Kaon production from 1 to 40 A GeV

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Abstract. Kaon production is studied within the Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) model. Results are compared with experiment and with other models. The influence of the kaon potential on the kaon azimuthal distributions at SIS energies is considered. We also discuss the role of the many-body collisions at high-density phase of reaction.

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1. Motivation

Strangeness production has been a hot topic of heavy-ion studies for about 20 years. Due to strangeness conservation, kaons can not be absorbed in the nuclear medium. The kaon-nucleon scattering cross section is also quite small ($\sim 10$ mb). Thus, kaons deliver a signal from the high-density phase of a reaction. This property of kaons was extremely useful to extract information on the nuclear equation of state from kaon multiplicities at 1-2 A GeV [1,2]. Another interesting observable at SIS energies is the kaon collective flow which is sensitive to the kaon potential. The measurements of the $K^+$ in-plane flow have been performed by the FOPI Collaboration [3,4]. The analysis within the Tübingen QMD model [5] has revealed that the data [3] can be described only by using a strongly repulsive $K^+$ potential given by the Brown-Rho (BR) parametrization ($U_K(\rho_0) \sim 30$ MeV). Recently the KaoS Collaboration published data on $K^+$ azimuthal distributions [6] which were analysed in [7].

The strange particle and pion multiplicities have also been measured at higher energies: AGS [8,9] and SPS [10,11]. The most interesting observable is the $K^+/\pi^+$ ratio plotted vs the beam energy, which has a maximum at $E_{\text{lab}} \sim 20$ A GeV (c.f. Fig. 3 below). So far, the transport models based on hadronic and string
degrees of freedom have failed to describe the maximum, which could also be a manifestation of the transition to the quark-gluon plasma phase.

We present here some selected results of calculations within the GiBUU model on the kaon azimuthal distributions at SIS energies and on the $K^+/\pi^+$ ratio and the slopes of kaon $m_\perp$-spectra at AGS-SPS energies. A full analysis can be found in [7] [12].

A brief description of the model is given in Sect. 2. Sect. 3 contains numerical results. Sect. 4 summarises our study.

2. GiBUU model

Our calculations are based on the GiBUU model in version of Refs. [13, 14]. The model describes a heavy-ion collision explicitly in time as a sequence of elementary two-particle collisions and resonance decays. Between collisions, the particles either propagate in the mean field (optionally) or along straight trajectories. The baryon-baryon collisions at $\sqrt{s} < 2.6$ GeV and the meson-baryon collisions at $\sqrt{s} < 2$ GeV are treated within the resonance model. At larger $\sqrt{s}$, the string model is applied (c.f. Ref. [15] for details).

At SIS energies, we treat strangeness production perturbatively and use the mean field potentials for the propagation of baryons and kaons [16]. For the baryons, the soft momentum-dependent mean field is used (SM, $K=215$ MeV, see [14] for details), which is well suited to reproduce the nucleon collective flows [17] and kaon multiplicities in Au+Au and C+C systems [2, 7].

The $K^\pm$ single-particle energies contain both vector and scalar parts (c.f. [5, 18]):

$$\omega^\pm(k) = \pm V_0 + \sqrt{k^*^2 + m_K^2},$$

(1)

where $k^* \equiv k \mp V$ is the kaon kinetic momentum,

$$V^\mu = \frac{3}{8 f_\pi^2} j_B^\mu$$

(2)

is the kaon vector potential, $j_B^\mu = \langle \bar{B} \gamma^\mu B \rangle$ is the baryon four-current.

$$m_K^* = \sqrt{m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2} \rho_s + V_0 V}$$

(3)

is the kaon effective (Dirac) mass, where $\rho_s = \langle \bar{B} B \rangle$ is the baryon scalar density, $f_\pi = 0.093$ GeV is the vacuum pion decay constant, $m_K = 0.496$ GeV is the bare kaon mass. $\Sigma_{KN}$ is the kaon-nucleon sigma term.

Following Ref. [5], we will use the BR [18] and the Ko-Li (KL) [19] parametrizations of the kaon single-particle energy which differ by the choice of the kaon-nucleon sigma-term and of the in-medium pion decay constant $f_\pi^*$. In case of BR (KL) $\Sigma_{KN} = 0.450 \ (0.350)$ GeV and $(f_\pi^*/f_\pi)^2 = 0.6 \ (1)$. 

