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Abstract

The yield and the phase-space distributions of particles produced in heavy-ion collisions are sensitive to the reaction dynamics and to the conditions inside the dense and hot fireball. At beam energies where the number of produced particles is still small as compared to the number of participating nucleons, newly created particles can be used as probes for dense baryonic matter. In particular, experimental data on strangeness production at SIS energies, together with their theoretical interpretation based on microscopic transport theory, permit to explore fundamental aspects of modern nuclear physics: the determination of the nuclear equation-of-state at high baryon densities and the properties of hadrons in dense nuclear matter. Experimental data and theoretical results will be reviewed.

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1 Introduction

Heavy-ion collisions offer the unique possibility to create and investigate extreme states of strongly-interacting matter in the laboratory. These experiments permit to obtain information on (i) the properties of hadrons in dense or hot baryonic/hadronic matter, (ii) the restoration of chiral symmetry at high temperatures and high baryon densities, (iii) the deconfinement phase transition from hadronic to quark-gluon matter at high temperatures and/or high baryon densities, and (iv) the nuclear equation-of-state at high baryon densities. These issues are related to fundamental aspects of strong interaction physics and its underlying theory, quantum chromodynamics (QCD), and are also of great importance for our understanding of astrophysical phenomena like supernova dynamics and the stability of neutron stars [1, 2]

When heavy nuclei collide at high energies the nucleons from projectile and target pile up in the overlap zone. Most of the longitudinal energy of these "participating nucleons" is dissipated in compressional energy, chaotic motion (heat) and intrinsic excitations of nucleons. The short-lived baryonic resonances decay by emission of mesons. At higher beam energies also baryon-antibaryon pairs are created. If the temperature or the density is high enough (T larger than 170 MeV or baryonic densities above about $5 \rho_0$) one expects that the hadrons lose their identity and melt into quarks and gluons moving freely in the reaction volume.

Figure 1 Pion multiplicity per participating nucleon measured in nucleus-nucleus collisions (symbols) and in nucleon-nucleon collisions as function of available energy in the NN system (taken from [3])

The high pressure built up in the dense and hot "fireball" drives the system apart leading to a collective flow of matter. In Au+Au collisions at top SPS energy of 158 AGeV, for example, the fireball explodes into about 2000 pions, 200 kaons, 200 etas and other particles. When the expanding fireball has reached the "freeze-out" density the particles cease to interact inelastically and their abundances - i.e. the chemical composition of the system - do not alter further. Elastic collisions between the particles may still continue and modify e.g. the momentum distributions.

A compilation of data on pion yields measured in symmetric nucleus-nucleus collisions and in proton-proton collisions is presented in figure 1 (taken from [3]). The data are plotted as total pion multiplicities per participating nucleons as function of beam energy which is expressed as the excess energy in the c.m. system $\sqrt{s}-2m_N$.

Figure 1 indicates that the pion-to-nucleon ratio in the fireball is about 0.05 to 0.3 for A+A collisions at SIS energies. At AGS energies, pions are as abundant as nucleons in the fireball whereas at top SPS energies the pion multiplicity exceeds the number of participating nucleons by a factor of about 6. At SIS energies, pions are produced mainly via excitation and decay of the Δ resonance. At higher beam energies, the decay of heavier baryonic resonances and vector mesons becomes increasingly important for pion production. The line in fig. 1 is based on data on pion production in proton-proton collisions which were corrected for isospin effects in order to obtain the pion yield from "nucleon-nucleon" (NN) collisions.

Figure 2: Compilation of data on the K^+ (left) and K^- multiplicity (right) per average number of participating nucleons in central Au+Au (Pb+Pb) collisions (symbols) and p+p collisions (line) as function of available energy per NN collision (taken from [3]).

An interesting feature of the pion yields presented in figure 1 is the difference between nucleus-nucleus data (symbols) and nucleon-nucleon data (denoted as solid line). In the SIS energy range, the relative pion yield is smaller for A+A than for N+N collisions. This "pion suppression" in A+A collisions might be caused by true pion absorption which is favored in systems where the number of pions is small as compared to the number of baryons. In the

AGS energy range $M_\pi / \langle A_{part} \rangle$ reaches a value of about 1 both for N+N and A+A. At CERN-SPS energies, the pion yield per participating nucleon is larger for A+A than for N+N collisions. At this very high beam energies, additional pions can be created in subsequent collisions of projectile and target participant nucleons, an effect which only occurs in A+A collisions.

