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Direct comparison of phase-space distributions of K^- and K^+ mesons in heavy-ion collisions at SIS energies — evidence for in-medium modifications of kaons?

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Abstract. The ratio of K^- to K^+-meson yields has been measured in the systems ^{96}Ru + ^{96}Ru at 1.69 A GeV, ^{96}Ru+^{96}Zr at 1.69 A GeV, and ^{58}Ni+^{58}Ni at 1.93 A GeV incident beam kinetic energy. The yield ratio is observed to vary across the measured phase space. Relativistic transport-model calculations indicate that the data are best understood if in-medium modifications of the kaons are taken into account.

PACS. 25.75.-q Relativistic heavy-ion collisions – 25.75.Dw Particle and resonance production

Recently there has been considerable effort, both experimentally and theoretically, to investigate changes of hadron properties in a hot and dense nuclear medium. In particular, a variety of theoretical approaches consistently predict that the effective mass of kaons increases slightly with increasing baryon density, while the mass of antikaons is expected to drop substantially [1]. This phenomenon could lead to the formation of a kaon condensate in a dense hadronic environment [2], which in turn would effect the nuclear equation of state, and have consequences for the physics of neutron stars [3]. The modifications of the properties of kaons in a hadronic medium might originate from the partial restoration of the chiral symmetry of QCD [4].

The question whether the kaon masses are modified in a dense hadronic environment can be addressed experimentally with studies on kaons produced in heavy-ion collisions at bombarding energies around 1–2 GeV per nucleon, which is close to the production threshold in elementary, nucleon-nucleon reactions (1.6 and 2.5 GeV for K^+ and K^--mesons, respectively). At these beam energies, kaons are most likely produced in the early stage and in the central region of the collision [5], where densities of up to 3 times the normal nuclear matter density and temperatures in the order of 100 MeV can be reached [6]. The production rate can be influenced not only by the surrounding medium (*e.g.*, its density) or the properties of the nucleons and their resonances, but also by possible changes of the kaon properties themselves.

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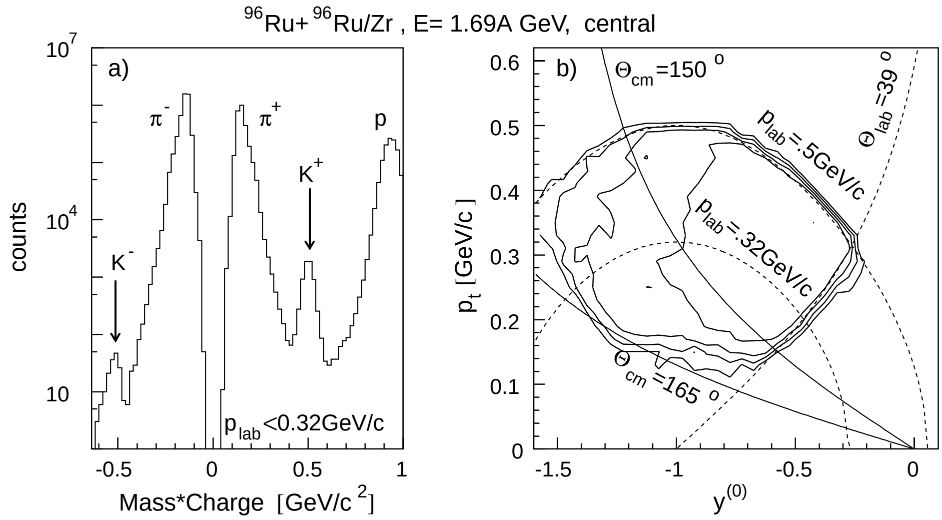

Fig. 1. (a) Mass spectrum of charge ±1 particles measured in the Ru + Ru/Zr experiment. (b) K^+-meson phase-space distribution within the acceptance of the FOPI detector. The meaning of the lines is explained in the text.

The observation of the enhanced K^--meson yield at midrapidity in heavy-ion collisions with respect to the elementary, nucleon-nucleon reactions [7] is a very interesting signature, possibly related to a substantial in-medium drop of the effective mass of K^--mesons. A change of the effective mass of a particle can be understood as an effect of a density dependent potential. Gradients of this potential cause forces that act on particles. While antikaons are attracted into regions of high baryon density, kaons are repelled from these regions. This effect offers an explanation [8] for the characteristic directed side-flow patterns of K^+-mesons that are observed experimentally [9]. It also predicts characteristic changes of the final-state phase-space distributions of kaons and antikaons [10].

