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Hadron production from a hadronizing quark–gluon plasma

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Abstract. Measured hadron yields from relativistic nuclear collisions can be equally well understood in two physically distinct models, namely a static thermal hadronic source versus a time-dependent, non-equilibrium hadronization off a quark–gluon plasma droplet. Due to the time-dependent particle evaporation off the hadronic surface in the latter approach the hadron ratios change (by factors of $\lessapprox 5$) in time. The overall particle yields then reflect time averages over the actual thermodynamic properties of the system at a certain stage of evolution.

Several thermal models have been applied [1–3] to (strange) particle yields and used to extract the characteristic thermodynamic properties of a supposedly static system (with a few macroscopic parameters) from chemical equilibrium. For a review see the contribution by Sollfrank [4] in these proceedings. The parameters of the system, in particular the temperature T and the quark chemical potential μ_q, are extracted in such a way to reproduce the observed hadronic particle ratios. Similar to the findings by Braun-Munzinger *et al* [3] we also find good agreement with many observed ratios (as extracted in [3]) from different experiments at the SPS within such a static approach [5]. (Basically, the temperature T and the quark chemical potential μ_{q} are hereby fitted to reproduce the p/π^+ and $\overline{\mathrm{p}}/\mathrm{p}$-ratios.) The value of μ_{s} has been determined by the requirement that the total net strangeness vanishes: $f_{\mathrm{s}}^{\mathrm{init}} = 0$. (The quantity f_{s} is the fraction of net strangeness over net baryon number $(f_{\mathrm{s}} = (N_{\mathrm{s}} - N_{\bar{\mathrm{s}}})/A)$.) The inclusion of higher lying resonances leading to an additional feeding on the predicted ratios turns out to be very important (factors of $\gtrapprox 3$!).

We now investigate whether the reasonable agreement of data and model, as reached within such a static equilibrium-plus-feeding model, can also be achieved with a dynamic model, which includes the formation and expansion of quark–gluon matter, a first-order phase transition into coexistence of quark and hadron matter, and an immediate time-dependent evaporation of hadrons from the system, as it evolves with time through the phase transition. We adopt a model for the hadronization and spacetime evolution of quark matter droplets given in [6]. This model assumes a first order phase transition of the quark–gluon plasma (QGP) to hadron gas with Gibbs conditions ($P^{\mathrm{QGP}} = P^{\mathrm{HG}}$, $T^{\mathrm{QGP}} = T^{\mathrm{HG}}$, $\mu_{\mathrm{q}}^{\mathrm{QGP}} = \mu_{\mathrm{q}}^{\mathrm{HG}}$, $\mu_{\mathrm{s}}^{\mathrm{QGP}} = \mu_{\mathrm{s}}^{\mathrm{HG}}$) for coexistence. The expansion and evaporation of the system takes into account equilibrium, as well as non-equilibrium features of the process: the

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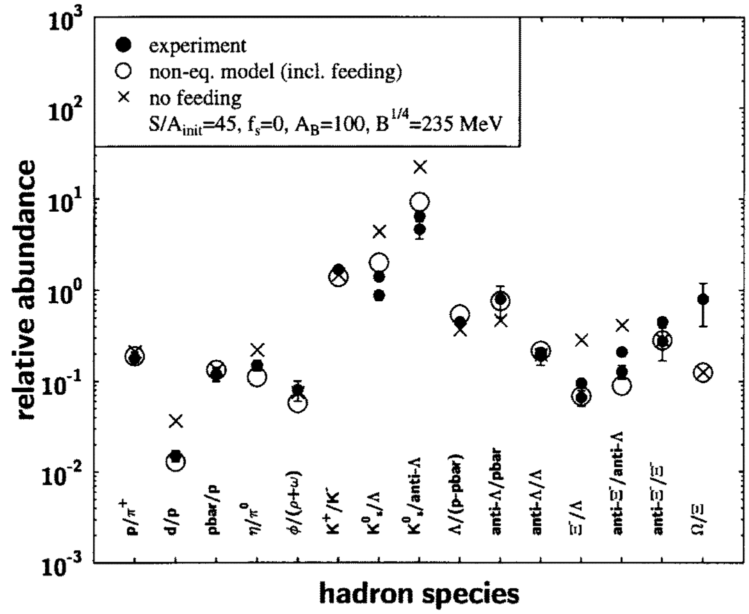

Figure 1. Final particle ratios in the non-equilibrium scenario with initial conditions $A_{\mathrm{B}}^{\mathrm{init}} = 100$, $S/A^{\mathrm{init}} = 45$, $f_{\mathrm{s}}^{\mathrm{init}} = 0$ and bag constant $B^{1/4} = 235$ MeV. The crosses denote the resulting values if contributions due to the decay of higher lying resonances are ignored. The circles include these effects. Data from various experiments as compiled in [3] are also shown.

plasma sphere is permanently surrounded by a layer of hadron gas, with which it stays in thermal and chemical equilibrium during the phase transition. Thus, the hadronic particle production is driven by the chemical potentials. In addition, sudden particle evaporation is incorporated by a time-dependent freeze-out of hadrons from the hadron phase surrounding the QGP droplet. Accordingly, the global properties, like (decreasing or increasing) entropy per baryon number S/A and the *net* strangeness fraction f_{s} of the remaining two-phase system, will then change in time [6].

