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STRANGE MESONS IN DENSE NUCLEAR MATTER *

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The production and propagation of kaons and antikaons in nucleus-nucleus collisions has been measured with the Kaon Spectrometer at SIS. We present the excitation function of K^+ production in C+C and Au+Au collisions. In Ni+Ni collisions at 1.93 AGeV we measured the phase-space distributions of K^- and K^+ mesons. The K^-/K^+ ratio was measured in C+C, Ni+Ni and Au+Au collisions at 1.5 AGeV and was found to be almost independent of the mass of the collision system. Within the framework of present days transport calculations, the measured K^+ and K^- yields can only be explained if in-medium modifications of the K meson masses are assumed. In Au+Au collisions at 1 AGeV, we observe a nonisotropic azimuthal emission pattern for K^+ mesons. This effect is can be explained by transport codes when a repulsive in-medium K^+N potential is taken into account.

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1. Introduction

The properties of strange particles in dense nuclear matter play a crucial role in the dynamics of supernovae and for the stability of neutron stars [1–3]. It was speculated that a Bose condensation of K^- mesons significantly softens the equation-of-state of neutron star matter and hence catalyzes the formation of low-mass black holes [1]. This idea is based on theoretical calculations predicting in-medium kaon-nucleon potentials which are repulsive

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for kaons but attractive for antikaons [4–6]. The ultimate goal is to relate the in-medium spectral function of kaons and antikaons to the anticipated chiral symmetry restoration at high baryon density [7].

Experiments with heavy-ion beams provide the unique possibility to study strange mesons in baryonic matter at densities well above saturation density. The in-medium KN potentials are expected to influence both the production and the propagation of kaons and antikaons in heavy ion collisions. The corresponding observables are *(i)* the differential production cross sections and *(ii)* the azimuthal angular distributions. The KN potentials will modify the in-medium production thresholds: the production of K^+ mesons is expected to be suppressed whereas the production of K^- mesons will be favored. The kaon 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 [8].

First data on kaon and antikaon production and propagation in heavy ion collisions at SIS energies have been published in [10,11,13,14]. In the following we will present data measured recently with the Kaon Spectrometer at SIS/GSI [9].

2. Production yield of K mesons in nucleus–nucleus collisions

The multiplicity of K^+ mesons has been measured in C+C collisions at beam energies between 0.8 and 2 AGeV and in Au+Au collisions between 0.6 and 1.5 AGeV [18]. Fig. 1 shows the inclusive K^+ multiplicity per average number of participating nucleons $M_{K^+}/\langle A_{\mathrm{part}}\rangle$ for C+C and Au+Au collisions as a function of beam energy. The data are compared to results of QMD transport calculations with (solid lines) and without (dashed lines) kaon in-medium effects [19]. The model calculation overpredicts the kaon yield both for the light and the heavy collision system if in-medium modifications of the kaons are neglected. The assumption of a repulsive K^+N potential reduces the kaon yield significantly. This effect is more pronounced in the Au+Au system with its high baryon density. Within the transport model calculations, the K^+ mesons are predominantly produced in secondary collisions such as $\pi N \to K^+ Y$ or $\Delta N \to K^+ N Y$ with $Y = (\Lambda, \Sigma)$. In these processes, the pions or the Δ resonances serve as energy reservoirs. Similarly, the antikaons are created in reactions like $\pi N \to K^+ K^- N$ or $\Delta N \to K^+ K^- N N$. However, K^- mesons may be created as well in the strangeness exchange reactions $\pi Y \to K^- N$ with a hyperon and a pion produced in the first step. On the other hand, K^- mesons are reabsorbed by the inverse process $K^- N \to Y \pi$ whereas K^+ mesons are not absorbed due to strangeness conservation.

