Subthreshold Production of Kaons and Antikaons in Nucleus-Nucleus Collisions at Equivalent Beam Energies

R. Barth,[1] P. Senger,[1] W. Ahner,[1] P. Beckerle,[3] C. Bormann,[3] D. Brill,[3] M. Cieślak,[5] M. Dębowski,[1] E. Grosse,[1,*]
P. Koczoń,[1] B. Kohlmeyer,[4] D. Miśkowiec,[1] C. Müntz,[2,†] H. Oeschler,[2] F. Pühlhofer,[4] E. Schwab,[1,3] R. Schicker,[1,‡]
Y. Shin,[3] J. Speer,[4] H. Ströbele,[3] Ch. Sturm,[2] K. Völkel,[4] A. Wagner,[2] and W. Waluś[5]

(KaoS Collaboration)

[1]*Gesellschaft für Schwerionenforschung, D-64220 Darmstadt, Germany*
[2]*Technische Hochschule Darmstadt, D-64289 Darmstadt, Germany*
[3]*Johann Wolfgang Goethe Universität, D-60325 Frankfurt am Main, Germany*
[4]*Phillips Universität, D-35037 Marburg, Germany*
[5]*Jagiellonian University, PL-30-059 Kraków, Poland*
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Kaon production has been studied in Ni + Ni collisions at beam energies of $0.8-1.8$ GeV/nucleon with the kaon spectrometer at GSI. The K^+ production cross section increases as $E_{\text{beam}}^{5.3\pm0.2}$. Both K^+ and K^- mesons are predominantly produced in central collisions. The K^-/K^+ ratio measured at equivalent beam energies below the respective particle production threshold is considerably larger for Ni + Ni collisions than for nucleon-nucleon collisions near threshold. This is evidence for an enhanced K^- production in the nuclear medium. [S0031-9007(97)03227-4]

Collisions between heavy nuclei at bombarding energies of $1-2$ GeV/nucleon provide unique possibilities to study nuclear matter at high temperature and density. The measured abundances and momenta of emitted particles contain information on the thermal and on the collective energy of the fireball and thus can be linked to the compressibility of nuclear matter [1]. Inside the hot and dense nuclear medium, chiral symmetry may be partially restored with the possible consequence of hadron mass modifications [2–4]. The production of kaons in nucleus-nucleus collisions and their propagation in the nuclear medium is regarded to be sensitive to both the nuclear equation of state and the modifications of hadron properties in the medium [5–10].

Data on kaon production in nucleus-nucleus collisions allow one to test predictions for the kaon self-energy in the dense nuclear medium [2,3,7]. A general consequence of the corresponding calculations—which is supported by the analysis of data on kaonic atoms [11]—is the reduction of the antikaon mass in nuclear matter due to an attractive antikaon-nucleon interaction. This effect may lead to a novel scenario for neutron star dynamics and black hole formation: K^- condensation sets in at nuclear densities of $\rho \approx 3\rho_0$ ($\rho_0 = 0.16$ fm^{-3}) and softens the nuclear equation of state. Therefore, neutron stars with lower masses than previously estimated would collapse into black holes [12]. In nuclear collisions, the evidence for an in-medium K^- mass reduction would be a significantly lowered effective K^- threshold and hence an increased cross section for K^- production at bombarding energies below 2.5 GeV (which is the K^- production threshold for free NN collisions). Therefore, subthreshold

K^- production experiments offer the means to measure the reduction of hadron masses in dense nuclear matter.

The available data on subthreshold K^- production in nucleus-nucleus collisions are very scarce. Experiments at the LBL Bevalac studied K^- production at $\Theta_{\text{lab}} = 0°$ in Ne + NaF and Si + Si collisions at beam energies of $1.65-2$ GeV/nucleon [13]. Similar experiments have been performed at GSI-SIS also observing K^- mesons at $\Theta_{\text{lab}} = 0°$ using Ne and Ni beams of $1.5-2$ GeV/nucleon [14,15]. Subthreshold K^+ production has been studied experimentally in Au + Au and Ne + NaF collisions at 1 GeV/nucleon [16,17].

