Stopping and the $\langle K \rangle / \langle \pi \rangle$ horn

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Abstract. We propose a non-equilibrium hadronic model to interpret the observed excitation function of kaon-to-pion ratios in nuclear collisions at AGS and SPS energies. The crucial assumption of our model is that due to stronger stopping at lower energies the lifetime of the fireball is prolonged because the system has to build up the longitudinal expansion from internal pressure.

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THE HORN

The excitation function of the ratio $\langle K^+ \rangle / \langle \pi^+ \rangle$ which exhibits a sharp peak (a “horn”) at projectile energies of 30 $\text{A GeV}$ is certainly one of the most intriguing experimental results from the energy scan performed at the CERN SPS [1]. Statistical hadronisation model expects a maximum connected with the transition from baryon to meson dominated energy regime but cannot reproduce the observed sharpness of the peak [2]. The sharp maximum together with the excitation functions of $\langle K^- \rangle / \langle \pi^- \rangle$ and $\langle \Lambda \rangle / \langle \pi \rangle$ is not reproduced in hadronic transport codes either [3,4]. The only successful, though schematic, interpretation of the data uses the framework of the so-called Statistical model of the early stage (SMES) [5]. The model is based on the assumption that the primordial particle production is realized according to grand-canonical equilibrium distribution and the steep descent of the peak corresponds to transition to deconfined phase via a mixed phase. A kinetic description of the excitation function, also including phase transition in the region of the peak, has been proposed recently [6].

Concerning the SMES, a question appears whether it is realistic to assume a chemical equilibrium thus early in the collision? Moreover, if the peak is to be regarded as a signature for deconfinement, are all hadronic scenarios safely excluded? We shall explore the possibility of reproducing the “horn” in a hadronic non-equilibrium model.

Let us recall the two important quantities which regulate the final amount of produced strangeness. Firstly, it is the energy density, because the rates of reactions producing strangeness depend on the energy of particles in the incoming channel. Secondly, it is the total lifespan of the fireball since strange particles are out of chemical equilibrium and the relative strangeness content, most probably, grows with time. Thus we propose the following scenario potentially leading to the $\langle K^+ \rangle / \langle \pi^+ \rangle$ “horn”: at lower energies ($\lesssim 30 \text{A GeV}$) the increase of the excitation function is due to an increase in the energy available for the strangeness production. With the further increase of the collision energy...
the nuclear stopping power decreases. Since we know from $M_T$-dependence of HBT radii that the longitudinal expansion pattern at freeze-out looks roughly the same at all energies, there must be accelerated longitudinal expansion and it must last longer at lower energies with stronger stopping. We put the sharp decrease of the ratio (on the right-hand side of the “horn”) into connection with shorter lifetime of the fireball in more energetic collisions. The fireball just has less time to “cook up” strangeness and therefore the relative strangeness yield is lower. This hypothesis will be tested with a kinetic model.

**THE MODEL**

As we only want to calculate the ratios of total yields, and not the yields themselves, it is enough to study the evolution of the spatially averaged densities of individual species only. The spatial distribution is inessential here. We will in particular investigate the evolution of kaon density. Assuming that kaons are kept in thermal equilibrium with a fireball medium, the variation of the kaon density follows from the simple relation

\[ \frac{dn_K}{d\tau} = \frac{d}{d\tau} \frac{N_K}{V} = \frac{1}{V} \frac{1}{V} \frac{dV}{d\tau} + \frac{1}{V} \frac{dN_K}{d\tau}, \tag{1} \]

where $N_K$ and $V$ are the total number of kaons and the volume of the system, respectively, and $\tau$ is the time in the co-moving frame. The second term on the right-hand side of this equation expresses the change of density due to chemical reactions. It can be split into gain term and loss term

\[ \frac{dn_K}{d\tau} = n_K \left( -\frac{1}{V} \frac{dV}{d\tau} \right) + \sum_{ij} \langle v_{ij} \sigma_{ij}^+ \rangle \frac{1}{1 + \delta_{ij}} n_in_j - \sum_{j} \langle v_{Kj} \sigma_{Kj}^- \rangle \frac{1}{1 + \delta_{Kj}} n_K n_j. \tag{2} \]

In the gain term we sum over all processes producing a kaon, in the loss term these are the processes destroying a kaon. The relative-velocity-averaged cross-sections are multiplied with densities of the incoming species.

The first term on the right-hand-sides of eqs. (1) and (2) includes the expansion rate and stands for the density change due to expansion. In a simulation of the collision (hydrodynamic or transport), the expansion rate is obtained naturally. Here, we shall adopt a parametrisation of the expansion. Though in this way we do not make a direct contact to the underlying microscopic equation of state, it gives us a possibility to explore many different evolution scenarios and their impact on data.

The ansatz for the energy density and the baryon density which will be used reads

\[ \varepsilon(\tau) = \begin{cases} \varepsilon_0(1 - a\tau - b\tau^2) & \text{for } \tau < \tau_s, \\ \varepsilon'_0 \frac{1}{(\tau - \tau_0)^{\alpha/\delta}} & \text{for } \tau > \tau_s \end{cases} \tag{3a} \]

\[ \rho_B(\tau) = \begin{cases} \rho_{B,0}(1 - a\tau - b\tau^2)^{\delta} & \text{for } \tau < \tau_s, \\ \rho'_{B,0} \frac{1}{(\tau - \tau_0)^{\alpha}} & \text{for } \tau > \tau_s \end{cases} \tag{3b} \]

In the above expressions the parameters can be tuned. Two of them are constrained by the requirements that the functions are continuous together with their first time derivatives.
Initially ($\tau < \tau_s$) the fireball expands acceleratedly with a quadratic dependence on time. Then, at $\tau > \tau_s$, the power-law expansion is dictated by the $M_\perp$-dependence of HBT radii. Note the shift by $\tau_0$: it allows to delay this type of expansion. Such a delay would be unobservable in the $M_\perp$-dependence of $R_{long}$ which is standardly used to argue for a short fireball lifetime \[7\]. The “lifetime” measured by $R_{long}$ would correspond in our case to the difference ($\tau_{total} - \tau_0$). Note also that the two parameterisations for energy and baryon density have similar forms and differ essentially by the exponent $\delta$ which is given by the assumed equation of state.

