Evidence for a Soft Nuclear Equation-of-State from Kaon Production in Heavy-Ion Collisions

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The production of pions and kaons has been measured in ^{197}Au + ^{197}Au collisions at beam energies from 0.6 to 1.5*A* GeV with the kaon spectrometer at SIS/GSI. The K^+ meson multiplicity per nucleon is enhanced in Au + Au collisions by factors up to 6 relative to C + C reactions, whereas the corresponding pion ratio is reduced. The ratio of the K^+ meson excitation functions for Au + Au and C + C collisions increases with decreasing beam energy. This behavior is expected for a soft nuclear equation-of-state.

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The equation-of-state of nuclear matter plays an important role in the dynamics of a supernova explosion and the stability of neutron stars. So far our knowledge on the behavior of dense nuclear matter is based on the study of nuclear excitations [1] and an extrapolation to high densities. Nucleus-nucleus collisions at relativistic energies offer the unique possibility to study experimentally the properties of dense nuclear matter in the laboratory. The collective flow of nucleons [2,3] and the yield of produced mesons [4] were considered to be sensitive to the compressibility of nuclear matter. For example, in pioneering experiments at the BEVALAC the production of pions was studied in heavy-ion collisions, and the pion multiplicity was correlated to the thermal energy of the fireball in order to extract information on the equation-of-state of nuclear matter [5].

Microscopic transport calculations indicate that the yield of kaons created in collisions between heavy nuclei at subthreshold beam energies ($E_{\rm beam} = 1.58$ GeV for $NN \rightarrow K^+ \Lambda N$) is sensitive to the compressibility of nuclear matter at high baryon densities [6,7]. This sensitivity is due to the production mechanism of K^+ mesons. At subthreshold beam energies, the production of kaons requires multiple nucleon-nucleon collisions or secondary collisions such as $\pi N \rightarrow K^+ \Lambda$. These processes are expected to occur predominantly at high baryon densities, and the densities reached in the fireball depend on the nuclear equation-of-state [8].

K^+ mesons are well suited to probe the properties of the dense nuclear medium because of their long mean-free path. The propagation of K^+ mesons in nuclear matter is characterized by the absence of absorption (as they contain an antistrange quark) and hence kaons emerge as messengers from the dense phase of the collision. In contrast, the pions created in the high density phase of the collision are likely to be reabsorbed and most of them will leave the reaction zone in the late phase [9,10].

The influence of the medium on the K^+ yield is amplified by the steep excitation function of kaon production near threshold energies. Early transport calculations find that the K^+ yield from Au + Au collisions at subthreshold energies will be enhanced by a factor of about 2 if a soft, rather than a hard, equation-of-state is assumed [6,7]. Recent calculations take into account the modification of the kaon properties in the dense nuclear medium [11,12]. When assuming a repulsive K^+N potential as proposed by various theoretical models (see [13] and references therein), the energy needed to create a K^+ meson in the nuclear medium is increased and hence the K^+ yield will be reduced. Therefore, the yield of K^+ mesons produced in heavy-ion collisions is affected by both the nuclear compressibility and the in-medium kaon potential.

Our idea is to disentangle these two competing effects by studying K^+ production in a very light (^{12}C + ^{12}C) and a heavy collision system (^{197}Au + ^{197}Au) at different beam energies near threshold. The reaction volume is more than 15 times larger in Au + Au than in C + C collisions and hence the average baryonic density—achieved by the pileup of nucleons—is significantly higher [12]. Moreover, the maximum baryonic density reached in Au + Au collisions depends on the nuclear compressibility [7,14], whereas in the small C + C system this dependence is very weak [15]. The repulsive K^+N potential is assumed to depend nearly (or less than) linearly on the baryonic density [13] and thus reduces the kaon yield accordingly. On the other hand, at subthreshold beam energies the K mesons are created in secondary collisions involving two or more particles and hence the production of K^+ mesons depends at least quadratically on the density. These multiple-step kaon production processes contribute increasingly with decreasing beam energy. Therefore, the K^+ production excitation function in Au + Au collisions is expected to be influenced stronger by the nuclear compressibility than by the in-medium potential. In contrast, the K^+ production processes in C + C collisions are expected to be little affected by the nuclear equation-of-state. Therefore, the comparison of precision data on K^+ production as a function of beam energy in C + C and Au + Au collisions should reveal effects caused by the compressibility of nuclear matter rather than in-medium modifications of the K^+ mesons.