Another important piece of information comes from the production of strange particles. Figure 2 presents compilations of the K^+ and K^- multiplicities per average number of participating nucleons as function of beam energy for central Au+Au (Pb+Pb) collisions (symbols) and proton-proton collisions [3]. The yields of kaons and antikaons from Au+Au (Pb+Pb) collisions exceed the yield from p+p collisions at all energies. In particular, at beam energies close to the production thresholds (1.6 GeV for K^+ and 2.5 GeV for K^- in p+p collisions) the strangeness production mechanisms differ strongly for nucleus-nucleus and proton-proton collisions. At subthreshold beam energies in-medium effects play an important role in strangeness production.

The CERN-NA49 collaboration recently reported exciting results from measurements performed at beam energies between 30 and 80 AGeV [4]. Figure 3 (left part) shows the K^+/π^+ ratio as function of the beam energy for Au+Au (Pb+Pb) collisions (symbols). The kink in the heavy-ion data around 30 AGeV beam energy cannot be explained by transport models (RQMD, URQMD) and statistical hadron gas models (see lines in figure 3 left part). The authors speculate that the kink is caused by a deconfinement phase transition [5]. This interpretation is supported by the observation that the slope of the K^+ (and of the K^-) meson spectra exhibits a constant value within the SPS energy range (see right part of figure 3). Again, transport models cannot explain the data and predict much lower values for the K^+ inverse slope parameters [6]. The surprising findings of the NA49 collaboration clearly demonstrate that the beam energy range between around 30 AGeV - where the baryon densities are expected to be very high - deserves further detailed investigations.

Figure 3: Ratio of K^+ to π^+ meson total yields (left part) and inverse slope parameters of the K^+ spectra (right part) as function of beam energy measured in Au+Au and Pb+Pb collisions (symbols) in comparison various model calculations (see [4]).

2 The phase diagram of strongly interacting matter

The baryon density and the temperature of the fireball can be varied within certain limits by the variation of the beam energy. Hence, energetic collisions of heavy nuclei permit to explore the phase diagram of strongly interaction matter as function of temperature T and baryon density ρ_B or baryon chemical potential μ_B . The usual approach is to determine the values of T and μ_B from measured particle ratios using a statistical model. This method is based on the assumptions that (i) the fireball has reached chemical equilibrium and (ii) all particle species freeze-out simultaneously at a given T and μ_B .

Figure 4 The phase diagram of strongly interacting matter. The symbols (grey dots) represent freeze-out points obtained with a statistical model analysis from particle ratios measured in heavy collisions [7, 8, 9]. The curve through the data points refers to a calculation of the chemical freeze-out which occurs at a constant baryon density of $\rho_B = 0.75 \rho_0$ (with $\rho_0 = 0.16 \text{ fm}^{-3}$). The curve labelled "Lattice QCD" represents the phase boundary as obtained with a lattice QCD calculation [13] with a critical point (full dot) at $T = 160 \pm 3.5$ MeV and $\mu_B = 725 \pm 35$ MeV ($\rho_B \approx 3 \rho_0$). In the region of the circle labelled "dilute hadronic medium" the baryon density is $\rho_B = 0.038 \text{ fm}^{-3} \approx 0.24 \rho_0$. The corresponding value for the other circle ("dense baryonic medium") is $\rho_B = 1.0 \text{ fm}^{-3} \approx 6.2 \rho_0$. The hatched area marks the region of high baryon densities.

However, these assumptions are not obvious. In the early stage of the reaction, the system is not chemically and thermally equilibrated. Furthermore, even if equilibration is rapidly achieved, the expansion of the fireball leads to a time dependence of the thermodynamic conditions. Particles decouple from the system at different times because of differences in

their mean free paths in hot and dense matter, and hence experience different conditions in the collision zone. One would expect these differences to influence observables like particle multiplicities and spectra. Indeed, as it will be discussed later, at SIS energies it was found that different particles experience different freeze-out conditions. On the other hand, at higher beam energies, the analysis of particle ratios within a statistical model supports the picture of an equilibrated system which freezes out at a given temperature and baryochemical potential. It is, however, still an open question which mechanisms drive the fireball rapidly into equilibrium. At very high hadron densities multi-body collisions may accelerate the equilibration process [10, 11].

