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KAON AND ANTIKAON PRODUCTION IN NUCLEUS–NUCLEUS COLLISIONS AT SIS*

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The production and propagation of kaons and antikaons has been studied in symmetric nucleus–nucleus collisions in the SIS energy range. The K^+ multiplicity was found to increase more than linearly with the mass number A of the collision system. This behaviour is due to collective effects such as multiple hadron–hadron interactions. In noncentral Au+Au collisions, the K^+ mesons are preferentially emitted perpendicular to the reaction plane. The K^-/K^+ ratio from $A+A$ collisions at equivalent beam energies is found to be 1–2 orders of magnitude larger than the corresponding ratio from $p+p$ collisions. This effect is an experimental signature for an enhanced K^- production in $A+A$ collisions. In order to reproduce the data, transport models consider a reduction of the K^- mass in the dense nuclear medium.

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1. Introduction

Collisions between heavy nuclei at bombarding energies of 1–2 AGeV provide the unique possibility to study nuclear matter at high densities. 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 [1–3]. K^+ mesons have a long mean free path in nuclear matter and therefore are well suited to probe the hot and dense stage of a nucleus–nucleus collision.

The properties of kaons and antikaons are expected to change significantly inside the dense and hot nuclear medium [4–6]. According to chiral

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perturbation theory, the mass of the K^+ mesons weakly increases with increasing nuclear density whereas the mass of the antikaon strongly decreases. The latter effect may lead to K^- condensation in neutron stars [7].

Experiments on kaon and antikaon production in nucleus–nucleus collisions allow to study both the nuclear equation of state and the properties of hadrons in the dense nuclear medium. This article concentrates on data which have been measured recently with the Kaon Spectrometer [8] at the heavy ion synchrotron (SIS) at GSI in Darmstadt.

2. Subthreshold kaon production in nucleus–nucleus collisions

The kaon production threshold in free nucleon–nucleon collisions is E_{beam}=1.58 GeV (for $NN \to \Lambda K^+ N$). Therefore, K^+ production is strongly suppressed in nucleus–nucleus collisions at beam energies around 1 AGeV. In this case kaon production depends on collective effects which favorably occur in large (and dense) collision systems. Fig. 1 shows the K^+ multiplicity per participating nucleon for $A+A$ collisions with $A = 12, 20, 58$ and 197 at 1 AGeV. The multiplicity is calculated from the inclusive K^+ production cross section σ_{K^+} by $M_{K^+} = \sigma_{K^+}/\sigma_{\mathrm{R}}$ with σ_{R} the reaction cross section as defined within a geometrical model ($\sigma_{\mathrm{R}} = 4\pi r_0^2 A^{2/3}$ with $r_0 = 1.2$ fm). The inclusive K^+ production cross section is determined from the differential cross section $d^2\sigma_{K^+}/dpd\Omega$ (measured at midrapidity) by integration over momentum and extrapolation to 4π assuming an isotropic emission. The average number of participating nucleons is given within a geometrical model by $\langle A_{\mathrm{part}}\rangle = A/2$ for symmetric $A + A$ collisions.

The increase of $M_{K^+}/\langle A_{\mathrm{part}}\rangle$ with increasing size of the collision system is an experimental signature for kaon production via collective effects. The K^+ multiplicity scales with the mass number of the colliding nuclei according to $M_{K^+} \propto A^{1.3\pm0.13}$.

Within the framework of transport models, "subthreshold" kaon production predominantly proceeds via sequential processes involving intermediate pions or Δ resonances: in a first step a Δ (or pion) is produced which collides subsequently with a baryon and produces a kaon [1, 14, 15]:

(i) $NN \to N\Delta$ ($\Delta \to N\pi$) and

(ii) $\Delta N \to KYN$ or $\pi N \to KY$

with $Y = \Lambda, \Sigma$.