Data on K^+ production in heavy-ion collisions at beam energies about and below the nucleon-nucleon threshold are still scarce. The creation of K^+ mesons in Au + Au collisions at 1A GeV has been investigated in an early experiment with large statistical errors [16]. Production cross sections of K^+ mesons have been measured in Ni + Ni collisions at several beam energies [17,18]. Data on K^+ production in C + C collisions at beam energies from 0.8 to 2.0A GeV have recently been published [19].

In this Letter we report on a series of experiments which were performed in order to study systematically the production of pions and kaons as a function of the beam energy in symmetric nucleus-nucleus collisions using light and very heavy nuclei. We measured differential production cross sections for K^+ and π^+ mesons in Au + Au collisions from 0.6 to 1.5A GeV at different polar emission angles. The experimental results are compared to inclusive cross sections for kaon and pion production in C + C collisions (the pion data are shown in this Letter for the first time).

The experiments were performed with the Kaon Spectrometer (KaoS) at the heavy ion synchrotron (SIS) at GSI in Darmstadt [20]. The magnetic spectrometer has a large acceptance in solid angle and momentum ($\Omega \approx 30$ msr, $p_{max}/p_{min} \approx 2$). The short distance of 5–6.5 m from target to focal plane minimizes kaon decays in flight. Particle identification and the trigger are based on separate measurements of velocity, momentum, and time of flight. The trigger suppresses pions and protons by factors of 10^2 and 10^3, respectively. The background due to spurious tracks and pileup is removed by trajectory reconstruction based on three large-area multiwire proportional counters. The remaining background below the kaon mass peak ($\approx$10% in Au + Au at 1.46A GeV and $\approx$30% at 0.78A GeV) is subtracted. The loss of kaons decaying in flight is determined and accounted for by Monte Carlo simulations using the GEANT code.

The ^{197}Au beam had an intensity of about 5×10^7 ions per spill. The K mesons were registered at polar angles between $\Theta_{lab} = 40°$ and $84°$ over a momentum range of $260 < p_{lab} < 1100$ MeV/c. The (approximate) raw numbers of detected K mesons are listed in Table I.

Figure 1 shows the inclusive production cross section for K^+ mesons as a function of the laboratory momentum measured in Au + Au collisions at different beam energies and laboratory emission angles. After correction for the energy loss in the Au target (thickness 0.5 and 1.0 mm) the average beam energies are reduced to 0.56, 0.78, 0.96, 1.1, and 1.46A GeV. The error bars shown are due to statistical uncertainties and background subtraction. An overall systematic error of 10% due to efficiency corrections and beam normalization has to be added. The solid lines represent the function

$$d^3\sigma/dp^3 = C(1 + a_2 \cdot \cos^2\Theta)\exp(-E/T) \quad (1)$$

which is fitted to the data in the center-of-mass (c.m.) system and transformed into the laboratory. C is a normalization constant, a_2 parametrizes the anisotropy of the polar angle distribution in the c.m. system, and the exponential describes the energy distribution (with T the inverse slope parameter). The function is fitted simultaneously to the spectra measured at different angles at a given beam energy. The parameters a_2 are determined by the fit for the beam energies of 0.78, 0.96, and 1.46A GeV; at 0.56 and 1.1A GeV the a_2 values are estimated by extrapolation and interpolation, respectively. The resulting values for T and a_2 are listed in Table I. The polar angle distribution is found to be forward-backward peaked in the c.m. system, and the values of a_2 correspond to a nonisotropic contribution of less than 30% (in C + C collisions the nonisotropic fraction is 20% [19]). The effect of the parameter a_2 on the laboratory spectra is demonstrated for the beam energy of 0.96A GeV by the dashed lines in Fig. 1. These lines represent calculations using Eq. (1) with $a_2 = 0$, i.e., with an isotropic angular distribution. The isotropic extrapolation underestimates the kaon data taken at $\Theta_{lab} = 84°$ by a factor of about 2.