A compilation of chemical freeze-out points in the QCD phase diagram obtained for different beam energies is presented in figure 4 [7, 8, 9]. The freeze-out line connecting all data points from SIS to RHIC shown in figure 4 is calculated for a constant value for the sum of baryon and antibaryon density of $0.75 \rho_0$ [12]. The line labeled "Lattice QCD" represents the phase boundary as predicted by a recent lattice QCD calculation for finite baryon chemical potential [13]. According to the calculations, the phase boundary and the freeze-out curve merge at small baryon chemical potentials ($\mu_B < 200\text{-}300$ MeV). The SPS and RHIC data suggest that - at ultra-relativistic beam energies - hadronization and chemical freeze-out occurs almost simultaneously. This would imply that no dense baryonic system is produced in nucleus-nucleus collisions at very high beam energies. The region of high baryon densities is marked by the hatched area which can be reached in collisions in the energy range between SIS and SPS.

3 Pion production

More than two decades of experimental and theoretical research on pion production in nucleus-nucleus collisions has not yet led to a satisfying quantitative understanding of this process. In particular, the production of soft pions emitted from very heavy collision systems poses a challenge for microscopic transport theory which is widely used to model nucleus-nucleus collisions. One reason for the complications is that the production, propagation and reabsorption of pions in a nuclear environment proceeds via the Δ -resonance. However, the properties of baryonic resonances in (dense) nuclear matter are not well known. The modification of the lifetime and the spectral function of the Δ and the ΔN cross sections in a dense and hot medium are still a subject of research.

A quantitative comparison of the results of a modern transport calculation (URQMD [15]) to pion spectra measured in Au+Au collisions at 1.5 AGeV [14] is presented in figure 5. It can be seen that theory and experiment differ both in yield and spectral slope. The model calculation underestimates the yield of soft pions and overpredicts the number of hard pions. This discrepancy is particularly strong in heavy collision systems. For light systems such as C+C the calculation agrees much better with the experiment (see figure 6).

Figure 5 clearly demonstrates that the slope of the pion spectra deviates from a single Boltzmann distribution. This finding suggests that the pions are produced continuously during the collision, and, hence, contain information on the different stages of the reaction.

Figure 5 Differential pion production cross sections measured at various polar emission angles in Au+Au collisions at 1.5 AGeV [14] (black triangles) as function of the kinetic energy in the c.m. system in comparison to results of URQMD transport calculations (grey dots) [15]

This information can be extracted by measuring the collective motion of the pions. In a semi-central nucleus-nucleus collision, the spectator fragments shadow the pions which are emitted from the fireball into the reaction plane. This effect destroys the azimuthal isotropy of the pion emission pattern and introduces a directed "collective flow" of the pions.

The spacial nucleon-distribution in a semi-central Au+Au collision at 1 AGeV as calculated by a QMD model is sketched in figure 7. The "snapshots" are taken at $t = 4$ fm/c, 10 fm/c and 16 fm/c (from left to right) with t the time after the first touch of the nuclei. The corresponding experiment has been performed by the KaoS collaboration. The detector selects pions in the reaction plane ($\pm 45^\circ$) near target rapidity (see arrows). The ratio $N_{proj}^\pi/N_{targ}^\pi$ as function of the pion transverse momentum is depicted in the right part of figure 7 for a polar emission angle of $\Theta_{lab} = 84^\circ$ [16].

The ratio $N_{proj}^\pi/N_{targ}^\pi$ decreases with increasing pion transverse momentum. This effect can be explained by rescattering and/or absorption in the spectator fragments. Pions which are emitted towards target rapidity in the early stage of the collision can be rescattered only at the projectile fragment but not at the target fragment. For those pions the ratio $N_{proj}^\pi/N_{targ}^\pi$ is smaller than unity. This is the case for pions with large transverse momenta. Pions which are emitted in the late stage of the collision are not influenced by the projectile spectator but are shadowed by the target spectator. This is the case for pions with low transverse momenta. The result of this experimental study is that hard pions are emitted in the early phase of a nucleus-nucleus collisions whereas soft pions freeze out late.

Figure 6 Differential pion production cross sections measured at various polar emission angles in C+C collisions at 1.0 AGeV [14] (black triangles) as function of the kinetic energy in the c.m. system in comparison to results of URQMD transport calculations (grey dots) [15]

Figure 7 Left panel Sketch of an Au+Au collision at 1 AGeV with an impact parameter of $b = 7$ fm as calculated by the QMD transport code. The snapshots are taken at 4 fm/c (left), 10 fm/c (middle) and 16 fm/c (right). The pions are emitted in the reaction plane at backward angles corresponding to a particular detector position. Right panel Pion number ratios $N^{\pi}_{proj}/N^{\pi}_{targ}$ as a function of transverse momentum. N^{π}_{proj} and N^{π}_{targ} denote the number of pions emitted to the projectile and to the target side, respectively, within a cone of $\pm 45^\circ$. The spectra are measured in peripheral ($b \geq 5.7$ fm) Au + Au collisions at 1 AGeV at target rapidities. Both figures are taken from [16]