By tuning the parameters $a$ and $b$ we specify the initial rate of density decrease and the pace on which the decrease accelerates. This way we quantify the stopping and re-acceleration. We can construct a large class of models “between Landau and Bjorken scenarios”.

Densities of kaons (i.e. $K^+, K^0, K^{*+}, K^{*0}$) are calculated according to eq. (2). We include the following processes:

$\pi N \leftrightarrow KY, \quad \pi N \rightarrow NK\bar{K}, \quad \pi \Delta \leftrightarrow KY, \quad \pi \Delta \rightarrow NK\bar{K}$

$NN \rightarrow KNY, \quad NN \rightarrow NNK\bar{K}, \quad NN \rightarrow K\bar{K}Y$

$N\Delta \rightarrow NYK, \quad N\Delta \rightarrow NNK\bar{K}, \quad N\Delta \rightarrow K\bar{K}Y$

$\Delta\Delta \rightarrow \Delta YK, \quad \Delta\Delta \rightarrow NNK\bar{K}$

$\pi\pi \leftrightarrow K\bar{K}, \quad \pi\rho \leftrightarrow K\bar{K}, \quad \rho\rho \leftrightarrow K\bar{K}$

$K^+ \leftrightarrow K\pi, \quad \pi Y \leftrightarrow K\Xi.$

For those processes with two particles in final state also inverse reactions have been included which annihilate kaons.

Species with negative strangeness must balance the total strangeness of the system to zero. Reactions which just swap the strange quark between them are quick. Therefore, we assume that these species are in chemical equilibrium with respect to each other, while the strangeness-weighted sum of their densities is given by the requirement of strangeness neutrality.

All non-strange species are assumed to be chemically equilibrated. We assume no antibaryons at these energies. Their influence would be highest at the top SPS energy $\sqrt{s_{NN}} = 17 A GeV$ where we expect 10% error due to their neglect. In a schematic model like ours this is acceptable.

In a model set up in this way, the total produced amount of strangeness is mainly controlled by the lifetime (as we shall show) and slightly less by the temperature. The rate at which strange quarks are distributed among $K^-$ and $\Lambda$ is fixed by the final temperature.

We try to choose the parameterisations \[3\] in such a way that the final state resulting from fits to chemical composition at different energies \[8\] is reached. The initial amount of strangeness is estimated from pp, pn, and nn collisions \[9\].

**RESULTS**

We show an example of our results in Figure I. Each point in that figure corresponds to
FIGURE 1. Calculated ratios $\langle K^+ \rangle / \langle \pi^+ \rangle$, $\langle K^- \rangle / \langle \pi^- \rangle$, $\langle \Lambda \rangle / \langle \pi \rangle$ as functions of the total lifetime of the fireball. Different curves correspond to different initial energy densities. Calculation for Pb+Pb collisions at projectile energy of 30 AGeV. The bands show values accepted by data [1].

a different evolution scenario; they differ by total lifetime and initial energy density. Though the presented results are obtained for Pb+Pb collisions at projectile energy of 30 AGeV, it applies generally that dependence on lifetime is crucial, while the dependence on initial energy density is less important. The latter gains more weight at lower energies and is completely irrelevant at the highest SPS energy. It mainly stems from the temperature dependence of reactions including nucleons like $\pi + N \rightarrow \Lambda + K$ which make up a bigger share of the total production rate at lower energies where the baryon density is higher.

Summary of the values of total lifetime and initial energy density allowed by comparison to data is presented in Figure 2. The more important limitations are put on the lifetime. In general, for SPS energies our hypothesis is confirmed that with increasing energy of the collision lifetime of the fireball decreases. Only at the lowest studied energy, 11.6 AGeV (AGS), we miss the $\langle \Lambda \rangle / \langle \pi \rangle$ ratio by about 3 standard deviations, see Figure 3. This is caused by much too high temperature in the final state, which can be fixed by re-parameterising the time dependence of the energy density. Otherwise, we reproduce the data well.

CONCLUSIONS

The excitation function of the ratios $\langle K^+ \rangle / \langle \pi^+ \rangle$, $\langle K^- \rangle / \langle \pi^- \rangle$ and $\langle \Lambda \rangle / \langle \pi \rangle$ can be reproduced in a non-equilibrium hadronic scenario. The crucial assumption is that the total
FIGURE 2. Values of initial energy density and total lifetime accepted by data [1].

FIGURE 3. Results obtained with parameter sets indicated in lower right panel of Figure 2 compared to data.
lifetime of the fireball is a decreasing function of the collision energy.

Thus we have made a specific prediction for the evolution dynamics of the fireball. Such a prediction must now be checked against other observables. Although we were lead by the knowledge of all particle abundances, transverse momentum spectra and HBT radii, a careful analysis of these data in the framework of the proposed model must be performed. Furthermore, dilepton spectra gained an unprecedented accuracy recently [10, 11, 12]. They are sensitive to whole fireball history [13] and could provide the crucial test of our hypothesis.

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