In these processes the pion or the Δ resonance serves as an energy reservoir which significantly lowers the K^+ production threshold. Hence the scaling of the K^+ multiplicity with the number of nucleons can be understood quantitatively: (i) the pion multiplicity was found to be proportional

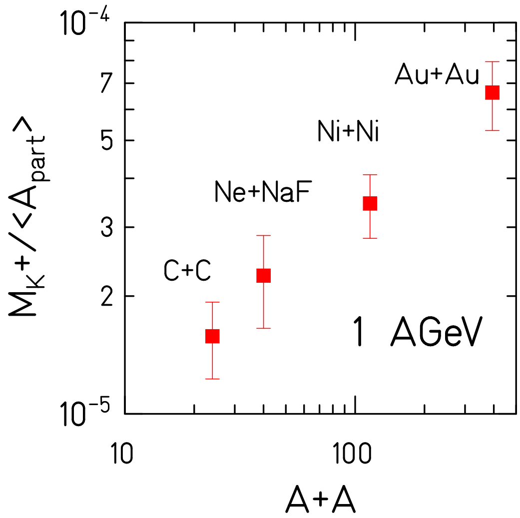

Fig. 1. K^+ multiplicity per participating nucleon from $A+A$ collisions at 1.0 AGeV as a function of A (preliminary). The data are taken from [9–12].

to the number of nucleons ($M_\pi \propto A$) and (*ii*) the probability for a secondary pion–nucleon (or Δ-nucleon) collision scales with the nuclear radius ($\propto A^{1/3}$). Thus the multiplicity of such a sequential process is proportional to $A^{4/3}$.

3. In-medium modifications of kaons and antikaons

The formation of a nuclear fireball in nucleus–nucleus collisions provides the possibility to study the properties of hadrons under extreme conditions. It has turned out, that the produced K-mesons are promising candidates for the experimental study of in-medium modifications.

The properties of kaons and antikaons in dense nuclear matter have been investigated using chiral perturbation theory [4, 6], chiral dynamics [5] and a relativistic mean field model [16]. The calculations find an attractive KN (scalar) in-medium potential which is related to explicit chiral symmetry breaking due to the large strange quark mass. The additional (vector) KN in-medium potential is repulsive for kaons but attractive for antikaons. Hence the total KN interaction in the medium is weakly repulsive for kaons but strongly attractive for antikaons. These in-medium KN potentials influence the propagation of kaons and antikaons in nuclear matter. As a consequence, their azimuthal emission pattern is expected to be modified according to the density profile of the nuclear medium: K^+ mesons will be repelled from the regions of increased baryonic density whereas K^- mesons will be attracted [17].

Another manifestation of the in-medium KN potentials is a modification of the K^+ and K^- rest mass in nuclear matter. With increasing nuclear density the K^+ mass is expected to increase weakly, whereas the K^- mass should decrease considerably. This effect should lead to a pronounced enhancement of the K^- cross section in nucleus–nucleus collisions at intermediate energies [3,18]. Fig. 2 shows the effective in-medium mass of kaons and antikaons as a function of nuclear density as calculated by various models.

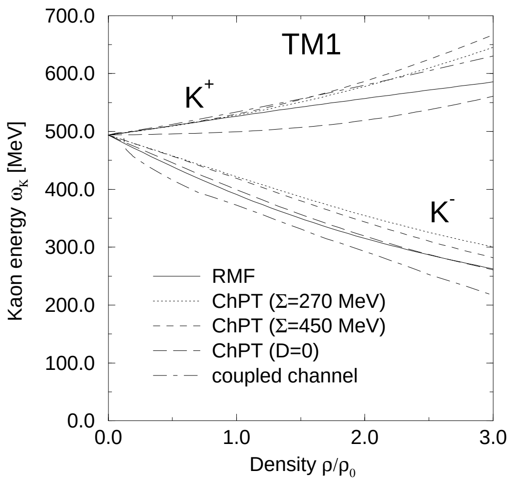

Fig. 2. Effective in-medium mass of kaons and antikaons as a function of nuclear density according to a different calculations. Taken from [16].

