KAON PRODUCTION IN RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS*

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Subthreshold kaon production has been measured in symmetric nucleus nucleus collisions as a function of the nuclear mass, the beam energy and the collision centrality. In Au + Au collisions at 1 AGeV the K^+ multiplicity increases more than linearly with increasing number of participating nucleons. Transport calculations have to assume a soft equation of state in order to reproduce our data. The in-medium K^- cross section measured in Ni + Ni collisions is enhanced by a factor of about 7 as compared to the free cross section when using the K^+ cross section at equivalent beam energies as a normalization.

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1. Introduction

Collisions between heavy nuclei at bombarding energies of 1–2 AGeV provide unique possibilities to study nuclear matter under extreme conditions. In the reaction volume, baryonic densities of $\rho = 2 - 3\rho_o$ and temperatures of $T \approx 100$ MeV are reached. A substantial amount of the nucleons is excited into resonances. Depending on the compressibility of nuclear matter, a fraction of the dissipated energy is stored in the compression

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and thus not available for particle production [1]. Inside the hot and dense nuclear medium, chiral symmetry is expected to be restored partially with the possible consequence of dropping hadron masses [2–4].In particular the production and the propagation of kaons is regarded to be sensitive both to the nuclear equation of state [5, 6] and to modifications of hadron properties in the medium [7]. Experiments at the heavy ion synchrotron (SIS) at GSI in Darmstadt allow to address these fundamental questions.

2. Strangeness experiments at SIS

Three different setups are used for experiments on strangeness production at SIS: the fragment separator (FRS), the kaon spectrometer (KaoS) and the 4π detector (FOPI). The FRS is a high resolution, small acceptance magnetic spectrometer with a very selective trigger and excellent background suppression capability. The apparatus has been used for experiments on K^- and $\bar{p}$ production in Ne + NaF and Ni + Ni collisions [8, 9]. The FOPI setup consists of a superconducting solenoid equipped with drift chambers, ToF scintillators and Cherenkov detectors. The apparatus covers the full solid angle but has no selective particle trigger. Up to now FOPI studied the production of kaons and lambdas in Ni + Ni collisions [10].

Most of the experiments on kaon production at GSI have been performed with the focusing QD magnetic spectrometer KaoS [11, 12]. KaoS has a large acceptance in solid angle ($\Omega \approx 30$ msr) and momentum ($p_{\max}/p_{\min} \approx 2$ up to 1.8 GeV/c). The momentum resolution is 1%. Meson decay in flight is minimized by short trajectories of 5–6.5 m. The large proton to kaon ratio ($10^4 : 1$) requires an efficient kaon trigger which is based on a simultaneous time-of-flight and momentum measurement and, for high momentum kaons, on a threshold Cherenkov detector. Trajectory reconstruction for background suppression and kaon identification is based on three large area multi-wire chambers.

The study of meson production as a function of the number of participating nucleons requires an event characterization. This is performed by means of two plastic scintillator arrays. The large-angle hodoscope consists of 96 modules and is positioned between 8 and 13 cm from the target. It covers polar emission angles from 12° to 48° and detects charged particles which are emitted from the reaction zone. The multiplicity of these particles, mainly protons and deuterons, are a measure of the collision centrality. The charged projectile spectator fragments are identified by their energy loss and time-of-flight measured with the small-angle hodoscope. This detector consists of 380 modules and is positioned 7 m downstream the target. It covers polar angles from 0.5° to 11°. The combined information from the two hodoscopes allows to determine the number of participating nucleons and the orientation of the reaction plane.