The $K^+$ potential $U_K(k) = \omega^+_K(k) - \sqrt{k^2 + m_K^2}$ at zero momentum is depicted in Fig. 1 as a function of the baryon density. The BR potential is much more repulsive than the KL potential.

![Graph showing the kaon potential at zero momentum as a function of the nuclear matter density.](image)

**Fig. 1.** The kaon potential at zero momentum as a function of the nuclear matter density.

The propagation of kaons is described by Hamiltonian equations of motion with the Hamilton function given by Eq. (1). We also use the in-medium thresholds of the cross sections for kaon production at SIS energies [2].

### 3. Numerical results

Fig. 2 shows the azimuthal distributions of $K^+$'s at midrapidity from semicentral Au+Au collisions at 1.5 A GeV. The experimental data reveal a pronounced out-of-plane emission of $K^+$'s. We see, however, that the squeeze-out signal is clearly too weak in the calculation without kaon potential. The KL parametrization also produces not enough anisotropy. The best description of the data is reached in the calculation with the BR parametrization of the kaon mean field. The mechanism of the kaon squeeze-out enhancement is a dynamical focusing by the repulsive mean field [7]. This seems to be different from the nucleon squeeze-out, which is mostly due to shadowing by spectators [20].

Fig. 3 shows the $K^+ / \pi^+$ ratio at midrapidity for the central Au+Au (2-10 A GeV) and Pb+Pb (30 and 40 A GeV) collisions. The GiBUU results are compared with the UrQMD and HSD calculations from Ref. [22]. Although the GiBUU model gives a better description of the data, all calculations underpredict the ratio at 10-30 A GeV due to overestimated pion production (c.f. [12, 22]). The GiBUU...
model produces somewhat more strangeness than the other models due to additional meson-meson channels for \( K\bar{K} \) production.

\[ \frac{K^+/\pi^+}{E_{lab}/A} \]  

\[ \text{data} \quad \text{GiBUU} \quad \text{UrQMD} \quad \text{HSD} \]

\( K^+/\pi^+ \) ratio at midrapidity vs the beam energy. Data from [8, 10, 11].

While the kaon multiplicities are described rather well, the slope parameters of the kaon transverse mass spectra are underpredicted by our model (Fig. 4).

To understand the reason of the discrepancies above and to do a step towards
model improvement, we estimate the role of many-body collisions in dense nuclear medium. In a central Au+Au collision at 20 A GeV the maximum baryon density reached in a central 1 fm$^3$ cell is $\rho_B \simeq 10\rho_0 = 1.6$ fm$^{-3}$. The gas parameter, i.e. the number of particles inside the interaction volume characterizing a two-body collision is

$$\gamma_{gas} = (\sigma/\pi)^{3/2}\rho_B \simeq 2,$$

(4)

where $\sigma \simeq 40$ mbarn is the total baryon-baryon cross section. Neglecting relativistic effects, one can conclude that the applicability condition of the Boltzmann equation, i.e. of the binary collision approximation, is violated (see also [23]), since $\gamma_{gas} > 1$. Relativistic effects, such as the Lorentz contraction of the interaction volume along the collision axis, favour binary collisions at the initial nonequilibrium stage, but quickly loose their importance at the high-density equilibrated stage.

4. Conclusions

To summarize, we have performed the transport GiBUU calculations of kaon and pion production at 1-40 A GeV. We have found that — at SIS energies — the kaon potential is needed to describe the out-of-plane squeeze-out of kaons. The BR parametrization ($U_K(\rho_0) \simeq 30$ MeV) is favoured.

At AGS — lower SPS energies, standard GiBUU gives overall agreement with HSD and UrQMD on $\pi^+$ and $K^+$ multiplicities. Data on $\pi^+$ multiplicity are overestimated, $K^+$ multiplicity is well described. Our model produces too soft kaon $m_t$-spectra, also reported for UrQMD and HSD in [24]. We believe that the major problem with the standard transport calculations is neglecting the many-body
collisions which are increasingly important at high densities.

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