Excitation function of strangeness in A+A reactions from SIS to RHIC energies

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The properties of $K^+$ and $K^-$ mesons are studied in nuclear reactions from SIS to RHIC energies within the covariant transport approach HSD in comparison to the experimental data whenever available. Whereas kaon abundancies and spectra indicate little repulsive or vanishing selfenergies in the medium, antikaons are found to experience strong attractive potentials in nucleus-nucleus collisions at SIS energies. However, even when including these potentials the $K^+$ and $K^-$ spectra at AGS energies are noticeably underestimated showing an experimental excess of strangeness that points towards a nonhadronic phase in these reactions. On the other hand the $K^+, K^-$ production at SPS energies is again well described by the HSD approach based on quark, diquark, string and hadronic degrees of freedom. At RHIC energies hadronic rescatterings are found to enhance the strangeness yield from the partonic phase quite substantially.

1. INTRODUCTION

The aim of high energy heavy-ion collisions is to investigate nuclear matter under extreme conditions, i.e. high temperature and density. The most exciting prospect is the possible observation of a signal for a phase transition from normal nuclear matter to a nonhadronic phase, where partons are the basic degrees of freedom. In this context strangeness enhancement in heavy-ion collisions compared to proton-proton collisions has been suggested as a possible signature for the phase transition [1]. On the other hand, precursor effects might already be seen at SIS energies since densities up to $3\times\rho_0$ can be achieved in central collisions of heavy nuclei and the effect of meson potentials can be studied with a higher sensitivity to the productions thresholds, respectively. In this contribution a brief survey is presented on the information gained so far in comparison of experimental data to nonequilibrium transport theory, here the Hadron-String-Dynamics (HSD) approach [2]. For a more detailed discussion of the issues presented the reader is refered to [3].

2. ANALYSIS OF EXPERIMENTAL DATA

Since the real part of the actual $K^+$ and $K^-$ self-energy $\Pi_{K^\pm}$ in hot and dense nuclear matter is quite a matter of debate we adopt a more practical point of view and as a guide

*Supported by BMBF and GSI Darmstadt
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for the analysis use a linear extrapolation of the kaon potential with density $\rho_B$ as

$$m_K^*(\rho_B) = m_K^0 \left(1 - \alpha \frac{\rho_B}{\rho_0}\right), \text{ i.e. } V_K' = -\alpha m_K^0 \frac{\rho_B}{\rho_0},$$

(1)

with $\alpha_K \approx 0.2 - 0.25$ for antikaons and $\alpha_K \approx -0.06$ for kaons in line with Refs. [4, 5]. In (1) a momentum dependence of the kaon or antikaon potential has been neglected for reasons of numerical simplicity. The dispersion analysis of Sibirtsev et al. [6] shows that this is roughly fulfilled for the kaon potential, however, the antikaon potential should be more strongly momentum dependent.

The Lorentz invariant $K^+$ spectra for Ni + Ni at 0.8, 1.0 and 1.8 A-GeV are shown in Fig. 1 (l.h.s.) in comparison to the data from the KaoS Collaboration [7]. Here the full lines reflect calculations including only bare $K^+$ masses ($\alpha_K = 0$) while the dashed lines correspond to calculations with $\alpha_K = -0.06$ in Eq. (1), which leads to an increase of the kaon mass at $\rho_0$ by about 30 MeV. The general tendency seen at all bombarding energies is that the calculations with a bare kaon mass seem to provide a better description of the experimental data for Ni + Ni than those with an enhanced kaon mass. This trend continues to hold also for the light system C + C as well as for the heavy systems Ru + Ru [8] and even Au + Au [2] within the cross sections for the $\Delta$ induced channels used.

The kaon flow in the reaction plane shows some sensitivity to the kaon potential in the nuclear medium as suggested by Li, Ko and Brown [9]. Here due to elastic scattering with nucleons the kaons partly flow in the direction of the nucleons thus showing a positive flow in case of no mean-field potentials. With increasing repulsive kaon potential the positive flow will turn to zero and then become negative. In fact, experimental data on kaon flow indicate a repulsive potential for kaons in the nuclear medium at SIS [10] as well as AGS energies [11].