4 Strangeness production

The study of strangeness production in heavy-ion collisions addresses fundamental issues in nuclear physics such as the equation of state at high baryon densities and the modification of hadron properties in dense and hot hadronic or baryonic matter. The role of strangeness as a possible probe for the phase transition from partonic to hadronic matter has been mentioned already above. In this section we will concentrate on the discussion of the nuclear equation-of-state and in-medium effects. Experiments on kaon and antikaon production and propagation in heavy-ion collisions at SIS energies have been performed with the Kaon Spectrometer and the FOPI detector. The most important results are published in [17, 18, 19, 20, 21, 22, 23].

4.1 Different freeze-out conditions for kaons and antikaons

In the following we will discuss recent results on the production of kaons and antikaons in Au+Au collisions at a beam energy of 1.5 A GeV [23]. The experiments were performed with the Kaon Spectrometer at SIS/GSI. In order to reach an energy of 1.5 A GeV for Au beams, an exceptional operation of the GSI accelerator facility was required: acceleration of the $^{197}\text{Au}^{63+}$ ions with the synchrotron up to an energy of 0.3 A GeV, then extraction and full stripping, then injection into the Experimental Storage Ring (ESR) where the beam was cooled by electron cooling, then re-injection into the synchrotron and acceleration up to 1.5 A GeV. The entire multi-stage acceleration cycle took about 25 s.

Figure 8: Differential production cross-sections for K^+ (left) and for K^- mesons (right) from Au+Au collisions at 1.5 A GeV for different centrality bins as a function of the kinetic energy in the c.m. system. The data were measured at a laboratory angle of $\theta_{\text{lab}} = 40^\circ$ which covers midrapidity. The spectra correspond to bins of decreasing centrality (from top to bottom, taken from [23]).

Figure 8 depicts the production cross sections for K^+ and K^- mesons measured close to midrapidity as a function of the kinetic energy in the center-of-momentum system for the five centrality bins in Au+Au collisions. The uppermost spectra correspond to the most central reactions. The solid lines represent a Boltzmann function. The spectra presented in figure 8 exhibit a distinct difference between K^- and K^+ . The slopes of the K^- spectra are steeper than those of the K^+ spectra.

The inverse spectral slope parameters T are displayed in the upper panel of figure 9 as a function of the number of participating nucleons A_{part} . T increases with increasing centrality and is found to be significantly lower for antikaons than for kaons, even for the most central collisions. When interpreting spectral slopes one should keep in mind that they are influenced by both the random and the collective motion of the particles (temperature and flow). The radial-flow contribution to the slope depends on the particle mass and hence cannot cause a difference between the K^+ and the K^- spectra. The temperature contribution to the slope is determined at kinetic freeze-out, i.e. at the time when the particles cease to interact.

Figure 9 First panel Inverse spectral slope parameters of K^+ (full symbols) and of K^- mesons (open symbols) produced in Ni+Ni (squares) and Au+Au collisions (circles) at 1.5 A GeV as a function of the number of participating nucleons. Second and third panel Multiplicity per number of participating nucleons A_{part} of K^+ and of K^- as a function of A_{part} both for Ni+Ni (squares) and for Au+Au (circles) at a beam energy of 1.5 A GeV. The data were taken at a laboratory angle of $\theta_{lab} = 40^\circ$. Lowest panel The ratio of the K^- to K^+ multiplicities as a function of A_{part} . The dashed line represents the result of a statistical model calculation [24]. The cross-hatched area corresponds to the results of a QMD transport model calculation assuming in-medium masses of K mesons [25] (taken from [23]).

Statistical models using a canonical formulation of strangeness conservation predict a constant K^-/K^+ ratio as a function of system size for heavy-ion collisions at SIS beam energies [24]. The result of such a calculation is shown in the lowest panel of figure 9 as a dashed line [24]. In this case a baryochemical potential of $\mu = 770$ MeV and a chemical freeze-out temperature of $T = 63$ MeV was assumed. The measured inverse slope parameters are substantially larger: $T(K^+) = 103 \pm 6$ MeV and $T(K^-) = 93 \pm 6$ MeV for near-central Ni+Ni collisions, and $T(K^+) = 116 \pm 7$ MeV and $T(K^-) = 90 \pm 8$ MeV for near-central Au+Au collisions (corresponding to the average value of the two most central bins in figure 9, upper panel).