TABLE I. Sample sizes N, inverse slope parameters T, anisotropy parameters a_2, and inclusive production cross sections σ for K^+ mesons in Au + Au collisions. The values for T, a_2, and σ are determined by fitting the function defined in Eq. (1) to the data (see text).

E_{beam} (A GeV)	Θ_{lab}	N	T (MeV)	a_2	σ (mb)
0.56	50°	300	49 ± 8	1.06 ± 0.5	0.5 ± 0.1
0.78	44°, 84°	1200	67 ± 4	1.08 ± 0.38	8.5 ± 1.2
0.96	44°, 84°	3200	82 ± 4	1.05 ± 0.22	31 ± 4.0
1.1	56°	1100	90 ± 6	1.06 ± 0.4	64 ± 10
1.46	40°, 48°, 56°	2900	100 ± 5	1.06 ± 0.3	267 ± 30

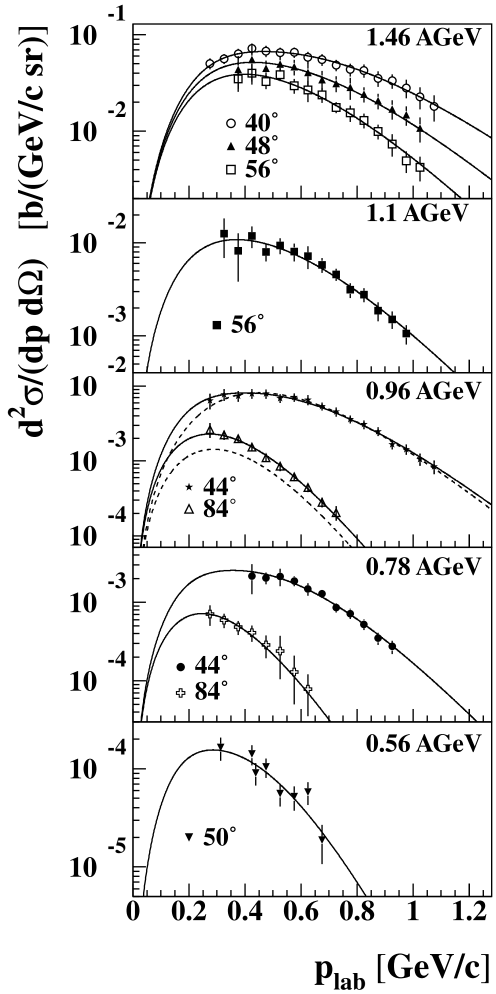

FIG. 1. Inclusive K^+ production cross section as a function of the laboratory momentum measured in Au + Au collisions at beam energies of 0.78, 0.96, 1.10, and 1.46A GeV at various laboratory angles. The solid lines represent fits to the data according to Eq. (1) assuming a nonisotropic polar emission pattern and the dashed lines at 0.96A GeV illustrate calculations assuming isotropic kaon emission (see text).

Inclusive kaon production cross sections are determined by extrapolations to the nonmeasured phase-space regions using Eq. (1) with the parameters as obtained by the fits to the spectra. Particle multiplicities are calculated by using the inclusive π^+ and K^+ production cross sections according to $M = \sigma/\sigma_R$, with σ_R being the geometrical cross section of the reaction [$\sigma_R = 4\pi(1.2A^{1/3})^2$ fm^2 = 0.95b for C + C and 6.1b for Au + Au collisions]. The latter value is in agreement with a minimum bias measurement [21].