The KaoS Collaboration has started to study systematically the in-medium production of K^- and K^+ mesons. Fig. 3 presents the K^+ azimuthal angular distribution measured in Au+Au collisions at 1 AGeV [19]. The kaons were accepted within a range of transverse momenta of 0.2 GeV$/c$ $\leq p_t \leq$ 0.8 GeV$/c$ around midrapidity ($0.4 \leq y/y_{\rm proj} \leq 0.6$). The data are corrected for the uncertainty of the determination of the reaction plane by a Monte Carlo simulation. The K^+ emission pattern clearly is peaked at $\phi = \pm 90^0$ which is perpendicular to the reaction plane. Such a behaviour is known from nucleons [20] and pions [21]. The K^+ mesons, however, have a long mean free path of about 6 fm and therefore should be little sensitive to the nuclear matter distribution. This is demonstrated in Fig. 3 by the dotted line which represents the result of a transport calculation taking into account K^+ rescattering only [17]. However, if an in-medium KN potential is assumed, the calculation reproduces the pronounced anisotropy of the data (solid line in Fig. 3).

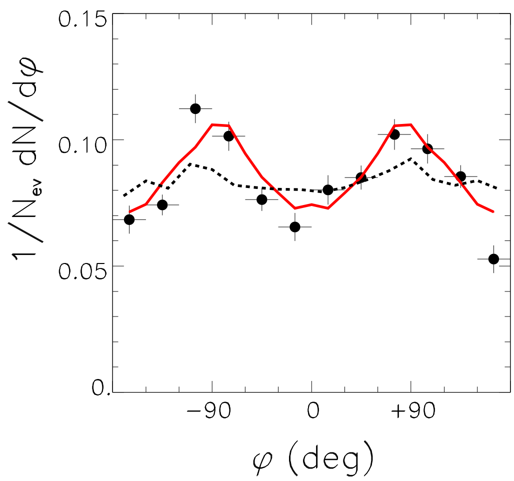

Fig. 3. K^+ azimuthal distribution for semi-central collisions and $0.4 < y/y_{\mathrm{proj}} < 0.6$ for Au+Au 1 AGeV [19]. The lines represent results of RBUU calculations with (solid line) and without (dashed line) in-medium KN potential [17].

Now we turn to the discussion of possible in-medium mass modifications of the K mesons. The strong K^-N mass reduction in the dense nuclear medium as indicated in Fig. 2 is expected to lower the K^- production threshold and thus enhancing the K^- production cross section in nucleus–nucleus collisions. The enhancement of the K^- yield should be very pronounced at beam energies below the kinematical threshold which is 2.5 GeV for the process $NN \to K^-K^+NN$. In order to find experimental evidence for this effect we compare the K^- to the K^+ yield at beam energies which are equivalently below the respective thresholds, *i.e.* which are at the same Q-value $\sqrt{s} - \sqrt{s_{\mathrm{thr}}}$. The comparison at equivalent beam energies is ment to be a rough correction for phase space effects.

Fig. 4 presents K^+ and K^- multiplicities per participating nucleon as a function of the excess energy in the NN system for C+C (left) and $p+p$ collisions (right). The C+C data measured by the KaoS experiment are still preliminary [12, 13]. The $p+p$ data have been measured recently at COSY [22]. The lines represent a recent parameterization of the elementary kaon production cross sections [23, 24]. For the C+C system, the K^+ and K^- yields agree for same values of $\sqrt{s} - \sqrt{s_{\mathrm{thr}}}$ in contrast to $p+p$ collisions where the K^+ yield exceeds the K^- yield by orders of magnitude. This striking difference for $A+A$ and $p+p$ collisions is a clear signature for an enhanced production of K^- mesons in nuclear collisions (the K^+ mesons cannot be absorbed because of their $\overline{s}$ quark).