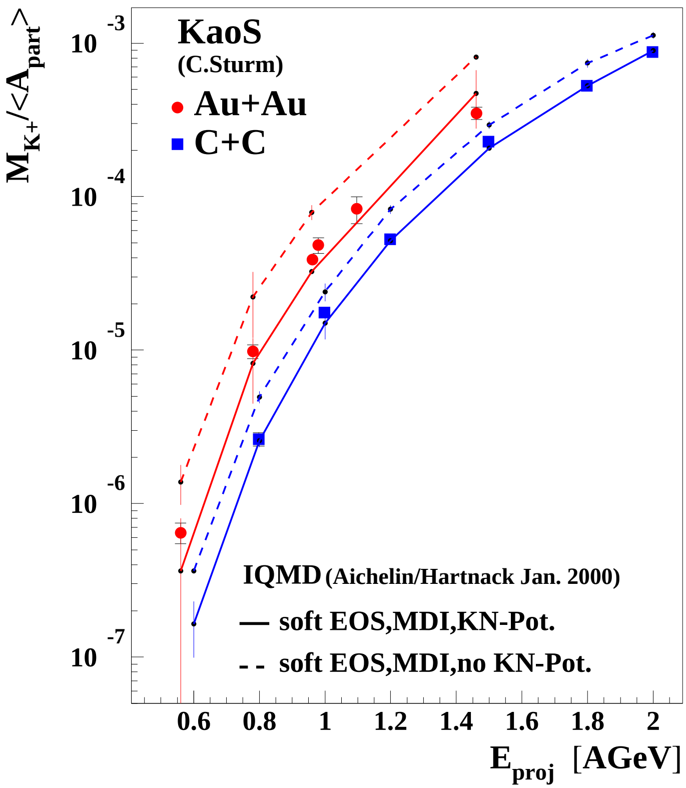

Fig. 1. Inclusive K^+ multiplicity per average number of participating nucleons for Au+Au and C+C collisions as function of the projectile energy per nucleon (symbols). The solid and dashed lines represent the results of QMD calculations with and without in-medium modifications [19]. The calculations are based on a soft nuclear equation-of-state and take into account momentum-dependent interactions.

Fig. 2 presents the K^-/K^+ ratio measured in C+C, Ni+Ni and Au+Au collisions at a beam energy of 1.5 AGeV. The ratio is approximately constant for the three systems, allthough the reabsorption probability for K^- mesons should be very different: the K^- mean free path is about 1.5 fm at saturation density. In a geometrical model, the losses of K^- mesons due to strangeness exchange $K^-N \to Y\pi$ are estimated to be more than 10 times larger in Au than in C nuclei. However, if the effective mass of a K^- meson is lowered in the nuclear medium, the process $K^-N \to Y\pi$ will not be exotherm any more and, therefore, is suppressed. The data in Fig. 2 suggest that in the Au+Au system the absorption of K^- is compensated by an enhanced production and/or that the K^- absorption process is suppressed. Both effects can be caused by a reduced in-medium effective mass of antikaons.

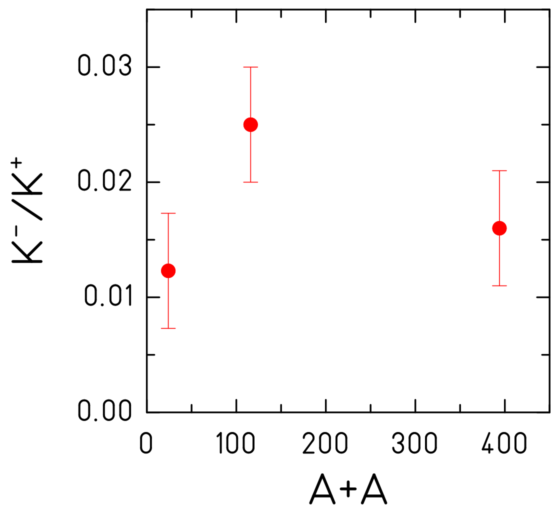

Fig. 2. K^-/K^+ ratio measured in C+C, Ni+Ni and Au+Au collisions at a beam energy of 1.5 AGeV.

In a recent experiment we have measured phase-space distributions of K^- and K^+ mesons in Ni+Ni collisions at 1.93 AGeV. The data were taken at laboratory angles $\Theta_{\rm lab} = 32$, 40, 50, and 60°. In Fig. 3 we show the K^+ and K^- rapidity densities dN/dy and their ratio for near-central Ni+Ni collisions at 1.93 AGeV (circles) as function of the rapidity $y_{\rm CM}$. The near-central collisions are defined as the most central 620±30 mb of the reaction cross section which corresponds geometrically to impact parameters smaller than $b = 4.4$ fm. The square symbols represent data measured by the FOPI collaboration around target rapidity [14]. In the overlap region both experiments find absolute yields which are in good agreement within the experimental errors. The rapidity is defined here as $y_{\rm CM} = y - 0.5 \times y_{\rm proj}$. The value $y_{\rm CM} = 0$ corresponds to midrapidity and $y_{\rm CM} = \pm 0.89$ to projectile or target rapidity, respectively.

The data are compared to results of RBUU transport calculations [20]. The dashed line represents the result of a calculation with bare kaon and antikaon masses whereas the solid line is calculated with in-medium masses. In the transport model, the in-medium masses of K mesons are assumed to vary linearly with baryon density according to $m_K^* = m_K^0(1 - \alpha\rho/\rho_0)$ with m_K^0 the bare K meson mass, ρ_0 the saturation density and $\alpha = 0.24$ for K^- and -0.06 for K^+. The "bare mass" calculations clearly overestimate the K^+ yield and underestimate the K^- yield. The results of the "in-medium" calculations deviate much less from the data.