3. Nuclear medium effects on subthreshold K^+ production

Medium effects in meson production can be studied by varying the masses of the colliding nuclei. It turns out, that the mass dependence is different for pion and kaon production. This is illustrated in Fig. 1 which shows the invariant cross sections of π^+ and K^+ as a function of the energy in the c.m. system $E_{\rm cm}^{\rm tot}$ [13, 14, 15]. The data are measured in $A + A$ collisions with $A = 20$ (Ne + NaF), $A = 58$ (Ni + Ni) and $A = 197$ (Au + Au) at 1 AGeV and at $\Theta_{\rm lab} = 44°$. The acceptance corresponds to $75° \le \Theta_{\rm cm} \le 115°$ $(0.34 \le y/y_{\rm proj} \le 0.64)$ for kaons and $72° \le \Theta_{\rm cm} \le 84°$ $(0.55 \le y/y_{\rm proj} \le 0.73)$ for pions with $y/y_{\rm proj}$ the reduced rapidity. $E_{\rm cm}^{\rm tot}$ is the total energy required to produce a particle with a given kinetic energy, *i.e.* $E_{\rm cm}^{\rm tot} = E_{\rm cm}^{\rm kin} + m_\pi$ for pions and $E_{\rm cm}^{\rm kin} + m_K + m_\Lambda - m_N$ for K^+ which are produced associated with a hyperon.

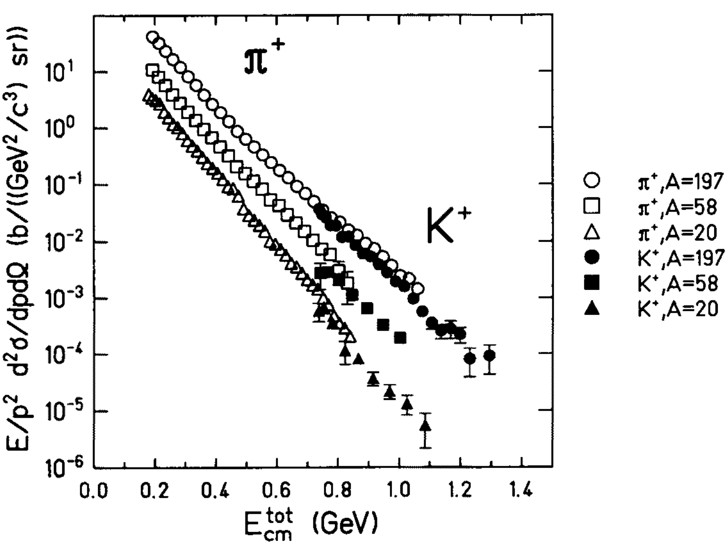

Fig. 1. Invariant inclusive cross section for π^+ and K^+ production in Au + Au, Ni + Ni and Ne + NaF collisions at 1 AGeV as a function of $E_{\rm cm}^{\rm tot}$, which is $E_{\rm cm}^{\rm kin}$ + m_π for pions (open symbols) and $E_{\rm cm}^{\rm kin}$ + m_K + m_Λ - m_N for K^+ (full symbols). The data are taken at $\Theta_{\rm lab} = 44°$

The energy available in a nucleon-nucleon collision at 1 AGeV bombarding energy is $E_{\rm cm}^{\rm tot}$=0.447 GeV. The production of particles with total energies larger than 0.447 GeV requires medium effects such as Fermi motion, multiple baryonic collisions *etc.*. The c.m. energy threshold for the process $NN \to K\Lambda N$ is 0.67 GeV. Therefore, subthreshold K^+ production is sensitive to the properties of the dense and hot nuclear medium and to the behaviour of hadrons inside this medium. Fig. 1 demonstrates clearly, that the K^+ yield increases stronger with increasing mass number A than the pion yield, which is dominated by low energy pions. The K^+ cross section increases approximately proportional with A^2. In a geometrical model, an exponent larger than 5/3 requires collective processes.

Further experimental evidence for the collectivity of the K^+ production mechanism is found when studying the K^+ multiplicity as a function of the collision centrality, *i.e.* the number of participating nucleons. We determine the collision centrality by the charged particle multiplicity as measured with our large-angle hodoscope.