In this note we report on measurements of K^+ and K^--mesons produced in ^{96}Ru + ^{96}Ru/^{96}Zr collisions at 1.69 A GeV and in ^{58}Ni + ^{58}Ni collisions at 1.93 A GeV incident beam kinetic energy. The experiments were performed at SIS/GSI, using the FOPI experimental setup [11] which allows for a simultaneous measurement of all charged reaction products. Thus, final-state distributions of the particles can be directly compared within the same event sample and with the same acceptance. Results on the phase-space population of $\pi^{\pm}$, p, d, and K^+ in the Ni+Ni experiment were reported elsewhere [12,13]. Here, we show, for the first time in this energy regime, the ratio of K^- to K^+-meson yields in the backward hemisphere. We extract the ratio across a relatively wide region of phase space, which provides high sensitivity to the dynamics of the propagation of kaons through the medium. We observe that the phase-space distributions of K^- and K^+-mesons differ and discuss the origin of this effect.

An ensemble of events biased to small impact parameters has been selected by requiring high charged-particle multiplicity in the polar-angle range $7° < \Theta_{\mathrm{lab}} < 30°$ on the trigger level. For the Ni+Ni experiment, $4.7\cdot10^6$ events were selected, corresponding to the centralmost 11% of the total geometrical cross-section. Since no difference in strangeness production was found between the Ru+Ru and Ru+Zr systems [14], the accumulated statistics was combined for a total of $7.7 \cdot 10^6$ events, corresponding to the centralmost 14% of the geometrical cross-section.

The identification of K^+ and K^--mesons with the FOPI detector relies upon the information on specific energy loss and track curvature in the Central Drift Chamber (CDC), and on the measurements of Time-of-Flight (ToF) in the surrounding Plastic Scintillator Barrel detector [11]. The acceptance is thus restricted to the polar-angle range in the laboratory reference frame $39° < \Theta_{\mathrm{lab}} < 130°$ and to transverse momenta $p_{\mathrm{t}} > 0.1$ GeV/c. The finite detector resolution limits the identification of K^+-mesons to laboratory momenta $p_{\mathrm{lab}} < 0.5$ GeV/c. Due to the much lower K^- yield compared to that of K^+-meson, the background contamination in the former increases more rapidly with momentum. In order to eliminate possible distortions due to a momentum-dependent background contribution, the considered momentum range for K^--meson identification is restricted to p_{lab} below 0.32 and 0.34 GeV/c in case of the Ru+Ru/Zr and Ni+Ni experiments, respectively. At $p_{\mathrm{lab}} \simeq 0.32$ (0.34) GeV/c the measured K^--meson yields have less than 20% background contamination and the K^+-meson yields are practically background free (the contamination is less than 5%).

With the different upper momentum limits for positive and negative kaons, mentioned above, around 26000 K^+ and 240 K^--mesons have been identified in the Ni+Ni experiment. The combined statistics of the Ru+Ru/Zr experiment is about 40000 K^+ and 220 K^--mesons. The mass spectrum of particles with charge ±1 measured in the Ru+Ru/Zr experiment is shown in fig. 1.a. Peaks from K^+ and K^--mesons are clearly visible. The portion of the phase space populated by K^+-mesons measured in the Ru+Ru/Zr experiment is shown in fig. 1.b in terms of normalized rapidity ($y^{(0)} = y^{\mathrm{lab}}/y^{\mathrm{CM}} - 1$, where y^{CM} is