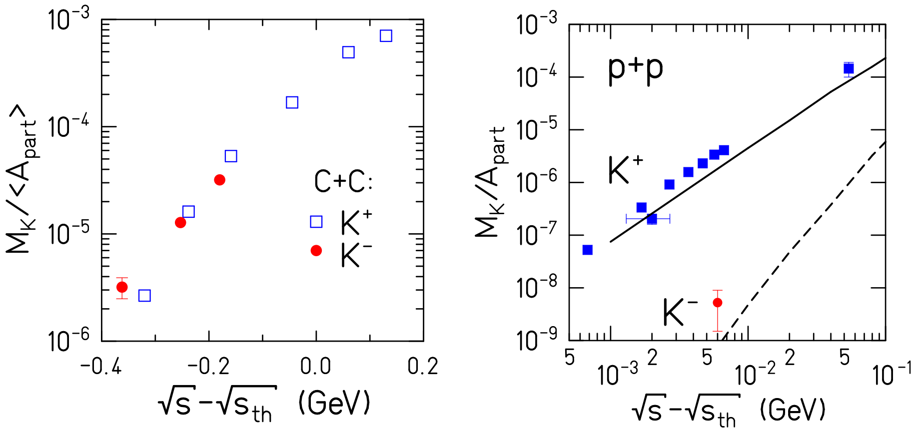

Fig. 4. Kaon and antikaon multiplicity per participant nucleons as a function of the Q-value in the NN system for C+C (left) and $p+p$ (right) collisions. The C+C data are preliminary [12, 13]. The $p+p$ data are taken from [22], the solid lines represent parameterizations [23, 24].

The enhanced K^- yield in A+A collisions is unexpected since K^- mesons are strongly absorbed in the nuclear medium by strangeness exchange reactions like $K^-N \to \pi Y$. On the other hand, the inverse process $\pi Y \to K^-N$ might be an additional in-medium source of K^- mesons as pions and hyperons are abundant (the hyperon yield at 1.8 AGeV corresponds roughly to twice the measured K^+ yield). Indeed, recent RBUU calculations claim that the process $\pi Y \to K^-N$ is the most important K^- production channel in Ni+Ni collisions at 1.8 AGeV [15]. These calculations are based on the parameterization of the elementary kaon production cross sections as shown in the right part of Fig. 4. Nevertheless, the sum of all K^- production channels considered by the transport calculations is about a factor of 4–5 below the measured data points, if in-medium effects on the K^- mass are neglected [15].

A similar discrepancy is found for C+C collisions. Fig. 5 presents preliminary K^+ and K^- spectra measured in C+C collisions at 1.8 (left) and 2.0 AGeV (right) together with RBUU predictions [25]. The dotted lines represent calculations for bare K^+ and K^- masses. The solid lines in Fig. 5 represent RBUU predictions when assuming an in-medium reduction of the K^- mass according to $m_K^*(\rho) = m_K^o$ $(1\text{–}\alpha \times \rho/\rho_o)$ with $\alpha = 0.24$. The RBUU calculations agree with the data for low K^- energies (where most of the yield is concentrated). For high K^- energies, however, the data seem to favor the results for the bare mass. This behaviour indicates a momentum dependence of the in-medium K^- properties as proposed by several authors [26, 27].