In this Letter we report on the first measurement of K^- mesons produced in nucleus-nucleus collisions at subthreshold bombarding energies with large kaon transverse momenta and with an impact parameter selection. These data allow one to study K^- production in central collisions (where the nuclear density is highest) and at midrapidity (where the kaons are little disturbed by interactions with spectator remnants). We present data on K^+ production in nucleus-nucleus collisions at 0.8, 1.0, and 1.8 GeV/nucleon, which represent the first experimental K^+ excitation function in the region of the threshold beam energy (which is 1.58 GeV for free NN collisions). The data allow one to compare kaon and antikaon production in the nuclear medium under equivalent kinematical conditions.

The experiments have been performed with the magnetic spectrometer KaoS installed at the heavy ion synchrotron SIS at GSI Darmstadt [18]. We used a ^{58}Ni beam with an intensity of 10^7 ions per spill impinging on a ^{nat}Ni target of 0.45 g/cm^2 thickness. Protons, pions,

TABLE I.   Kaon numbers, inverse slope parameters, and inclusive cross sections for kaon production $d\sigma/d\Omega_{c.m.}$ at midrapidity for Ni + Ni collisions. The values are determined by fitting the data with a Maxwell Boltzmann distribution $d^3\sigma/dp^3 \propto \exp(-E/T)$ and integrating the fitted curve over momentum. The factor 4π assumes isotropic emission. The error of $d\sigma/d\Omega_{c.m.}$ includes the uncertainty of the extrapolation to low momenta and a systematical error of 15% which is due to the uncertainties of acceptance determination, detector and analysis efficiencies, and beam flux normalization. The error of the inverse slope parameter T is determined by the fit procedure.

E (GeV/nucleon)	$N(K)$	T (MeV)	$4\pi \times d\sigma/d\Omega_{c.m.}$ (mb)
0.8	1050 K^+	59 ± 6	0.85 ± 0.2
1.0	1280 K^+	75 ± 6	2.7 ± 0.5
1.8	9360 K^+	88 ± 7	57 ± 15
1.8	270 K^-	90 ± 15	2.7 ± 1

and kaons were observed within a polar angular range of $40° < \Theta_{lab} < 48°$ and within a momentum range of $0.3 \text{ GeV}/c < p_{lab} < 1.15 \text{ GeV}/c$. The numbers of registered kaons are given in Table I. The proton and pion data have been published elsewhere [19].

Figure 1 shows the invariant K^+ cross sections integrated over impact parameter (open symbols) as a function of the c.m. kinetic energy measured in Ni + Ni collisions at 0.8, 1.0, and 1.8 GeV/nucleon around midrapidity. The K^- data (full symbols) are measured at 1.8 GeV/nucleon. The error bars represent the counting statistics and the uncertainty of kaon identification.
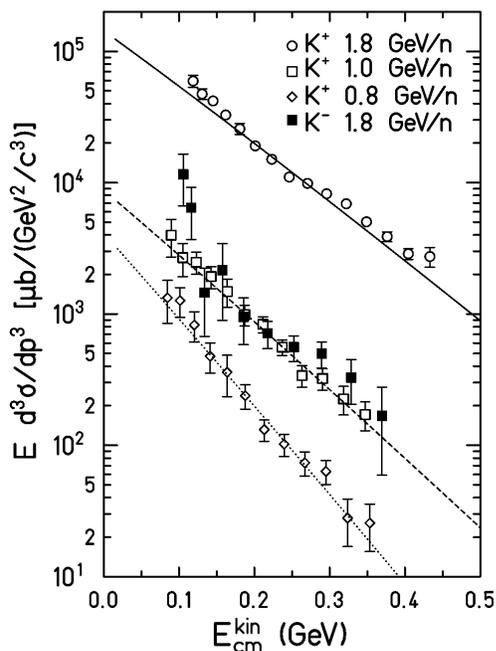
The absolute values of the cross sections are affected by an additional error of 15% (see Table I). The lines in Fig. 1 correspond to Boltzmann distributions $d^3\sigma/dp^3 \propto \exp(-E/T)$ fitted to the K^+ spectra. The resulting inverse slope parameters T and energy integrated cross sections for kaon production $d\sigma/d\Omega_{c.m.}$ at midrapidity are given in Table I. The K^+ data taken at 1.8 GeV/nucleon show deviations from the Boltzmann fit which are included in the systematic error of the integrated cross section. The increase of the K^+ cross section with increasing beam energy E_{beam} can be parametrized according to $d\sigma/d\Omega_{c.m.} \propto E_{beam}^{5.3\pm0.2}$. The K^- invariant cross section in Fig. 1 agrees reasonably well with the K^- data measured in Ni + Ni collisions at 1.85 GeV/nucleon by the FRS spectrometer positioned at $\Theta_{lab} = 0°$ [14,15]. This agreement suggests isotropic K^- emission in the c.m. frame.