The observation of different spectral slopes of K^+ and K^- mesons is at variance with a scenario in which both kaons and antikaons have the same flow velocity and thermal energy at chemical freeze-out. In consequence, the statistical model does not offer a consistent explanation for both the yields and spectral slopes of K^+ and K^- mesons. The difference in spectral slopes rather indicates that K^+ and K^- mesons decouple from the fireball sequentially due to their very different KN inelastic cross sections.

Figure 10 Polar angle distributions of K^+ (upper panel) and of K^- mesons (lower panel) produced in peripheral (left) and near-central (right) Au+Au collisions at 1.5 A GeV. Near central and non-central collisions correspond to impact parameters $b < 6$ fm and $b > 6$ fm, respectively. The data were taken at laboratory angles between $\theta_{lab} = 32^\circ$ and 72° . Full data points are measured and mirrored at $\cos(\theta_{CM}) = 0$ (open points). The lines correspond to the function $1 + a_2 \cos^2(\theta_{CM})$ fitted to the data (see text). The resulting values for a_2 are indicated (taken from [23]).

Another observable sensitive to the production mechanism is the polar angle emission pattern. Figure 10 displays the anisotropy ratio for K^+ (upper panel) and K^- (lower panel) and for near-central (right) and non-central collisions (left) as a function of $\cos(\theta_{CM})$. For

an isotropic distribution this ratio would be constant and identical to 1. The anisotropy ratio is defined as $\sigma_{inv}(E_{CM}, \theta_{CM})/\sigma_{inv}(E_{CM}, 90^\circ)$. Here, $\sigma_{inv}(E_{CM}, \theta_{CM})$ is the invariant kaon production cross-section measured at the polar angle θ_{CM} in the center-of-momentum frame and $\sigma_{inv}(E_{CM}, 90^\circ)$ is the one measured at $\theta_{CM} = 90^\circ$. The solid lines in figure 10 represent the function $1 + a_2 \cos^2(\theta_{CM})$ which is fitted to the experimental distributions with the values of a_2 given in the figure. In near-central collisions the K^- mesons exhibit an isotropic emission pattern whereas the emission of K^+ mesons is forward-backward peaked. The angular distributions observed for K^+ and K^- in Ni+Ni collisions at 1.93 A GeV are similar to the ones presented in Fig. 10 [21]. The measured emission patterns indicate that the antikaons - in contrast to the kaons - have lost the memory of the beam direction for central heavy-ion collisions.

4.2 The nuclear equation-of-state

K^+ mesons have been proposed already many years ago as a promising diagnostic probe for the nuclear equation of state at high densities. Microscopic transport calculations indicate that the yield of kaons created in collisions between heavy nuclei at subthreshold beam energies ($E_{beam} = 1.58$ GeV for $NN \rightarrow K^+ \Lambda N$) is sensitive to the compressibility of nuclear matter at high baryon densities [26, 27]. 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 [29]. Figure 11 demonstrates that - according to a QMD transport calculation - in central Au+Au collisions the bulk of K^+ mesons is produced at nuclear matter densities larger than twice saturation density [30].

Figure 11: Upper panel: central density reached in Au+Au collisions at 1.5 AGeV as a function of time. Lower panel: number of K^+ and K^- mesons produced as a function of time [30].

Moreover, 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 (see figure 7)

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 [26, 27]. Recent calculations take into account the modification of the kaon properties in the dense nuclear medium [31, 32]. When assuming a repulsive K^+N potential as proposed by various theoretical models (see [33] 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.

Figure 12 Left upper panel Pion and K^+ multiplicity per participating nucleon M/A_{part} for Au+Au and C+C collisions as function of the projectile energy per nucleon. The pion multiplicities include all pions (see text). The lines represent a fit to the data. Left lower panel Ratio of the multiplicities per nucleon (Au+Au over C+C collisions) for K^+ mesons (full circles), pions (full triangles) and high-energy pions ($E_{kin}^{cm} > 0.6$ GeV, open squares) as function of the projectile energy per nucleon. Right panel Production cross section of K^+ mesons in Au+Au and C+C collisions as function of beam energy. The data are represented by the full diamonds [22]. The open symbols correspond to results of QMD calculations assuming no in-medium potentials (C+C collisions) whereas the full dots represent calculations with in-medium potentials [34].