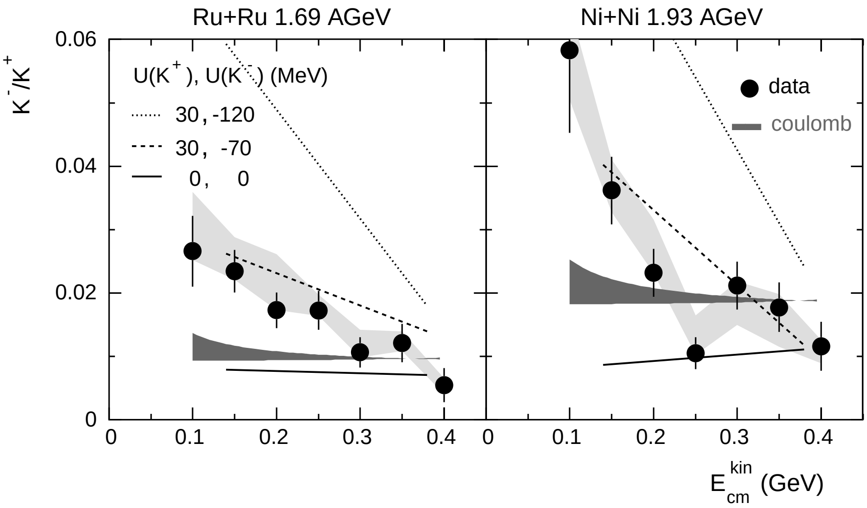

Fig. 2. The K$^-$/K$^+$ ratio as a function of $E_{\rm cm}^{\rm kin}$ in the Ru+Ru/Zr (left) and Ni+Ni experiments (right). The data are extracted in the polar-angle range $150° < \Theta_{\rm cm} < 165°$. The light-grey shaded areas correspond to the estimate of systematic errors. The lines depict predictions of the RBUU transport model with different strength $U(\rho = \rho_\circ)$ of the in-medium (anti)kaon potentials at normal nuclear matter density. Statistical uncertainties of the predictions are similar to those of the experimental data. The horizontal dark-grey shaded areas show the results of numerical simulations carried out in order to estimate the influence of the Coulomb potential on the K$^-$/K$^+$ ratio.

half of the beam rapidity) and transverse momentum. In this representation -1 and 0 on the rapidity axis correspond to the target and the midrapidity, respectively. The yield of K$^+$-mesons is depicted by the contour lines on a linear scale. The geometrical limit at $\Theta_{\rm lab} = 39°$ and the upper $p_{\rm lab}$ limits for K$^+$ and K$^-$-meson identification are depicted by dashed lines. The solid lines show the polar-angle range in the center-of-mass (c.m.) reference frame $150° < \Theta_{\rm cm} < 165°$, which will be referred to later.

To quantitatively examine and compare the phase-space distributions of K$^+$ and K$^-$-mesons, where for the latter case low statistics does not allow to extrapolate the measured yields to experimentally not accessible regions of the phase space, we study the *ratio* of K$^-$ to K$^+$-meson yields in the limited phase-space region defined by the K$^-$-meson identification. This offers two advantages with respect to analysing the single particle distributions. i) Experimental difficulties, like detection efficiencies and acceptance deficiencies, cancel to a large extent [14]. ii) In-medium effects act in opposite ways on K$^-$ and K$^+$-mesons, hence the ratio should reveal these more clearly.

In FOPI, the efficiency for particle detection is given by the tracking efficiency in the CDC and the matching efficiency with the ToF Barrel. Possible systematic bias on the measured K$^-$/K$^+$ ratio was estimated using a Monte Carlo simulation in which the full detector response was modelled with the GEANT package [15]. The simulated data were analysed in the same way as the experimental data. Comparing the output of the simulation to its input, the final K$^-$/K$^+$ ratio was found to be overestimated by 15%, independently of transverse momentum and rapidity. This effect is attributed to different efficiencies of the track finding for positively and negatively charged particles due to the geometry of the CDC. A similar asymmetry of the efficiency was reported in [16] for π^+ and π^--mesons. All data points shown in the following figures are corrected for this systematic bias, *i.e.*, all ratios are reduced to 87% of the directly measured value. Furthermore, the systematic uncertainties due to the identification criteria ($< 30\%$) and the background contamination ($< 20\%$) were estimated by varying the conditions that were imposed on track parameters in order to select K$^+$ and K$^-$-mesons. These systematic errors are depicted by light-grey shaded areas in fig. 2 and 3. The systematic distortion due to the nuclear scattering of K$^-$-mesons in the target material is neglected, since for the targets used in the experients (1% interaction length in the beam direction and a transverse diameter of about 12 mm), this interaction probability is estimated to be below 3%.