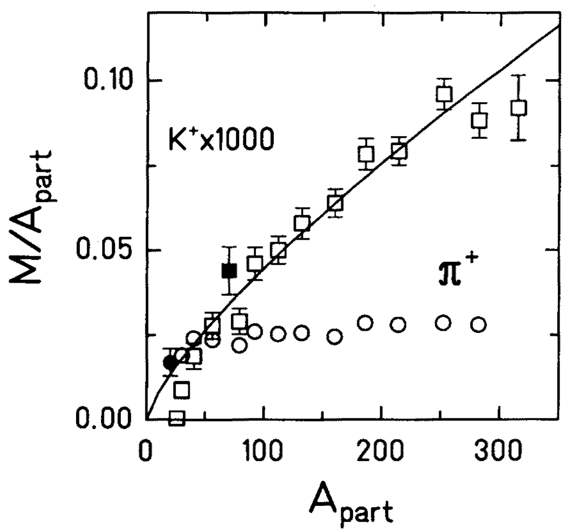

Fig. 2. Meson multiplicity per number of participant nucleons M/A_{part} as a function of A_{part} for Au + Au collisions at 1 *A*GeV at Θ_{lab}=54° (preliminary). Open symbols: K^+ (squares) and π^+ (circles). Solid line: fit to K^+ (see text). Full symbols: K^+ from central collisions of Ne + NaF (circle) and Ni + Ni (square) at 1 *A*GeV.

From the corresponding projectile spectator charge sum measured with the small-angle hodoscope, the number of participating nucleons A_{part} can be determined for each centrality bin. The meson multiplicity per centrality bin is given by $M = \sigma/\sigma_R$ with σ the total meson cross section and σ_R the reaction cross section measured with a minimum bias trigger. The total meson cross section σ is determined by extrapolating the double differential cross section $d^2\sigma/dpd\Omega$ as measured around midrapidity over the full phase space by assuming a Maxwell–Boltzmann distribution and isotropic emission.

Fig. 2 shows the pion and K^+ multiplicity per participating nucleon $M/A_{\rm part}$ for Au + Au at 1 AGeV as a function of $A_{\rm part}$ [13]. The pion multiplicity per $A_{\rm part}$ is independent of $A_{\rm part}$, whereas $M_{K^+}/A_{\rm part}$ increases significantly with increasing $A_{\rm part}$. The solid line in Fig. 2 represents a fit to the data according to $M_{K^+} \propto A_{\rm part}^{\alpha}$ with $\alpha = 1.75 \pm 0.15$. This enhanced kaon production is an experimental hint for multiple baryon-baryon collisions which are more likely to occur in central collisions. The values of $M_{K^+}/A_{\rm part}$ for central Ni + Ni and Ne + NaF collisions at 1 AGeV (full symbols) agree well with the corresponding Au + Au data. According to microscopic transport calculations, subthreshold K^+ production proceeds predominantly via secondary collisions involving baryonic resonances: $\Delta N \to K^+YN$ $(Y = \Lambda, \Sigma)$. The channel $NN \to K^+YN$ contributes only 20% to the K^+ yield at 1 AGeV and not more than 5% at 0.8 AGeV [16].

4. Kaons in nuclear matter and the equation of state

The sensitivity of K^+ production to the nuclear environment allows to study interesting questions like the nuclear equation of state and the in-medium modification of the kaon properties. The in-medium self energy of kaon and antikaon has been calculated from an approximation to the chiral Lagrangian [2, 3, 7] and from the empirical scattering length of the kaon-nucleon interaction [17]. Both approaches derive a KN scalar potential which is attractive both for kaons and antikaons and a KN vector potential which is repulsive for kaons but attractive for antikaons. The resulting KN interaction is repulsive for kaons but attractive for antikaons.

It has been argued that the repulsive K^+N interaction modifies the kaon emission pattern in a nucleus-nucleus collision [18]. The K^+ mesons are repelled from the nucleons and therefore the K^+ emission should not follow the proton collective flow in the reaction plane. Indeed, in an experiment on Ni + Ni collisions at 1.93 AGeV performed with the FOPI detector it was found, that in contrast to protons and Λ's, the K^+ mesons do not exhibit any flow pattern [10]. Further experimental and theoretical studies have to be performed in order to clarify the sensitivity of the kaon emission pattern to the kaon-nucleon potentials.

