle-differential \( K^+ \) production cross section \( d\sigma/d\Omega \) is estimated by fitting a Maxwell-Boltzmann distribution to the spectra and integrating over momentum. The results of the fits are shown in Fig. 3 and the parameters are summarized in Table II. Because of the poor kaon statistics of the carbon data, the fit parameters \( A_0 \) and \( T_0 \) are highly correlated. Therefore, the carbon data are fitted by varying the amplitude \( A_0 \) only, whereas \( T_0 \) is taken from the lead data. This procedure changes the resulting cross sections by less than 10% because they are mainly determined by the first point in the spectrum.

The \( K^+ \) inverse slope parameters measured with the Pb target are significantly lower than the ones of the corresponding \( \pi^+ \) spectra. This indicates the limitation of phase space available in reactions involving few nucleons only. In contrast, the \( K^+ \) spectra measured in collisions between heavier nuclei (such as Ne + NaF) at 1 GeV/nucleon exhibit the same slope as the high energy pions [18].

From Fig. 3 and Table II one can deduce that the \( K^+ \) yield increases by a factor of 11.8±3.3 (for the d projectile) or a factor of 14.3±2.5 (for the \( \alpha \) projectile) when using a Pb target instead of a C target. This value is larger than the ratio of geometrical cross sections
but is close to the mass ratio of the target nuclei. The parameterization $\sigma^{K^+} \propto A_T^{\kappa}$ gives $\kappa=0.87\pm0.1$ for the deuteron beam and $\kappa=0.93\pm0.06$ for the $\alpha$ beam. This result confirms the expectations that $K^+$ are produced all over the reaction volume and are not absorbed on their way out of the nucleus in contrast to the pions. When using an $\alpha$ projectile instead of a deuteron the $K^+$ yield increases (similarly as the yield of high energy pions) by a factor $\sigma^{K^+}(\alpha + A)/\sigma^{K^+}(d + A)=4.3\pm0.7$ for Pb and $3.5\pm1.0$ for the C target.

At beam energies above the $K^+$ production threshold a quite different dependence of the $K^+$ yield on the projectile mass was observed: in d and Ne induced reactions at 2.1 GeV/nucleon the $K^+$ cross section depends only linearly on the projectile mass: $\sigma^{K^+}(Ne + A)/\sigma^{K^+}(d + A)=10\pm4$ $^{[12]}$. In this experiment the $K^+$ yield scales with the size of the target nucleus according to $\sigma^{K^+} \propto A_T^{\kappa}$ with $\kappa=0.77^{+0.17}_{-0.3}$. The errors are due to the uncertainties of the $K^+$ production cross sections as quoted in $^{[12]}$.

In order to understand why the $K^+$ yield increases by nearly a factor of 4 when the number projectile nucleons increases only by a factor of 2 (as observed at 1.15 GeV/nucleon) we have performed calculations using a transport equation system of the Boltzmann-Uehling-Uhlenbeck type. The details of the model are given in Ref. $^{[19]}$. This code has reproduced our data on $K^+$ and $\pi^+$ production in p+A collisions at beam energies of 1.2, 1.5 and 2.5 GeV $^{[20]}$. We have calculated the $K^+$ double differential cross sections at $\theta_{lab}=40^\circ$ for d+C,Pb and $\alpha+C,Pb$ collisions at 1.15 GeV/nucleon.

Figure 4 shows the total $K^+$ yields and their decomposition into the different contributions according to the BUU model. The calculations seem to overestimate the $K^+$ data slightly. We have used the parameterization of the elementary cross sections as proposed by Zwermann and Schürmann $^{[21]}$ and took into account momentum-dependent nucleon-nucleon interactions. We did not consider a kaon-nucleon potential which would decrease the kaon yield $^{[22]}$. Due to these approximations we do not expect perfect agreement with the data but rather we want to study the change of the kaon yield for different target-projectile combinations. Both the target and projectile dependence of the measured $K^+$ production
cross section is well reproduced by the calculations. The total K\(^+\) yield differs by a factor of about 11 when comparing the BUU results for the Pb and the C target and by a factor of about 5 between the d and the α projectile. The last factor is found to be practically independent of the initial internal momentum distribution of the projectiles.