Since produced particles, and especially kaons, are found to be emitted almost isotropically in the c.m. system [12], we plot in fig. 2 the K$^-$/K$^+$ ratio as a function of the kinetic energy in the c.m. reference frame ($E_{\rm cm}^{\rm kin}$) for both the Ru+Ru/Zr (a) and the Ni+Ni (b) experiments. The polar-angle range $150° < \Theta_{\rm cm} < 165°$ has been chosen since there the kinetic-energy acceptance is largest (see fig. 1.b). We observe that the ratio rises towards small $E_{\rm cm}^{\rm kin}$.

In order to test whether the effect can be caused by the electric field of the hadronic fireball formed in the collision, we performed numerical calculations following the studies on the influence of the Coulomb potential on charged-particle spectra reported in [17]. We followed the propagation of K$^-$ and K$^+$-mesons in an electric field of a net charge Z, which was originally homogeneously distributed in a sphere of a radius R_f, and expanded radially with a flow velocity $\beta_{\rm rad}$. Initially, the K$^-$ and K$^+$-

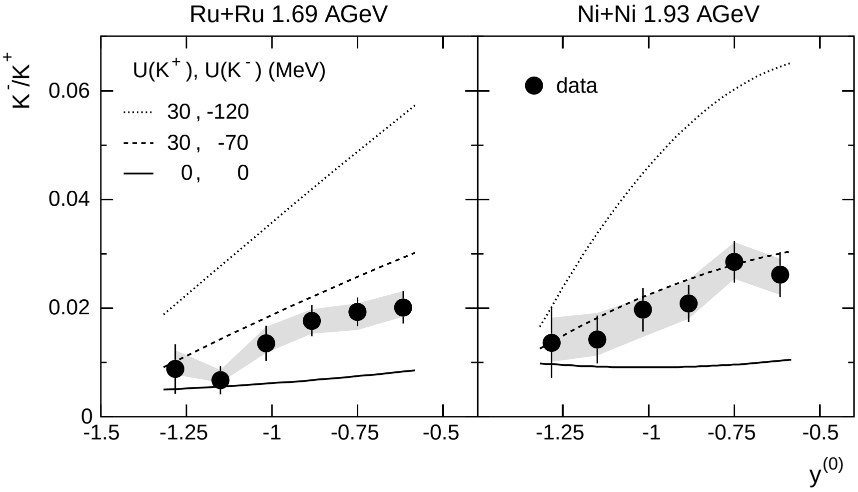

Fig. 3. The K^-/K^+ ratio as a function of $y^{(0)}$ in the Ru+Ru/Zr (left) and Ni+Ni (right) experiments. The light-grey shaded areas correspond to the estimate of systematic errors. The lines depict predictions of the RBUU transport model with different strength $U(\rho = \rho_\circ)$ of the in-medium (anti)kaon potentials at normal nuclear matter density. The results are filtered through the geometrical acceptance of the detector.

mesons were evenly distributed within the expanding volume, and had identical energy spectra that corresponded to an isotropic emission from a midrapidity source with a temperature T_f. The yields of K^- and K^+-mesons were arbitrarily normalized in order to allow a direct comparison with the experimental data. The parameters of the simulation (total charge Z, expansion velocity $\beta_{\rm rad}$, temperature T_f, and radius R_f) were varied in a reasonable range in order to model possible freeze-out conditions. The dark-grey shaded areas in fig. 2 correspond to the results obtained with different sets of parameters. Comparing this to the data, we conclude that the influence of the Coulomb potential of the net positive charge of colliding ions on the K^-/K^+ ratio is too small to account for the observed relative narrowing (widening) of the K^- (K^+)-meson final-state phase-space distributions.

In fig. 3 we plot the K^-/K^+ ratio as a function of $y^{(0)}$, *i.e.*, in the direction parallel to the beam axis. The result is biased by the detector acceptance but has the best statistical significance, which is given by the error bars attached to the data points. We observe that the K^-/K^+ ratio rises towards midrapidity. How representative the trend in the data is for the unbiased rapidity density distribution depends on the variation of the ratio as function of transverse momentum for fixed rapidity. For a meaningful comparison with the model predictions (see below), an acceptance filter was applied to the results of the model, taking into account the angular boundaries and the maximum laboratory momentum. The distortion due to acceptance turned out to be smaller than 20% in the case of the rapidity dependence of the ratio shown in fig. 3. The kinetic-energy dependence of the ratio presented in fig. 2 is not biased by the acceptance in the considered range of $E^{\rm kin}_{\rm cm}$.