The kaon production probability increases strongly with increasing centrality. This is demonstrated in Fig. 2 which shows the kaon and pion multiplicities per solid angle and A_{part} as a function of the number of participating nucleons A_{part}. The data are measured around midrapidity in Ni + Ni collisions at 1.8 GeV/nucleon (left panel) and at 1.0 GeV/nucleon (right panel). For comparison the K^- data taken at 1.8 GeV/nucleon are superimposed on the data taken at 1.0 GeV/nucleon. The collision centrality is tagged by the number of charged particles measured with a granulated large-angle plastic-scintillator hodoscope [18]. We define the meson multiplicity per solid angle around midrapidity as $dM/d\Omega_{c.m.} = (d\sigma/d\Omega_{c.m.})/\sigma_R$ with $d\sigma/d\Omega_{c.m.}$ the differential meson production cross section integrated over momentum (measured around $\Theta_{c.m.} = 90°$) and σ_R the reaction cross section. The meson production cross sections are measured for each centrality bin. For σ_R we take the geometrical

FIG. 1.   Inclusive invariant K^+ and K^- production cross sections for Ni + Ni collisions as a function of the c.m. energy. The data are taken at $40° < \Theta_{lab} < 48°$. The K^+ spectra are fitted by Maxwell-Boltzmann distributions (see Table I).
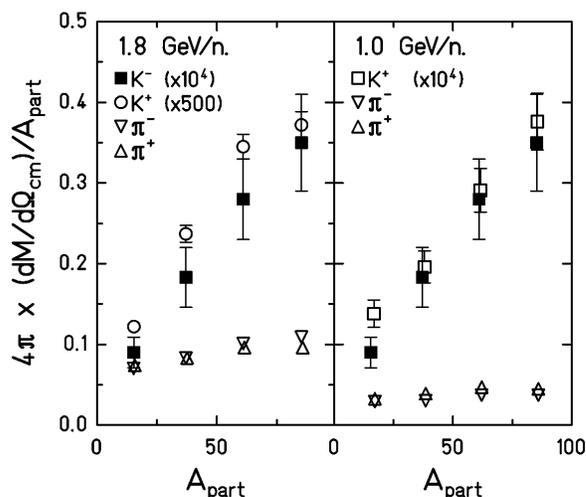
FIG. 2.   Kaon and pion multiplicities per c.m. solid angle and per number of participating nucleon $dM/d\Omega_{c.m.}/A_{part}$ as a function of A_{part} for Ni + Ni collisions at 1.8 GeV/nucleon (left) and at 1.0 GeV/nucleon (right). The black squares in both panels represent K^- data for 1.8 GeV/nucleon.

cross section $4\pi r_0^2 A^{2/3}$ with $r_0 = 1.2$ fm. The number of participating nucleons A_{part} is assumed to be proportional to the geometrical overlap of the colliding nuclei for a given impact parameter. The values of A_{part} then are determined by a Monte Carlo simulation for each centrality bin. The calculation is based on measured yields and slopes of protons, deuterons, and pions and reproduces the charged particle multiplicity as measured by the large-angle hodoscope.

In contrast to the pions, the K^+ and K^- multiplicity per A_{part} increases strongly with increasing A_{part}. This effect was first found in Au + Au collisions at 1.0 GeV/nucleon and interpreted as a signature of multiple collisions contributing dominantly to subthreshold K^+ production [16]. For Ni + Ni collisions the centrality dependence of the kaon multiplicity can be parametrized by $dM_K/d\Omega_{c.m.} \propto A_{part}^\alpha$ with $\alpha = 1.65 \pm 0.15$ for K^+ at 1.8 GeV/nucleon, $\alpha = 1.8 \pm 0.3$ for K^- at 1.8 GeV/nucleon, and $\alpha = 1.70 \pm 0.25$ for K^+ at 1.0 GeV/nucleon. The quoted errors result from the uncertainty in the determination of A_{part} and of the differential cross section $d\sigma/d\Omega_{c.m.}$ (see Table I).