The magnitude of the attractive K^+N potential can be studied by analyzing K^+ cross section measured in nucleus–nucleus collisions at subthreshold energies. This is demonstrated in Fig. 3, where the double differential K^+ cross section measured in Au + Au collisions at 1 AGeV is compared

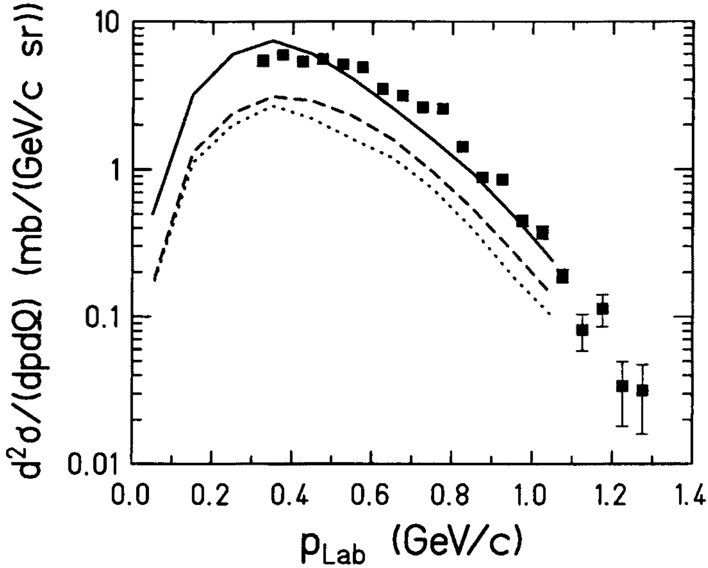

Fig. 3. Double differential K^+ cross sections measured in Au + Au collisions at 1 AGeV and at $\Theta_{\rm lab}$=54° (preliminary). The data are compared to RBUU calculations [19, 20] based on different assumptions: soft equation of state (eos) and KN scalar potential (solid line), stiff eos and KN scalar potential (dashed line) and soft eos without KN scalar potential (dotted line).

with results from a relativistic transport code [19, 20]. The RBUU model incorporates an equation of state and a kaon dispersion relation in the nuclear medium. The data can be reproduced when assuming a soft equation of state and an attractive kaon–nucleon scalar potential (solid line). When assuming a hard equation of state (dashed line) or neglecting the KN scalar potential (dotted line) the calculation underpredicts the data by a factor of 2–3.

The sensitivity of the K^+ cross section to in-medium effects increases with decreasing bombarding energy. This is demonstrated in Fig. 4, where double differential K^+ cross sections measured in Ni + Ni collisions at different bombarding energies are compared to results of transport calculations. The left part shows results of a RBUU calculation [21] assuming a soft equation of state with a KN scalar potential (solid lines) and without a scalar potential (dotted lines). For 0.8 AGeV bombarding energy the result of the model calculation depends strongly on the KN scalar potential.

The influence of the nuclear compressibility on the K^+ yield for different bombarding energies is illustrated in the right part of Fig. 4. It shows results

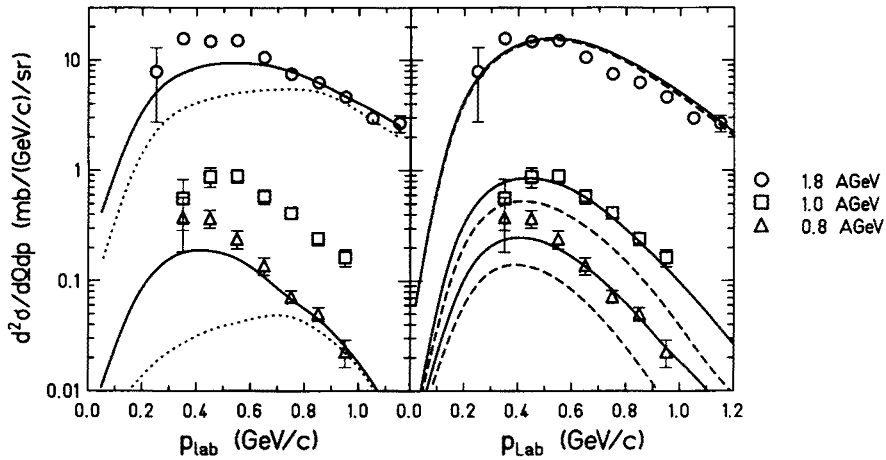

Fig. 4. Double differential K^+ cross sections for Ni + Ni collisions measured at Θ_{lab}=44° at different beam energies (preliminary). The data are compared to model calculations. Left part: RBUU results for 1.8 and 0.8 AGeV assuming a soft eos with KN scalar potential (solid lines) and without (dotted lines) [21]. Right part: QMD results for a soft eos (solid lines) and for a stiff eos (dashed lines) [16].