The KaoS collaboration proposed to disentangle these two competing effects by studying K^+ production in a very light ($^{12}\text{C}+^{12}\text{C}$) and a heavy collision system ($^{197}\text{Au}+^{197}\text{Au}$) at different beam energies near threshold [22]. 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 pile-up of nucleons - is significantly higher [32]. Moreover, the maximum baryonic density reached in Au+Au collisions depends on the nuclear compressibility [27, 28] whereas in the small C+C system this dependence is very weak [34]. The repulsive $K^+\text{N}$ potential is assumed to depend nearly (or less than) linearly on the baryonic density [33] 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 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.

Figure 13 Left panel K^+ ratio measured in inclusive Au+Au and C+C collisions as function of beam energy [22]. The data are compared to QMD calculations assuming nuclear compressibilities of $\kappa = 200$ MeV (full dots) and 380 MeV (open squares) [34]. Right panel Skyrme nuclear equation of state for different values of the compressibility.

Figure 12 (left upper panel) shows the measured pion and K^+ multiplicities per nucleon for C+C and Au+Au collisions as a function of beam energy [22]. 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 the isobar model [35]. 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 way.

Recent QMD transport calculations which take into account a repulsive kaon-nucleon potential reproduce the energy dependence of the kaon ratio if a compression modulus of $\kappa = 200$ MeV for nuclear matter is assumed [34]. These calculations use momentum-dependent Skyrme forces to determine the compressional energy per nucleon (i.e. the energy stored in compression) as function of nuclear density. The result of this calculation is presented in the right panel of figure 12 in comparison with the data [22].

In order to reduce systematic uncertainties both in experiment (normalization, efficiencies, acceptances etc.) and theory (elementary cross sections etc.) the K^+ multiplicities are plotted as ratios $(K^+(\text{Au+Au}) / K^+(\text{C+C}))$ in figure 13 (left panel). In this representation also the in-medium effects cancel to a large extent. The calculations are performed with a compression modulus of $\kappa = 380$ MeV (a "hard" equation-of-state, dashed line) and with $\kappa = 200$ MeV (a "soft" equation-of-state, solid line) [34] (see figure 13, right panel). The data clearly favor a soft equation of state (see figure 13, left panel).

4.3 In-medium properties of kaons and antikaons

In order to illustrate in-medium effects on K^+ and K^- production we compare nucleus-nucleus to proton-proton collisions. Fig. 14 shows the multiplicity of K^+ and K^- mesons per average number of participating nucleons $M_K / \langle A_{part} \rangle$ as function of the Q-value in the NN system. The data were measured in C+C and Ni+Ni collisions by the KaoS Collaboration [19, 21, 36]. The lines represent parameterizations of the available proton-proton data averaged over the isospin channels [37, 38, 39]. In "nucleon-nucleon" collisions the K^+ multiplicity exceeds the K^- multiplicity by 1-2 orders of magnitudes at the same Q-value. This large difference has disappeared for nucleus-nucleus collisions where the kaon and antikaon data nearly fall on the same curve. This observation demonstrates that in nucleus-nucleus collisions the production of antikaons is much more enhanced than the production of kaons. Within transport calculations, the K^- yield enhancement is explained by two effects (i) strangeness exchange reactions such as $\pi\Lambda \rightarrow K^-N$ and (ii) a reduced effective K^- mass in dense nuclear matter [32].

According to various calculations, the properties of kaons and antikaons are modified in dense baryonic matter (see e.g. [32, 33, 40]). In mean-field calculations, this effect is caused by a repulsive K^+N potential and an attractive K^-N potential. It has been speculated that an attractive K^-N potential will lead to Bose condensation of K^- mesons in the core of neutron stars above baryon densities of about 3 times saturation density [41].

Figure 15 illustrates the dependence of the kaon and antikaon total energy on the nuclear density according to various calculations. The compilation of theoretical results is taken from [33]. The calculations have been performed with a relativistic mean-field model (RMF), chiral perturbation theory (ChPT) and a coupled channel code [42]. All models exhibit quite similar features: the kaon energy increases and the antikaon energy decreases with increasing density. The parameterizations shown in figure 15 are used in transport model

simulations of heavy ion collisions (see e g [32, 33, 40])

Figure 14 K^+ (circles) and antikaon (squares) multiplicity per participating nucleon as a function of the Q-value for C+C (open symbols) and Ni+Ni (full symbols) collisions [19, 21, 36]. The lines correspond to parameterizations of the production cross sections for K^+ (solid) and K^- (dashed) in nucleon-nucleon collisions [37, 38, 39].