In the following we discuss a method to systematically investigate K^- production in the nuclear medium. We compare the K^- yield measured in nucleus-nucleus collisions to the K^- yield from free nucleon-nucleon collisions. However, this comparison cannot be performed at the same bombarding energy, as we study subthreshold K^- production in order to amplify a possible effect. Therefore, we introduce an intermediate step: we determine the K^-/K^+ ratio at equivalent bombarding energies both in nucleus-nucleus and in nucleon-nucleon collisions. The concept of equivalent beam energies corrects for the different production thresholds. For example, a set of equivalent beam energies is 1 GeV/nucleon for K^+ production and 1.8 GeV/nucleon for K^- production. The resulting Q values are identical: $\sqrt{s} - \sqrt{s}_{thres} = -0.23$ GeV for both processes $NN \to K^+\Lambda N$ at 1.0 GeV and $NN \to K^+K^-NN$ at 1.8 GeV. The study of K^+/K^- ratios at equivalent beam energies has the advantage that trivial medium effects like Fermi motion or multiple collisions largely cancel out.

According to Figs. 1 and 2 the K^+ yield at 1 GeV/nucleon agrees roughly with the K^- yield at 1.8 GeV/nucleon. Not only the cross section but also the dependence on A_{part} is equal for K^+ and K^- observed at equivalent energies. The corresponding K^-/K^+ ratio is found to be 1 ± 0.4. This result for nucleus-nucleus collisions is quite different from the K^-/K^+ ratio for proton-proton collisions. Figure 3 shows the available data on inclusive cross sections for K^+ and antikaon production in proton-proton collisions as a function of the energy above threshold. The K^+ data are taken from [20,21]. Data on K^- production in pp collisions are very rare. The antikaon data points at $\sqrt{s} - \sqrt{s}_{thres} = 0.48$ and 0.63 GeV in Fig. 3 are determined by taking the sum of the measured cross section for $pp \to K^+\bar{K}^\circ pn$ and $pp \to K^\circ\bar{K}^\circ pp$
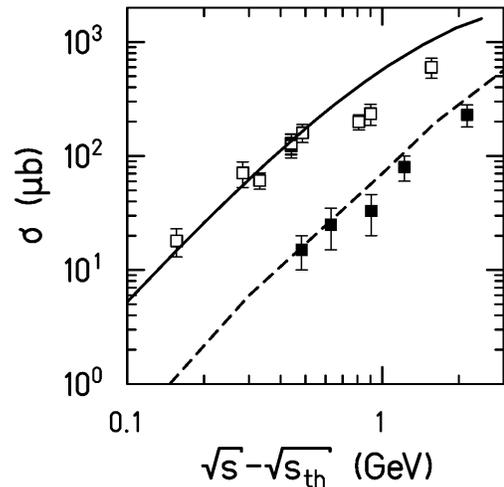
FIG. 3. Inclusive K^+ and K^- cross sections in $p + p$ collisions as a function of the energy above threshold. Open symbols: $pp \to K^+ + X$. Full symbols: $pp \to K^- + X$ (the two data points near threshold are deduced from $\bar{K}^\circ$ measurements, see text). The data are taken from [20]. The lines correspond to parametrizations according to [23].

[20]. According to isospin considerations these processes correspond to K^- production in pn and nn collisions and are used to estimate the cross section for the reaction $pp \to K^+K^-pp$ [22]. The K^- data above $\sqrt{s} - \sqrt{s}_{thres} = 1$ GeV in Fig. 3 are the sum of different exclusive cross sections including those with one or two additional pions in the exit channel [22]. The lines in Fig. 3 represent a parametrization of the elementary kaon and antikaon cross sections performed within the framework of a quark statistical phase space calculation [23]. The calculation is in rough agreement to a new experimental value of $\sigma(pp \to ppK^+\Lambda) = 8.2 \pm 1.8$ nb measured at $\sqrt{s} - \sqrt{s}_{thres} = 2$ MeV [24]. According to Fig. 3 the elementary K^+ cross section is larger than the K^- cross section by about 1 order of magnitude for equivalent proton energies close to threshold. The antikaon data as presented in Fig. 3 and the parametrizations do not depend on isospin [23]. When assuming $\sigma(pp \to K^+ + X) \approx \sigma(pn \to K^+ + X)$ and neglecting K^+ production via neutron-neutron collisions, the K^+/K^- ratio reduces from 10 for proton-proton collisions to about 7 for nucleon-nucleon collisions at equivalent beam energies.