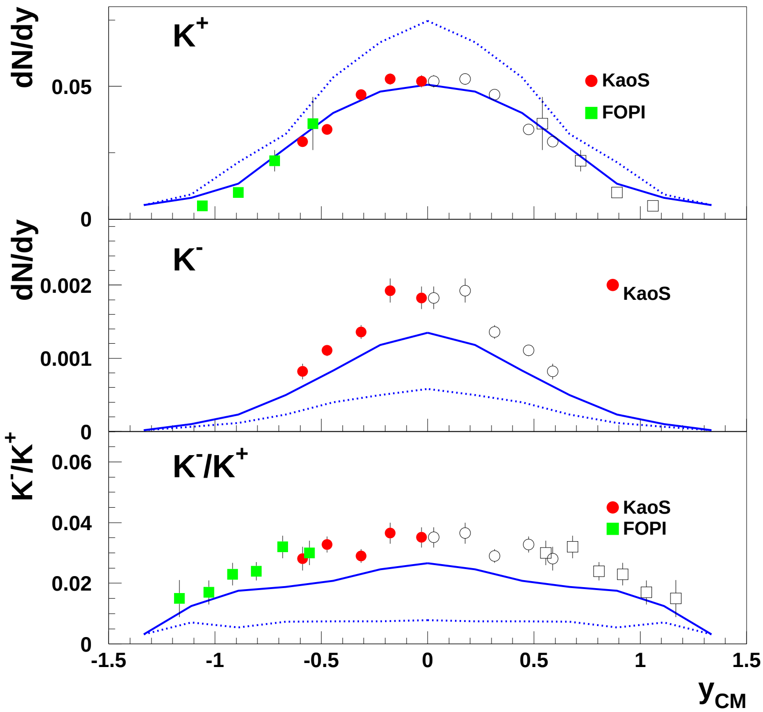

Fig. 3. Rapidity density distributions of K^+ (upper panel) and K^- mesons (center panel) for near-central ($b < 4.4$ fm) Ni+Ni collisions at 1.93 AGeV. Circles: KaoS data [12], squares: FOPI data [14]. Full data points are measured and mirrored at $y_{\rm CM}$=0 (open points). Lower panel: K^-/K^+ ratio. The data are compared to BUU transport calculations [20]; solid line: with in-medium effects, dotted line: without in-medium effects.

3. The azimuthal emission pattern of K^+ mesons

Figure 4 presents the K^+ azimuthal angular distribution measured in Au+Au collisions at 1 AGeV [13] with the Kaon Spectrometer at SIS/GSI. The kaons were accepted within a range of transverse momenta of 0.2 GeV/c $\leq p_{\rm t} \leq$ 0.8 GeV/c for two ranges of normalized rapidities $0.4 \leq y/y_{\rm proj} \leq 0.6$ (left) and $0.2 \leq y/y_{\rm proj} \leq 0.8$ (right) with $y_{\rm proj}$ the projectile rapidity. The reaction plane is reconstructed from the projectile fragments detected at small forward angles ($\Theta_{\rm lab} = 0.5°$–$7°$). The collision centrality is determined via the multiplicity of charged particles measured at larger angles ($\Theta_{\rm lab}$= 12°–48°). The data are corrected for the uncertainty of the determination of the reaction plane on the basis of a Monte Carlo simulation.

The K^+ emission pattern clearly is peaked at ϕ=±90° which is perpendicular to the reaction plane. Such a behaviour is known from pions [16]

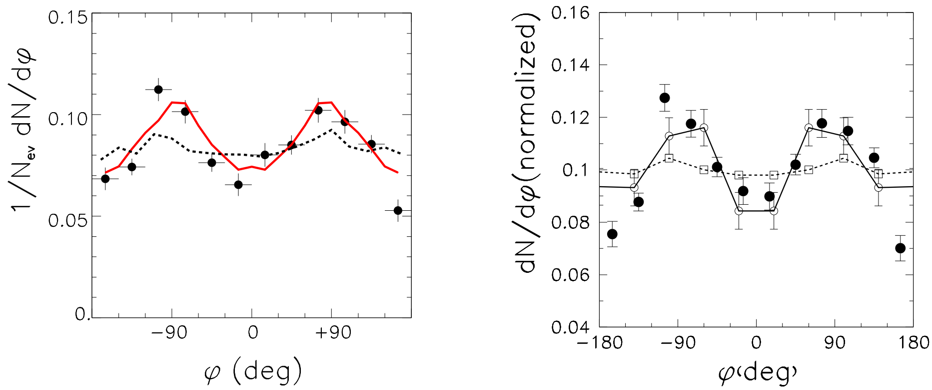

Fig. 4. K^+ azimuthal distribution for semi-central Au+Au collisions at 1 AGeV (full dots). The data are analyzed at $0.4 < y/y_{\rm proj} < 0.6$ (left) and $0.2 < y/y_{\rm proj} < 0.8$ (right) [13]. The lines represent results of transport calculations from the Stony Brook group using a RBUU model (left [8]) and a QMD model from the Tübingen group (right [15]). Both models take into account rescattering, the QMD version also considers Coulomb effects. Solid lines: with in-medium KN potential; dashed lines: without in-medium KN potential.