Figure 4 displays also the production channels which contribute to the K\(^+\) yield. The most important processes are collisions between nucleons and resonances NR→KYN (R = \(\Delta_{33}\) (≈40\%) and heavier resonances (≈60\%), Y = Λ, Σ) and between pions and baryons \(\pi B\rightarrow K Y\) (with B = N (≈90\%) and R (≈10\%)). The contribution from multiple nucleon-nucleon collisions (NN→KYN) to the kaon yield is only 5-10\%. The calculations illustrate that pions and baryonic resonances serve as energy reservoirs and thus contribute dominantly to subthreshold K\(^+\) production.

In the framework of the model calculation the pions are produced via decay of baryonic resonances like Δ and N\(^*\). The pion data obtained with the Pb target are reasonably well reproduced by the calculations whereas for the C target the pion yield is overestimated by a factor of about 2. This discrepancy may be due to the fact, that for the light C target the pion angular distribution in the laboratory is strongly forward peaked (in contrast to the one for the Pb target). Small errors in the calculation of the steep rising pion angular distribution or in the treatment of pion rescattering change dramatically the pion yield at \(\theta_{lab}=40^o\) for the C target. The total pion yield, however, which influences the kaon production is not affected by this problem.

According to our calculations, the total number of hadron-hadron collisions (NR, \(\pi B\), NN) increases by a factor of 2 when comparing d+C and α+C reactions. In addition, the kinetic energies of the projectile nucleons pile up by multiple hadron-hadron collisions. This accumulation effect is more efficient for larger number of projectile nucleons: the average center-of-mass energy of a hadron-hadron encounter which produces a K\(^+\) is \(<\sqrt{s}-\sqrt{s_{th}}>=120\) MeV in d+C collisions and \(<\sqrt{s}-\sqrt{s_{th}}>=250\) MeV in α+C collisions with \(\sqrt{s_{th}}\) the K\(^+\) threshold energy. The difference in the available energies per hadron-hadron collision in combination with the steep rise of the elementary K\(^+\) excitation functions near threshold
results in a K\(^+\) production cross section which is about 5 times larger for α induced reactions than for d projectiles.

In summary, we have measured double differential cross sections for \(\pi^+\) and K\(^+\) mesons emitted in d+C, d+Pb, α+C and α+Pb collisions at 1.15 GeV/nucleon. The cross sections for \(\pi^+\) and K\(^+\) production scale approximately with the surface and the mass of the target nucleus, respectively. This demonstrates that K\(^+\) are produced all over the reaction volume and are not absorbed in contrast to pions. The K\(^+\) yield increases by a factor of about 4 when using an α beam instead of a deuteron beam whereas the total pion yield increases only by factor of about 2. According to transport calculations, the K\(^+\) mesons are predominantly produced in secondary collisions involving pions or/and baryonic resonances. In addition, the calculations demonstrate that not only the number of hadron-hadron collisions (which produce K\(^+\) mesons) increases linearly with the number of projectile nucleons, but also the average value of the energy available in a hadron-hadron collision. This effect is able to explain the observed projectile dependence of the K\(^+\) yield.

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REFERENCES

[1] R. Stock, Phys. Rep. 135 (1986) 259.

[2] J. Aichelin and C. M. Ko, Phys. Rev. Lett. 55 (1985) 2661.

[3] T. Maruyama et al., Nucl. Phys. A573 (1994) 653.

[4] G. Q. Li and C. M. Ko, Phys. Lett. B 349 (1995) 405.

[5] D. Miśkowiec et al., Phys. Rev. Lett. 72 (1994) 3650.

[6] C. Hartnack et al., Nucl. Phys. A580 (1994) 643.

[7] X. S. Fang, C. M. Ko, G. Q. Li and Y. M. Zheng, Nucl. Phys. A575 (1994) 766.

[8] G. E. Brown, C. M. Ko, Z. G. Wu and L. H. Xia, Phys. Rev. C 43 (1991) 1881.

[9] V. P. Koptev et al., Sov. Phys. JETP 67(11) (1988) 2177.

[10] N. A. Tarasov, V. P. Koptev and M. M. Nesterov, Pis’ma Zh. Eksp. Teor. Fiz. 43 No. 5 (1986) 217 [JETP Lett. 43 (1986) 274].

[11] W. Cassing et al., Phys. Lett. B 238 (1990) 25.

[12] S. Schnetzer et al., Phys. Rev. Lett. 49 (1982) 989; Phys. Rev. C 40 (1989) 640.

[13] M. Dębowski et al., Z. Phys. A 356 (1996) 313.

[14] M. P. Combes-Comets et al., Phys. Rev. C 43 (1991) 973.

[15] R. Brockmann et al., Phys. Rev. Lett. 53 (1984) 2012.