Since the elementary reaction threshold is higher for K^- than it is for K^+-mesons (2.5 and 1.6 GeV respectively), one might expect that at the time of production, the average kinetic energies are lower for K^- than for K^+-mesons. However, when the incident beam energy is far below threshold, the production of K^- is dominated by channels involving intermediate baryon resonances and/or pions. According to Relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) transport-model calculations [18,19], owing to this mechanism the initial momentum-space distribution of K^--mesons is even wider than that of K^+-mesons. In addition, particles are further rescattered, which tends to equalize their phase-space distributions. The solid lines in fig. 2 and 3 show the values of the K^-/K^+ ratio predicted by the RBUU transport model [19] when describing the kaon scattering in a fashion consistent with the free particle properties. No significant dependence of the ratio on $y^{(0)}$ and $E^{\rm kin}_{\rm cm}$ is found, which results in a manifest contradiction to the data. The same conclusion has been drawn with another realization of a RBUU-type model [18].

Finally, we try to explain the variation of the K^-/K^+ ratio in the phase space by in-medium modifications of kaon properties. Dashed and dotted lines in fig. 2 and 3 show the values of the ratio predicted by the RBUU model when in-medium effects are taken into account by a linear dependence of the in-medium potential on density [19]. Two scenarios with different strength $U(\rho = \rho_\circ)$ of the in-medium kaon potentials at the normal nuclear matter density are presented.

The attractive K^- potential influences the results shown in fig. 2 and 3 in a systematic fashion: with increasing depth of the K^- potential, the K^-/K^+ ratio increases on average, and in addition the slope of the ratio with respect to rapidity and kinetic energy rises. While the first effect is caused by the corresponding drop of the effective mass, the rapidity and kinetic-energy dependencies are generated by the forces originating from the gradients of the potentials. Similar observations have been made on the p_t-dependence of the K^-/K^+ ratio [20]. Varying the repulsive potential for K^+-mesons does not modify the ratios significantly, as also shown in [18]. It has to be noted, however, that the calculations presented above underestimate the production yield of K^+ in the Ni+Ni collisions by a factor of two, while with very similar parameters ($U(\rho = \rho_\circ) = +20$ MeV for K^+-mesons the production rate is reproduced in [21]. Despite this discrepancy, in-medium modifications of kaon masses are presently the only mechanism explaining the trends found in the data.

Recently very similar observations of the K^-/K^+ ratios in heavy-ion collisions have been obtained at AGS energies (11.6 A GeV) [22]. Discrepancies to transport-model calculations were interpreted as signal for multi-body collisions owing to the very high densities that are reached in this energy regime. While the sensitivity of kaon-production ratios to in-medium properties is enhanced in the vicinity of the elementary reaction thresholds, it remains to be seen by careful model analysis whether both mechanisms can be clearly separated.

In summary, we measured the ratio of K^- to K^+-meson yields as a function of different kinematic variables in the experiments ^{96}Ru + ^{96}Ru^{96}/Zr at 1.69 A GeV and ^{58}Ni + ^{58}Ni at 1.93 A GeV incident beam kinetic energy. We found the K^--mesons final-state phase-space distribution to be narrower than that of K^+-mesons. It is unlikely that this effect is due to the different kinematical conditions of meson production or to the influence of the Coulomb potential of the net positive charge of colliding ions on meson propagation. However, it can be explained when assuming modifications of kaon properties in a dense nuclear medium. Theories that implement and exploit chiral symmetry breaking patterns of QCD argue that these modifications are a consequence of the restoration of the symmetry in a hot and dense nuclear matter [4]. However, the drop of the K^- effective mass can be also explained as an effect of the in-medium modifications of the $\Lambda(1405)$ spectral function due to the Pauli blocking of the proton [23]. In addition, it was suggested in [24] that in heavy-ion experiments the chaotic as well as the coherent movement of the baryonic matter may additionally mask the influence of the in-medium potential on the measured antikaon yields. In order to address the outstanding problems, more systematic studies of various systems and energies and with a better acceptance is needed. A further theoretical clarifications of the origin of the in-medium effects on kaons is also necessary.

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