of a QMD calculation [16] for a soft (solid lines) and a stiff equation of state (dashed lines). At a bombarding energy of 1.8 AGeV no effect of the equation of state can be seen, whereas at subthreshold beam energies the calculations differ by a factor of two depending on the equation of state. The QMD calculation agrees reasonably well with the data although it does not take into account in-medium self energies of hadrons. This indicates, that the modification of the K^+ production threshold in the medium is small when taking into account the in-medium masses of all hadrons participating in the K^+ production process. The agreement of the calculations with the data should not be considered as a proof for the model assumptions, as there are still uncertainties, *e.g.* in the elementary K^+ cross section. Nevertheless the calculations show, that the kaon probe has a measurable sensitivity to medium effects.

The question is, whether there is a possibility to disentangle experimentally the different medium effects on kaon production and to reduce the uncertainties of the elementary cross section. Transport model calculations predict that the relation between the K^+ multiplicity and the mass number of the colliding nuclei depends distinctly on the compressibility of nuclear matter. When parameterizing the calculated K^+ multiplicity according to $M_{K^+} \propto A^\alpha$, the exponent is expected to be $\alpha = 1.38$ for a stiff equation of state and $\alpha = 1.62$ for a soft one [16]. Assuming a linear relation between

A and A_{part} for symmetric collision systems, we can compare the model prediction to our preliminary data on the K^+ multiplicity as a function of participating nucleons for the Au + Au system at 1 AGeV (see Fig. 3). A fit to our data according to $M_{K^+} \propto A_{\text{part}}^{\alpha}$ yields $\alpha = 1.75 \pm 0.15$. This value is in favor of a soft equation of state. However, it should be stressed, that also the collective flow of particles and light fragments is influenced by the nuclear compressibility [22]. A consistent description of all relevant observables is required to get an understanding of the role of the nuclear equation of state in heavy ion collisions.

5. In-medium modification of the antikaon mass

As mentioned above, the antikaon mass is expected to drop significantly in dense nuclear matter due to the attractive antikaon-nucleon interaction. A small antikaon mass reduces the in-medium threshold for the process $NN \to K^+K^-NN$ and consequently the K^- production is enhanced as compared to free NN collisions. This effect is expected to be large at subthreshold bombarding energies, where the K^- excitation function is very steep and thus acts as an amplifier: even a small mass reduction might result in a strong K^- enhancement.

Up to now the data on subthreshold K^- production in nucleus-nucleus collisions are very scarce. Experiments at the Bevalac studied K^- production in light collision systems at Θ_{lab}=0° only [23]. Similar experiments have been performed at SIS with the FRS measuring K^- mesons also at $\Theta_{\text{lab}} = 0°$ using Ne and Ni beams of 1.5 AGeV to 2 AGeV [8, 9]. Using the kaon spectrometer we have performed the first measurement of K^- mesons with large transverse momenta ($\Theta_{\text{lab}} = 44°$) and with an impact parameter selection [14].

In order to study a possible enhancement of the K^- yield in the nuclear medium we compare subthreshold K^- production in nucleus–nucleus collisions to the K^- production probability for free NN collisions. However, this comparison cannot be performed at the same bombarding energy. Therefore, we introduce an intermediate step: we determine the K^-/K^+ ratio for nucleus–nucleus collisions and for nucleon–nucleon collisions both at equivalent bombarding energies and take the double ratio

$$R = \frac{\sigma(AA \to K^- + X)}{\sigma(AA \to K^+ + X)} \times \frac{\sigma(NN \to K^+ + X)}{\sigma(NN \to K^- + X)} \,. \tag{1}$$

A value of R>1 would provide an experimental hint for an enhanced in-medium K^- production. The K^+ meson cannot be absorbed due to its anti-strange content and the charge exchange reaction $K^+n \leftrightarrow K^\circ p$ does not lead to kaon losses. The double ratio R has in addition the advantage, that "trivial" in-medium effects like Fermi motion and multiple collisions are cancelled.