We now turn to the production of antikaons which do clearly show the effect from attractive potentials in the medium. We recall that for $\alpha_K = 0$ in Eq. (1) we recover the
limit of vanishing antikaon self-energy, whereas for $\alpha_{\bar{K}} \approx 0.2$ we approximately describe the scenario of Refs. [4,5]. The $K^-$ spectra for Ni + Ni at 1.85 and 1.66 A GeV [12] are shown in Fig. 1 (r.h.s.) for $\alpha_{\bar{K}} = 0, 0.2$ and 0.24 where the latter cases correspond to an attractive potential of $-100$ and $-120$ MeV at density $\rho_0$, respectively. We note, that due to the uncertainties involved in the elementary $BB$ production cross sections we cannot determine this value very reliably. With increasing $\alpha_{\bar{K}}$ not only the magnitude of the spectra is increased, but also the slope becomes softer. This is most clearly seen at low antikaon momenta because the net attraction leads to a squeezing of the spectrum to low momenta [8].

Whereas the kaon and antikaon dynamics at SIS energies is reasonably described within the hadron-string transport approach when including meson potentials [2], this no longer holds at AGS energies [3]. The heaviest system studied here is Au + Au at $\approx 11$ A GeV. In the 'bare mass' scenario the data are underestimated strongly while for $\alpha_K = -0.06$ and $\alpha_{\bar{K}} = 0.24$ the situation improves significantly [2]. Whereas the $K^-$ yield is almost reproduced in the latter scheme, the $K^+$ yield is still underestimated as in case of the Si + Al and Si + Au system at 14.6 A GeV [2,3].

Without explicit representation we note that for all systems at SPS energies [3] the $h^-$, $K^+$ and $K^-$ distributions are reproduced rather well showing even a tendency for an excess of kaons and antikaons in the calculations rather than missing strangeness. At RHIC energies we also find a sizeable enhancement of the $K^\pm$ yield in central Au + Au compared to pp collisions or pure parton (VNI) cascade calculations due to a long lasting hadronic rescattering phase [2].

The E866 and E895 Collaborations, furthermore, have measured Au + Au collisions at 2, 4, 6 and 8 A GeV kinetic energy at the AGS [13]. Thus it is of particular interest to look for a discontinuity in the excitation functions for pion and kaon rapidity distributions and to compare them to the hadron-string transport approach. In Fig. 2 the calculated $K^+/\pi^+$ ratios (open squares) at midrapidity ($|y_{cm}| \leq 0.25$) for central (b=2 fm) Au + Au collisions at 1, 2, 4, 6, 8 and 11 A GeV and Pb + Pb collisions at 160 A GeV are shown together with the preliminary data (full dots). The ratio at midrapidity is slightly higher than the total $K^+/\pi^+$ ratio, because the kaon rapidity distribution is narrower than that of the pions. While the scaled kaon yield at 1 and 2 A GeV (SIS energies) is well described in the HSD approach within the errorbars, the experimental $K^+/\pi^+$ ratio at 4 A GeV is underestimated already by a factor of 2 and increases up to roughly 19% for 11 A GeV. As mentioned before the calculated and measured ratio coincide again at 160 A GeV. Data at 40 A GeV from the SPS as well as at 21.5 A TeV from RHIC are expected to come up soon and to complete the picture from the experimental side.

3. SUMMARY

We find an enhancement of the $K^+/\pi^+$ ratio in heavy-ion collisions relative to p + p reactions due to hadronic rescatterings both with increasing system size and energy. The excitation function in the $K^+/\pi^+$ ratio from the HSD transport approach has a similar slope in nucleus-nucleus and p + p collisions (cf. Fig. 2) indicating a monotonic increase of strangeness production with bombarding energy. However, the experimental $K^+/\pi^+$ ratio for central Au + Au collisions at midrapidity increases up to $\approx 19\%$ at 11 A GeV.
Figure 2. The calculated $K^+ / \pi^+$ ratio at midrapidity for central Au + Au reactions (open squares) from SIS to RHIC energies in comparison to the preliminary experimental data from 1 - 160 A·GeV and the corresponding ratio for p + p collisions (open circles) from the HSD approach (see text).

– it is unknown if a local maximum will be reached at this energy – and decreases at SPS energies to $\approx 16.5\%$. Such a decrease of the scaled kaon yield from AGS to SPS energies is hard to obtain in a hadron-string transport model. On the contrary, the higher temperatures and particle densities at SPS energies always tend to enhance the $K^+ / \pi^+$ yield closer to its thermal equilibrium value of $\approx 20 - 25\%$ at chemical freezeout and temperatures of $T \approx 160$ MeV. Thus the steep rise of the strangeness yield and its decrease suggests the presence of nonhadronic degrees of freedom which might become important already at about 4 A·GeV in central Au + Au collisions.

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