Figure 2 (upper panel) shows the pion and K^+ multiplicity per nucleon for C + C and Au + Au collisions as a function of beam energy. The error bars include systematic uncertainties due to the extrapolation to full phase space and due to beam normalization and efficiencies. The pion data points are scaled by a factor of 1/100; they represent the sum of charged and neutral pions as calculated from the measured π^+ multiplicities according to

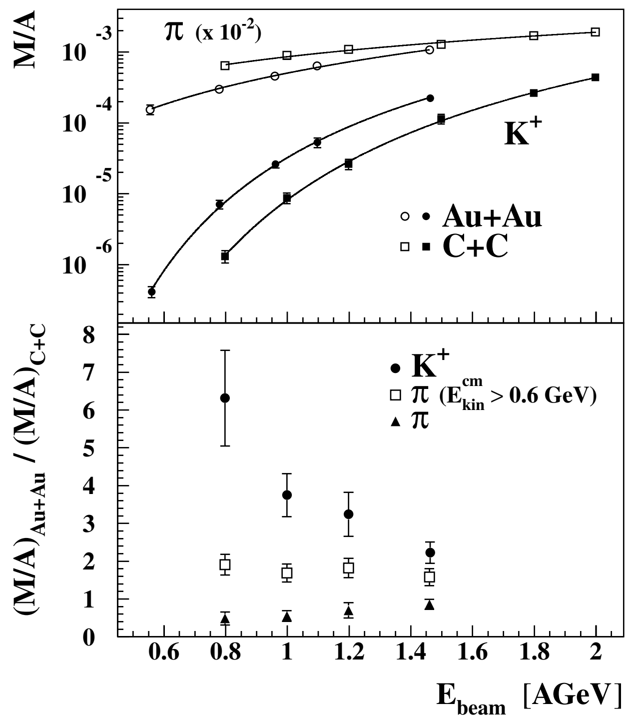

FIG. 2. Upper panel: pion and K^+ multiplicity per nucleon M/A for Au + Au and C + C collisions as a function of the projectile energy per nucleon. The pion multiplicities include all pions (see text). The lines represent a fit to the data. Lower panel: ratio of the multiplicities per nucleon (Au + Au over C + C collisions) for K^+ mesons (solid circles), pions (solid triangles), and high-energy pions ($E_{\rm kin}^{\rm cm} > 0.6$ GeV, open squares) as a function of the projectile energy per nucleon.

the isobar model [22]. This model—which explains very well the π^+/π^- ratios measured in Au + Au collisions [23]—gives a ratio of all pions to positively charged pions of $\pi^{\rm all}/\pi^+ = 4.4$ (at 0.56A GeV) and 4.1 (at 1.46A GeV) for Au + Au and $\pi^{\rm all}/\pi^+ = 3$ for C + C collisions. The pion multiplicity per nucleon is smaller in Au + Au than in C + C collisions whereas the K^+ multiplicity per nucleon is larger. This observation demonstrates that the nuclear medium—as formed in the heavy system—affects the production (and absorption) of pions and kaons in a very different manner.

In order to illustrate the different behavior of pions and kaons in nuclear matter we plot the ratio of the pion and kaon excitation functions $(M/A)_{\rm Au+Au}/(M/A)_{\rm C+C}$ for Au + Au and C + C in the lower panel of Fig. 2. Because of the different energy losses of the Au and C projectiles in the respective targets, the excitation functions for Au + Au and C + C collisions are not measured exactly at the same effective beam energies. The ratio $(M/A)_{\rm Au+Au}/(M/A)_{\rm C+C}$ is determined at 0.8, 1.0, 1.2, and 1.46A GeV. At 0.8–1.2A GeV we take the meson data measured in C + C collisions and interpolate the results from Au + Au collisions. At 1.46A GeV we take the Au + Au data and interpolate the C + C data. For the interpolation we use the fit functions shown as lines in the upper panel of Fig. 2. The error bars of the kaon multiplicity ratios include systematic uncertainties due to the extrapolation procedure. The experimental uncertainties due to efficiencies, acceptances, and beam normalization, however, cancel in the ratio and therefore have not been taken into account.