The concept of equivalent beam energies takes care of the energy balance: different processes are studied at the same Q-value. For example, a set of equivalent beam energies is 1 AGeV for K^+ production and 1.8 AGeV for K^- production. The resulting Q-values are identical:

$$NN \to K^+ \Lambda N: \quad \sqrt{s} - \sqrt{s}_{\mathrm{thres}} = 2.32\mathrm{GeV} - 2.55\mathrm{GeV} = -0.23\mathrm{GeV},$$
$$NN \to K^+ K^- NN: \quad \sqrt{s} - \sqrt{s}_{\mathrm{thres}} = 2.63\mathrm{GeV} - 2.86\mathrm{GeV} = -0.23\mathrm{GeV}.$$

Fig. 5 shows invariant K^+ cross sections (open symbols) as a function of the c.m. energy measured in Ni + Ni collisions at 0.8, 1.0 and 1.8 AGeV around midrapidity. The K^- data (full symbols) measured at 1.8 AGeV agree with the K^- invariant cross section as measured in Ni + Ni collisions at 1.85 AGeV by the FRS at $\Theta_{\mathrm{lab}} = 0°$ [8, 9]. From Fig. 5 one can conclude that the K^- cross section at 1.8 AGeV equals the K^+ cross section taken at 1 AGeV (open squares).

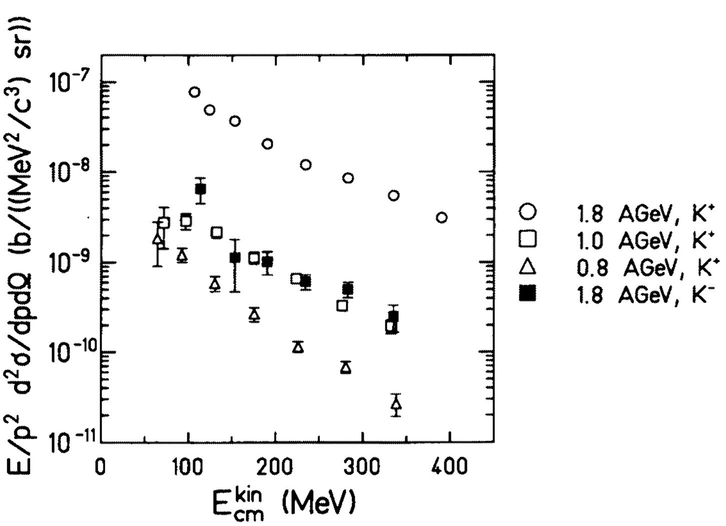

Fig. 5. Invariant kaon cross sections as a function of the c.m. kinetic energy for Ni + Ni collisions (preliminary). Open symbols: K^+ at 1.8, 1.0 and 0.8 AGeV. Full symbols: K^- at 1.8 AGeV. The date are taken at $\Theta_{\mathrm{lab}} = 44°$ corresponding to normalized rapidities of $0.26 \leq y/y_{\mathrm{proj}} \leq 0.52$ (for 1.8 AGeV), $0.34 \leq y/y_{\mathrm{proj}} \leq 0.64$ (1.0 AGeV) and $0.40 \leq y/y_{\mathrm{proj}} \leq 0.71$ (0.8AGeV).

The K^-/K^+ ratio for proton-proton cross sections at equivalent bombarding energies is illustrated in Fig. 6. It shows the available data on pp→K$^+$+X (squares) and on $pp \to K^- + X$ (circles) as a function of the energy above threshold. The data are taken from [24]. The lines represent a parameterization of the elementary kaon cross sections performed with the ROC model [25]. According to Fig. 6 the K^+ cross section is larger than the K^- cross section by about one order of magnitude for equivalent energies: $\sigma(pp \to K^+ + X)/\sigma(pp \to K^- + X) \approx 10$. In order to determine the kaon cross sections for nucleon-nucleon collisions one has to consider the different isospin channels. Experiments found that $\sigma(pp \to K^+ + X) \approx \sigma(pn \to K^+ + X)$ for proton beam energies above 5 GeV [24]. To make a conservative estimate we neglect the process nn→ $K^+\Sigma^- n$. Then we get

$$\begin{aligned}\sigma(NN \to K^+ + X) &= \tfrac{1}{4}\sigma(pp \to K^+ + X) + \tfrac{2}{4}\sigma(pn \to K^+ + X)\\ &= \tfrac{3}{4}\sigma(pp \to K^+ + X)\,.\end{aligned}$$

The production of K^- mesons does not depend on isospin:

$$\sigma(NN \to K^- K^+ NN) = \sigma(pp \to K^- K^+ pp)\,.$$

Hence we estimate for the elementary kaon production at equivalent beam energies

$$\sigma(NN \to K^+ + X)/\sigma(NN \to K^- + X) \approx 7\,.$$

According to equation (1) we find an in-medium K^- production enhancement of $R \approx 7$.