[16] C. Müntz et al., Z. Phys. A 352 (1995) 175

[17] D. Pelte et al., Z. Phys. A 357 (1997) 215

[18] W. Ahner et al., Phys. Lett. B 393 (1997) 31.

[19] S. Teis et al., Z. Phys. A356 (1997) 421
[20] G.Wolf, APH N.S., Heavy Ion Physics I (1995) 359

[21] W.Zwermann and B.Schürmann, Phys.Lett. B 145 (1984) 315

[22] E.Bratkovskaya et al., nucl-th/9703017 and submitted to Nucl.Phys. A
**Fig.1:** Inclusive $\pi^+$ production cross sections $d^3\sigma/dp^3$ vs kinetic energy of pions in the nucleon-nucleon center of mass frame measured at $\theta_{lab} = 40^\circ$. Left side: d+C and d+Pb collisions, right side: $\alpha+C$ and $\alpha+\text{Pb}$ collisions. The lines represent Maxwell-Boltzmann distributions fitted to the data (cf. Table I).

**Fig.2:** Upper part: ratio of pion differential cross sections as a function of the pion kinetic energy in the center of mass frame measured for the same projectile (d or $\alpha$) on different targets (Pb and C). The solid line is the corresponding ratio for a proton projectile [13]. Lower part: pion ratios measured for the same target nucleus (Pb or C) but for different projectiles ($\alpha$ and d). The solid line represents the $\pi^+$ ratio for d+Pb/p+Pb. The arrow denotes the maximum pion energy which can be obtained in free N-N collisions at a bombarding energy 1.15 GeV/nucleon.

**Fig.3:** Inclusive $K^+$ cross sections $d^3\sigma/dp^3$ vs kinetic energy of kaons in the nucleon-nucleon center of mass frame measured at $\theta_{lab} = 40^\circ$. Upper part: d+C and d+Pb collisions, lower part: $\alpha+C$ and $\alpha+\text{Pb}$ collisions. The lines are Maxwell-Boltzmann fits to the data (cf. Table II).

**Fig.4:** BUU calculation of the double differential $K^+$ production cross sections (at $\theta_{lab} = 40^\circ$, $E_{\text{beam}}=1.15$ GeV/nucleon) as a function of the laboratory momentum for collisions of d+C (upper left panel), $\alpha+C$ (upper right panel), d+Pb (lower left panel) and $\alpha+\text{Pb}$ (lower right panel) in comparison with the data (full symbols). The solid lines correspond to the total $K^+$ yield. The dotted, dashed and dashed-dotted lines represent contributions of pion-baryon, nucleon-resonance and nucleon-nucleon collisions, respectively.
TABLE I. Fit parameters and resulting cross sections for $\pi^+$ production. The numbers in brackets give a one-\sigma uncertainty of the last digits.

|       | $A_0$ (mb/(GeV/c)$^3$) | $T_0$ (MeV) | $d\sigma/d\Omega$ (mb/sr) | $\chi^2$/NDF |
|-------|------------------------|-------------|-----------------------------|---------------|
| d+C   | 9.3(4)                 | 46(3)       | 10.1(4)                     | 1.40          |
| $\alpha$+C | 6.2(3)            | 55(5)       | 9.6(6)                      | 0.87          |
| d+Pb  | 29(1)                  | 48(3)       | 36(1)                       | 1.17          |
| $\alpha$+Pb | 25(1)               | 57(5)       | 43(3)                       | 0.97          |

TABLE II. Fit parameters and resulting cross sections for $K^+$ production. The numbers in brackets give a one-\sigma uncertainty of the last digits. The $T_0$ parameters for C marked with * were not fitted but adopted from the Pb data.

|       | $A_0$ (mb/(GeV/c)$^2$) | $T_0$ (MeV) | $d\sigma/d\Omega$ ($\mu$b/sr) | $\chi^2$/NDF |
|-------|------------------------|-------------|-------------------------------|---------------|
| d+C   | 0.14(3)                | 31*         | 0.4(1)                        | 0.43          |
| $\alpha$+C | 0.36(6)           | 38*         | 1.4 (2)                       | 0.70          |
| d+Pb  | 1.8(2)                 | 31(8)       | 4.7(6)                        | 1.48          |
| $\alpha$+Pb | 5.0(5)              | 38(4)       | 20(2)                         | 0.72          |
\[
\frac{d^2\sigma}{dp\,d\Omega} \text{ (mb/GeV/c sr)}
\]

\[p_{lab}(\text{GeV/c})\]