A comparison of experimental data to results of transport calculations (BUU model [44]) is presented in figure 16. The figure shows the K^+ and K^- multiplicity densities dN/dy and their ratio for near-central Ni+Ni collisions at 1.93 AGeV as function of the c.m. rapidity y_{CM} . Figure 16 combines data measured by the KaoS Collaboration (circles) [21] and by the FOPI Collaboration (squares) [17, 45]. The transport calculations disagree clearly with the data if in-medium effects are neglected (dotted lines). However, taking into account a repulsive K^+N potential and an attractive K^-N potential, reduces the K^+ yield and enhances the K^- yield, respectively, and brings the calculations closer to the data (solid lines).

Figure 15 The total energy of kaons and antikaons (at rest) in nuclear matter as a function of density for a soft equation of state. The curves are calculated with a relativistic mean-field model (RMF), chiral perturbation theory (ChPT with different Σ terms) and a coupled-channel code (taken from [33]).

Figure 16 Multiplicity 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 [21], squares: FOPI data [17, 45]. The measured data (full symbols) are mirrored at $y_{CM}=0$ (open symbols). Lower panel: K^-/K^+ ratio. The data are compared to BUU transport calculations [44]. Solid lines: with in-medium effects. Dotted lines: without in-medium effects.

Figure 17 Left panel: K^- to K^+ ratio as a function of the transverse mass for near-central ($b < 5$ fm) Au+Au collisions at 1.5 AGeV around midrapidity [23]. The curves represent the predictions of a transport model calculation (BUU) including in-medium potentials (solid line) and for free K meson masses (dashed line) [44]. The data (full dots) were taken at $\theta_{lab} = 40^\circ$. Right panel: K^- to K^+ ratio as a function of the c.m. energy for inclusive C+C collisions at 1.8 AGeV around midrapidity. The curves denote results of a BUU calculation with in-medium potentials (dotted line) and without (solid line). Taken from [46].

In-medium effects are observed also in Au+Au and C+C collision systems. Predictions of a BUU model calculation [44] for the K^-/K^+ ratio as a function of transverse mass for near-central Au+Au collisions at 1.5 A GeV are shown in the left panel of figure 17 together with experimental results. The right panel of figure 17 depicts the K^-/K^+ ratio measured in C+C collisions at 1.8 A GeV [46]. A similar result was found for Ni+Ni collisions at 1.93 A GeV [45]. As demonstrated in Figure 17 the calculations assuming free K meson masses and in-medium masses clearly disagree. In this case the differences in spectral slope are caused by the opposite mean-field potentials of kaons and antikaons.

Another observable consequence of in-medium KN potentials is their influence on the propagation of kaons and antikaons in heavy-ion collisions. The measured azimuthal emission patterns of K^+ mesons contradict the expectations based on a long mean free path in nuclear matter. The particular feature of sideward flow [20] and the pronounced out-of-plane emission around midrapidity [18] indicate that K^+ mesons are repelled from the regions of increased baryonic density as expected for a repulsive K^+N potential [47, 48].

Figure 18: K^+ azimuthal distribution for semi-central Au+Au collisions at 1 AGeV (full dots). The data are analyzed at $0.4 < y/y_{proj} < 0.6$ (left) and $0.2 < y/y_{proj} < 0.8$ (right) [18]. The lines represent results of transport calculations from the Stony Brook group using a RBUU model (left [47]) and a QMD model from the Tübingen group (right [48]). 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.

The azimuthal angle distribution of K^+ mesons from Au+Au collisions at a beam energy of 1 AGeV is shown in figure 18. The data stem from the same measurement but are analyzed in slightly different rapidity bins [18]. The K^+ emission pattern clearly is peaked at $\phi = \pm 90^\circ$ which is perpendicular to the reaction plane. Such a behavior is known from pions which interact strongly with the spectator fragments. In the case of K^+ mesons, however, the anisotropy can be explained by transport calculations only if a repulsive in-medium K^+N potential is assumed. This is demonstrated by the solid line in fig. 18. A flat distribution

(dotted lines) is expected when neglecting the in-medium potential and only taking into account K^+ rescattering ([47], left) and additional Coulomb effects ([48], right)

The key observable is the azimuthal emission pattern of K^- mesons. If an attractive K^-N potential exists as suggested by the measured K^- yields, the K^- mesons will be emitted isotropically in semicentral Au+Au collisions [48]. This observation would be in contrast to the behavior of pions and K^+ mesons and hence would provide strong experimental evidence for in-medium modifications of antikaons. Such an experiment has been performed by the KaoS collaboration. The results are given in figure 19 which presents the azimuthal emission pattern of K^+ and K^- mesons emitted semicentral Au+Au collisions at 1.5 AGeV around midrapidity. The solid lines denote the Fourier expansion

$$dN/d\phi \propto [1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi)] \quad (1)$$

which is fitted to the measured azimuthal distributions. The Fourier coefficient $v_1 = \langle \cos(\phi) \rangle$ quantifies the in-plane emission of the particles parallel ($v_1 > 0$) or antiparallel ($v_1 < 0$) to the impact parameter vector, whereas $v_2 = \langle \cos(2\phi) \rangle$ stands for an elliptic emission pattern which may be aligned with the event plane ($v_2 > 0$) or oriented perpendicular to the event plane ($v_2 < 0$).