Before drawing conclusions on a possible in-medium mass shift of the antikaon one has to consider other in medium processes which might affect the K^- yield. In the nuclear medium K^- mesons are absorbed by strangeness exchange reactions like $K^- N \to Y\pi$ with $Y = \Lambda, \Sigma$. This absorption cross section has been parameterized by $\sigma_{\text{abs}} \approx 23/p_K$ mb with p_K the antikaon momentum in GeV/c in the restframe of the nucleon [26]. Low momentum K^- mesons are very likely absorbed. For example, an antikaon with $p_K = 0.4$ GeV/c ($\sigma_{\text{abs}} \approx 57$ mb) will be absorbed in a Ni + Ni fireball with a probability of $P_{\text{abs}} = 1 - \exp(-r \times \sigma_{\text{abs}} \times \rho) \approx 0.98$ when being emitted in a reaction volume with radius $r = 4$ fm and density ρ=0.17fm^{-3}. In order to overcome this large in-medium absorption probability the K^- production must be even more enhanced.

On the other hand there is also a certain probability to produce a K^- meson by the inverse process $Y\pi \to K^- N$, as the abundance of hyperons and pions is not small. From the K^+/K^- ratio in Ni + Ni at 1.8 AGeV one can derive, that in average the hyperon to K^- ratio is about 30. The π/K^- ratio is even 1000. However, the reaction $Y\pi \to K^- N$ is an endothermal process. Therefore, the K^- mesons are predominantly produced with

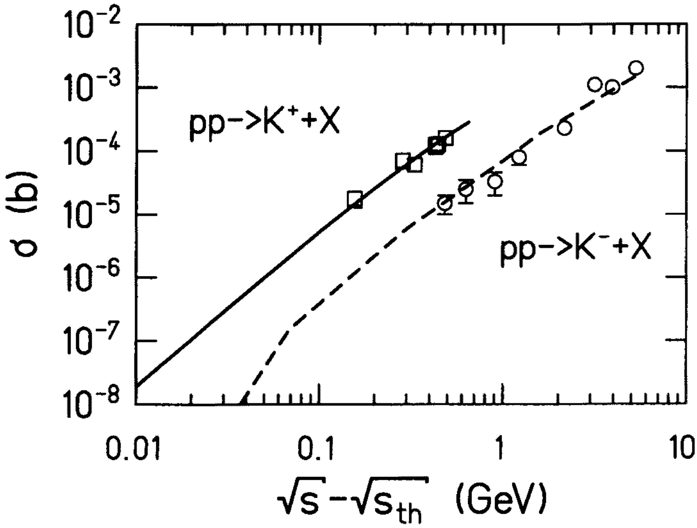

Fig. 6. Kaon cross sections in $p+p$ collisions as a function of the available energy. The data are taken from [24]. The lines correspond to parameterizations according to [25].

low energies and hence are reabsorbed with a high probability. Relativistic transport model calculations find the absorption of K^- to be very important but the secondary production via $Y\pi \to K^- N$ to be negligible [7]. Nevertheless, further experiments on strangeness production in nucleus–nucleus and also in nucleon–nucleon collisions are needed to quantify the effect of an enhanced in-medium antikaon production.

6. Summary

Our data demonstrate, that the multiplicity of K^+ mesons created in $A+A$ collisions at subthreshold energies increases more than linearly with increasing mass A of the collision system and with increasing number of participating nucleons A_{part}. This experimentally evidences the important role of collective effects such as multiple baryon–baryon collisions. According to transport calculations, the mass and centrality dependence of subthreshold K^+ production favors a soft equation of state. The in-medium K^- cross section is enhanced by a factor of about 7 as compared to the free K^- cross section when using the K^+ cross section as a normalization. Future experimental and theoretical work is needed to confirm and to explain this observation.

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