As shown above we find a K^+/K^- ratio of 1 ± 0.4 in Ni + Ni collisions at equivalent beam energies: this corresponds to an enhanced in-medium K^- production by a factor of 7 ± 3. The error is due to the uncertainty in the determination of the differential cross sections (see Table I). The enhancement of the K^- yield is contrary to the expectation, as K^- mesons are strongly absorbed in the nuclear medium by strangeness exchange reactions like $K^-N \to Y\pi$ with $Y = \Lambda, \Sigma$ [25]. In contrast, the K^+ meson can hardly be absorbed due to its antistrange quark and the charge exchange reaction $K^+n \to K^\circ p$ does not lead to K^+ losses in isospin symmetric nuclear matter. In

the following we discuss in-medium effects which might cause an enhanced K^- production in nucleus-nucleus collisions with respect to nucleon-nucleon collisions:

(i) If thermodynamical equilibrium would be approached already in Ni + Ni collisions at 1.8 GeV/nucleon, the small elementary K^- cross section is compensated by a large number of baryonic collisions. However, the steep rise of both the K^+ and K^- multiplicity per participant with increasing number of participants (see Fig. 2) is at variance with the picture of an equilibrated system.

(ii) In medium kaon production may proceed via secondary processes involving pions: $\pi N \rightarrow K^+ K^- N$ and $\pi N \rightarrow K^+ Y$ with $Y = \Lambda, \Sigma$ [26]. Close to the respective thresholds, the isospin averaged cross sections for $K^+ Y$ production is a factor of 5–10 larger than the $K^+ K^-$ cross section [22,26]. In addition, the number of pions above the threshold for K^+ production ($p_{lab}^\pi = 0.9$ GeV/c) in Ni + Ni collisions at 1.0 GeV/nucleon is a factor of 2-3 higher than the pion yield above $p_{lab}^\pi = 1.5$ GeV/c (threshold for $K^+ K^-$ production) in Ni + Ni at 1.8 GeV/nucleon. Therefore, the pion induced kaon production cannot enhance the K^- yield with respect to the K^+ yield at equivalent energies.

(iii) Inside the dense and excited nuclear medium, K^- mesons can be produced by hyperons in secondary collisions like $Y\pi \rightarrow K^- N$ or $YN \rightarrow Y^* N \rightarrow NNK^-$ with $Y^* = \Lambda(1520)$, for example. Hyperons are about 2 times more abundant than K^+ mesons. However, for free masses these reactions are endothermal processes: the K^- mesons are predominantly produced with low energies and hence are reabsorbed with a high probability [7]. On the other hand, in the nuclear medium one has to consider effective masses for nucleons, hyperons, and kaons [27]. Then, with increasing nuclear density K^- production via hyperon-pion and hyperon-nucleon collisions becomes favorable and K^- absorption is suppressed.

(iv) A reduction of the effective masses of nucleons, hyperons and antikaons in the medium will strongly enhance the K^- production via NN and ΔN collisions [7]. For Ni + Ni at 1.0 to 1.8 GeV/nucleon twice the normal nuclear matter density is reached in central collisions where most of the kaons are produced (see Fig. 2). At $\rho = 2\rho_0$ the effective K^- mass is expected to drop to a value of about 300 MeV [28,29]. Using the measured kaon excitation function and the in-medium enhancement factor of 7 ± 3, the reduction of the K^- threshold can be roughly estimated from our data. Assuming a similar beam energy dependence of the K^+ and K^- production cross sections in nucleus-nucleus collisions, the ratio of beam energies for a given enhancement factor is determined by $(E_2/E_1)^{5.3\pm0.2} = 7 \pm 3$. When using a value of $E_1 = 1.8$ GeV, the difference of available energies is $\sqrt{s_2} - \sqrt{s_1} = 270^{+55}_{-90}$ MeV. This value could be considered as a first estimate for the in-medium K^- mass reduction from experimental data.

In summary, kaon production has been measured in Ni + Ni collisions at 0.8–1.8 GeV/nucleon. The K^+ production excitation function rises according to $\sigma^{K^+} \propto E_{beam}^{5.3\pm0.2}$. The K^+ and the K^- multiplicity per solid angle rises strongly with an increasing number of participating nucleons. The K^+/K^- ratio at equivalent beam energies yields experimental evidence for an enhanced K^- production in the nuclear medium as compared to free nucleon-nucleon collisions.

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  *Present address: Forschungszentrum Rossendorf, D-01314 Dresden and Technische Universität Dresden.
  †Present address: Brookhaven National Laboratory, Upton, NY 11973.
  ‡Present address: University of Cyprus, Nicosia, Cyprus.

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