The K^+ distribution clearly exhibits structure which demonstrated that the kaons are emitted preferentially perpendicularly to the event plane. According to transport calculations, this effect is caused by a repulsive K^+N potential. The K^- data, however, show evidence for an isotropic azimuthal distribution as expected for an attractive in-medium potential. Further clarification will come from high statistics data which have been measured and are presently being analyzed.

Figure 19 Azimuthal emission pattern of K^+ and K^- mesons measured in semi-central Au+Au collisions at 1.5 AGeV at a laboratory angle of 40° [23]. The lines represent Fourier expansions fitted to the data. The resulting coefficients are indicated.

4.4 Off-shell transport calculations

In the mean field calculations as discussed above the K^- mesons are treated as quasi-particles which are on the mass shell. Microscopic coupled-channel calculations based on a chiral Lagrangian, however, predict a dynamical broadening of the K^- meson spectral function in dense nuclear matter [42, 43]. The ultimate goal of these calculations is to relate the in-medium spectral function of kaons and antikaons to the anticipated chiral symmetry restoration at high baryon density.

The results of such a self-consistent calculation are presented in figure 20. The antikaon spectral function is shown for momenta $q = 0$ and $q = 0.5$ GeV/c and for various nuclear matter densities. With increasing nuclear matter density, the width of the spectral function increases and strength shifts towards lower energies, in particular for the low momentum antikaons [49]. The in-medium antikaon spectral function and the in-medium scattering amplitudes affect drastically the cross sections for the strangeness exchange reactions $\pi Y \rightarrow K^- N$ with $Y = \Lambda, \Sigma$ in the nuclear environment. It turns out that it is very important to incorporate the $\Sigma(1385)$ resonance into transport model simulations of heavy-ion collisions in order to obtain a quantitative understanding of the measured antikaon yields [49].

Figure 20: Antikaon spectral function at momenta of $q = 0$ and 0.5 GeV for various nuclear matter densities [49].

Recently, first calculations using off-shell transport theory and taking into account antikaon spectral functions have been performed [50]. The in-medium properties of antikaons were determined in a coupled channel G-matrix approach. One result of this calculation is presented in figure 21 which depicts the invariant production cross section of K^+ and K^- mesons emitted in Au+Au collisions at 1.5 AGeV. The solid, dashed and dotted lines correspond to free kaon masses, in-medium effects without and with pion dressing, respectively.

None of these assumptions results in a satisfactory agreement with the data (full symbols) [23]. This approach should be considered as a first step towards an off-shell description of the production and propagation of antikaons in nucleus-nucleus collisions. In a next step, the spectral functions and in-medium cross sections of Lutz et al. should be used as these results were shown to be consistent with differential elementary cross sections.

Figure 21: K^+ and K^- spectral distributions from inclusive Au+Au collisions at 1.5 AGeV [23]. The lines denote the results of off-shell transport calculations (HSD) taking into account in-medium spectral functions for antikaons and hyperons [50].

5 Conclusions

Particle emission in nucleus-nucleus collisions is a sensitive diagnostic probe for the properties of dense and hot hadronic matter. In particular, the production and propagation of strangeness provides information on the nuclear equation-of-state and on in-medium modifications of hadrons. Systematic measurements of K^+ and K^- production cross sections and phase-space distributions as function of system size and beam energy provide evidence for a soft nuclear equation-of-state and for the existence of in-medium potentials which are repulsive for kaons and attractive for antikaons. Quantitative statements require the comparison of experimental data to results of microscopic transport theory. A major improvement is expected from off-shell transport calculations with realistic spectral functions and in-medium cross sections as calculated with chiral effective field theory. The final goal is to extract information on the restoration of Chiral symmetry in dense baryonic matter. New experimental information on the in-medium modification of vector mesons is expected from the dilepton experiments with HADES at GSI. Highest baryon densities will be produced and explored with the Compressed Baryonic Matter (CBM) experiment at the future accelerator facility in Darmstadt [51].

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