which interact with the spectator fragments. The K^+ mesons, however, have a long mean free path of about 5 fm and therefore are less sensitive to rescattering. This is demonstrated in Fig. 4 by the dotted lines which represent the results of a transport calculation taking into account K^+ rescattering only ([8], left) and additional Coulomb effects ([15], right). However, if a repulsive in-medium KN potential is assumed, the calculations reproduce the pronounced anisotropy of the data (solid lines in Fig. 4). Although it is encouraging that a consistent picture arises from different transport models, additional data and a less model dependent experimental signature of in-medium effects is highly desirable. A promising observable in this sense is the azimuthal emission pattern of antikaons. In contrast to the K^+ mesons, the K^- are expected to exhibit a pronounced enhancement at $\varphi = \pm 90°$ if the attractive antikaon in-medium potential is absent. This anisotropy is caused by the strong absorption of K^- mesons in the spectator fragments. In contrast, if an attractive antikaon-nucleon potential exists, it will compensate for the K^- meson loss and hence the K^- emission pattern is predicted to be isotropic around midrapidity. The two cases are illustrated in Fig. 5 which presents the results of a QMD transport calculation for the K^- emission pattern around midrapidity in Au+Au at a beam energy of 1.8 AGeV [15]. Accordingly, the K^- pronounced antiflow signal expected at target/projectile rapidities without in-medium effect is expected to vanish in the case of an attractive potential [17]. The KaoS Collaboration has

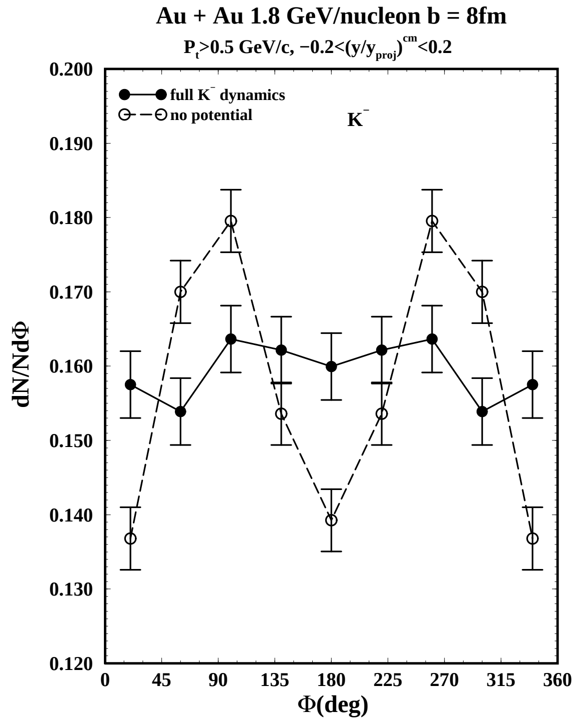

Fig. 5. K^- azimuthal distribution as predicted by QMD transport model calculations for Au+Au collisions at a beam energy of 1.8 AGeV [15]. Open circles: no in-medium K^-N potential; full circles: with in-medium K^-N potential.

performed an exploratory measurement of the K^- azimuthal emission pattern in Au+Au collisions at 1.5 AGeV. Within a preliminary analysis, the K^+ azimuthal angular distribution is peaked around $\Phi = \pm 90°$ as expected for a repulsive K^+N potential. The K^- distribution, however, still has large error bars and further measurements will have to reduce the statistical uncertainties.

4. Conclusions and outlook

We have presented data on the production and propagation of strange mesons in heavy ion collisions in the SIS energy range. The production yields of kaons are overestimated by transport calculations by about a factor of two whereas the yields of antikaons are underestimated by a factor of about four when neglection in-medium effects. The observation of similar values for the K^-/K^+ ratio for C+C, Ni+Ni and Au+Au collisions at 1.5 AGeV provides evidence for suppressed K^- absorption. This effect indicates a modification of antikaon properties in nuclear matter. In Au+Au collisions at 1 AGeV the K^+ azimuthal emission pattern is found to be nonisotropic. Around midrapidity the kaons are emitted preferentially perpendicular to the reaction plane. This effect can be reproduced by transport calculations only if a repulsive KN potential is assumed. The measurement of the K^- azimuthal emission pattern offers the possibility to find almost model independent evidence for an attractive K^-N potential in nuclear matter. More information on the in-medium properties of kaons and antikaons can be expected from production yields in proton-nucleus collisions which has been measured with the Kaon Spectrometer.

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