The pion ratio $(M/A)_{\mathrm{Au+Au}}/(M/A)_{\mathrm{C+C}}$ (solid triangles) is smaller than unity and decreases by a factor of about 1.7 with decreasing beam energy (from 1.46 to 0.8*A* GeV). A ratio smaller than unity might be caused by the reabsorption of pions, which is more effective in the larger system. In principle, the decompressional flow of nuclear matter—which is expected to be more important in Au + Au than in C + C collisions—reduces the energy available for particle production and therefore may contribute to the pion deficit as well. This argument is also valid for the kaons; in this case, however, the opposite effect is observed.

In contrast to the pion data, the kaon ratio $(M/A)_{\mathrm{Au+Au}}/(M/A)_{\mathrm{C+C}}$ increases by a factor of almost 3 with decreasing beam energy. An increase of the K^+ yield with decreasing beam energy is found by a transport model calculation in central Au + Au collisions if a soft, instead of a hard, equation-of-state is used [7]. The sensitivity of the kaon multiplicity on the nuclear compressibility is enhanced at beam energies well below the kaon production threshold because the energy required to create a K^+ meson has to be accumulated by multiple collisions of the participating nucleons.

In order to exclude trivial phase-space effects as the reason for the observed effect we present in the lower panel of Fig. 2 the ratio $(M/A)_{\mathrm{Au+Au}}/(M/A)_{\mathrm{C+C}}$ for pions with kinetic c.m. energies above $\mathrm{E}_{\mathrm{kin}}^{\mathrm{cm}} = 0.6$ GeV. The production of these pions is equivalent—in terms of available energy—to the production of K^+ mesons with a kinetic energy of 70 MeV. At this energy the kaon yields have reached their maximum values.

Both pions and kaons are created with three particles in the final state ($NN\pi$ and $K\Lambda N$, respectively), and thus we consider the yield of high-energy pions to reflect the phase space available for particle production. Figure 2 (lower panel) demonstrates that the high-energy pion data (open squares) do not show any beam-energy dependence. Therefore, the increase of the kaon ratio (solid circles) with decreasing beam energy is not caused by phase-space effects.

Recent quantum molecular dynamics transport calculations, which take into account a repulsive kaon-nucleon potential, reproduce the energy dependence of the kaon ratio as presented in Fig. 2 if a compression modulus of $\kappa = 200$ MeV for nuclear matter is assumed [15]. These calculations use momentum-dependent Skyrme forces to determine the compressional energy per nucleon (i.e., the energy stored in compression) as a function of nuclear density. For a compression modulus of $\kappa = 380$ MeV (a "hard" equation-of-state), the calculations find a kaon ratio $(M/A)_{\mathrm{Au+Au}}/(M/A)_{\mathrm{C+C}}$ which is below a value of 2 in the beam energy range considered [15].

In summary, we have compared pion and kaon production cross sections measured in C + C collisions at beam energies from 0.8 to 2.0*A* GeV and in Au + Au collisions from 0.6 to 1.5*A* GeV. At the beam energy of 0.8*A* GeV, the K^+ meson multiplicity per nucleon is about a factor of 6 larger in Au + Au than in C + C collisions, whereas the pion multiplicity per nucleon is smaller by a factor of about 2. The multiplicity of high-energy pions per nucleon is nearly independent of collision system size and beam energy. These high-energy pions are considered to be a reference for the phase space available for kaon production. Therefore, the observed enhancement of the kaon yield per nucleon in Au + Au collisions as compared to C + C collisions is not due to a smaller phase-space volume in the light system but rather due to collective effects which do not affect pion production in the same way. Our data indicate that the baryonic densities reached in the heavy system are as high as expected for a soft nuclear equation-of-state.

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