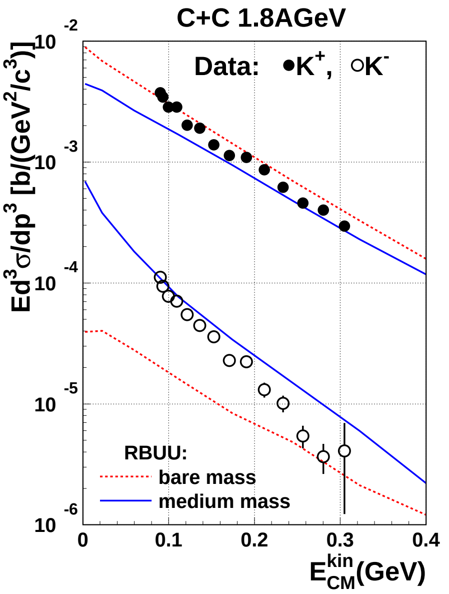

Fig. 5. Invariant cross sections for K^+ and K^- production in C+C collisions at 1.8 AGeV and 2.0 AGeV as a function of the cm kinetic energy (preliminary) [13]. The data are compared to predictions of RBUU calculations without in-medium modifications (dotted lines) and with in-medium effects (solid lines) [25].

The enhancement of the K^- yield was found both in C+C and in Ni+Ni collisions. However, medium effects should be more pronounced in the Ni+Ni system. On the other hand, the absorption of K^- mesons is also stronger in larger systems. Therefore, the K^-/K^+ ratio at equivalent energies might be constant for $A+A$ collisions independent of A. Whether this hypothesis is correct will be checked by a forthcoming KaoS experiment which will measure kaon and antikaon production in Au+Au collisions at 1.5 AGeV.

The kaon in-medium modification and its effect on the kaon yields from Ni+Ni collisions has been also studied theoretically by the Stony Brook group using a RBUU transport code [28]. The result of the calculation is presented in Fig. 6. It shows the K^+/K^- ratio for equivalent beam energies as a function of kaon energy without (dotted line) and with kaon medium effects (solid line). In order to get agreement with the KaoS data (symbols, [10]) the authors varied the density dependence of the kaon potentials. Based on the kaon in-medium properties as constrained by the heavy ion data the authors predict K^- condensation in neutron stars and a maximum neutron star mass of about 1.5 solar masses [28].

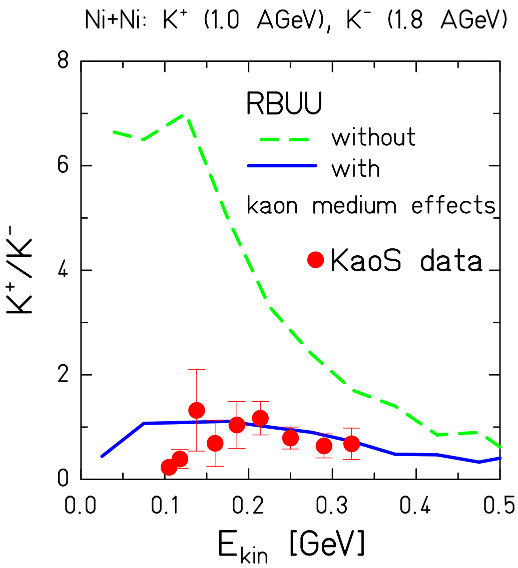

Fig. 6. K^+/K^- ratio for equivalent beam energies as a function of the kaon c.m. kinetic energy (K^+ calculated at 1.0 AGeV and K^- at 1.8 AGeV) [28]. Dashed line: RBUU without kaon medium effect. Solid line: RBUU with kaon medium effect. Full circles: KaoS data [10].

4. Summary

Recent results on kaon and antikaon production in nucleus–nucleus collisions at intermediate beam energies have been presented. In $A+A$ collisions at 1 AGeV, the K^+ multiplicity scales like $M_{K^+} =\propto A^{1.3\pm0.13}$. The nonlinear increase is caused by collective effects such as multiple hadron-hadron collisions. The K^+ mesons are preferentially emitted perpendicular to the reaction plane. This strong anisotropy of the azimuthal emission pattern is predicted for a repulsive K^+N potential in the nuclear medium. The large K^-/K^+ ratio measured in C+C and Ni+Ni collisions at equivalent beam energies (compared to the K^-/K^+ ratio from $p+p$ collisions) indicates an enhanced production of K^- mesons in the nuclear medium. According to transport models this effect is caused by a reduction of the K^- mass in dense nuclear matter.

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