In figure 1 the final (time-integrated) ratios are plotted for a rather large phenomenological bag constant of $B^{1/4} = 235$ MeV, initial strangeness fraction $f_{\mathrm{s}} = 0$ and an initial specific entropy per baryon of $S/A = 45$. (We choose an initial net baryon number $A_{\mathrm{B}}^{\mathrm{init}} = 100$. Obviously, the particle ratios will not depend on this choice.) The theoretical ratios show an equally good overall agreement with the data points as a comparable static fit! This scenario results in rather rapid hadronization. The quasi-isentropic expansion of the system is due to those hadrons which are subsequently evaporated. Decays and feeding occur after the hadrons leave the system.

Using much lower bag constants ($B^{1/4} \leqslant 180$ MeV) the overall particle yields obtained within this model are not in good overall agreement with the observed ratios. Either the number of produced baryons (nucleons and hyperons) or the number of produced antibaryons fail by more than one order of magnitude, which is mainly due to the lower temperatures of the coexistence phase when employing lower bag constants.

Figure 2 shows the time evolution of the system (initial conditions as in figure 1) in the plane of quark and strange-quark chemical potential. The quark chemical potential is at the beginning of the evolution in the order of the temperature of the system. It is $\mu_{\mathrm{q}} \approx 110$ MeV. This is twice the value assumed in the static approach, $\mu_{\mathrm{q}} \approx 60$ MeV. However, in the

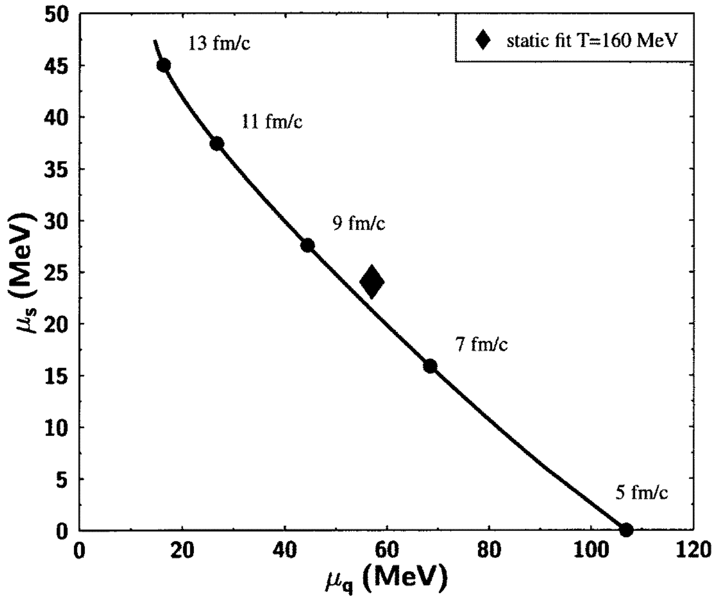

Figure 2. Time evolution of the quark chemical potential and the strange-quark chemical potential for the parameter set of figure 1 (The hadronization starts at an initial time of $t_0 = 5$ fm c^{-1}). The diamond denotes the chemical potentials extracted with a corresponding static fit [5].

course of the hadronization, the quark chemical potential drops to $\mu_q \approx 15$ MeV. On the other hand, the strange chemical potential increases from $\mu_s = 0$ to values of $\mu_s \approx 50$ MeV at the end of the evolution, as compared with $\mu_s \approx 25$ MeV in the static fit.

The initial specific entropy of $S/A = 45$ in combination with the bag constant $B^{1/4} = 235$ MeV leads to a fast decomposition of the quark phase within ≈ 8 fm c^{-1}. The system moves on a path along the phase boundary. In our case we met the situation $(S/A)^{\mathrm{QGP}}/(S/A)^{\mathrm{HG}} > 1$ which leads to a reheating, i.e. $(S/A)^{\mathrm{QGP}}$ increases with time [6], to a final value of $S/A \approx 140$. As a consequence the temperature also increases, but only slightly ($T \approx 160$ MeV). This also explains why the quark chemical potential μ_q does evolve to a much smaller final value, when hadronization is completed. (We note, that the system can cool within this model if $(S/A)^{\mathrm{QGP}}/(S/A)^{\mathrm{had}} < 1$ [6, 7], which can only be achieved for somewhat lower bag constants when using the equation of state for both phases as in our model.)

Due to the 'strangeness distillery' effect [8] strange and antistrange quarks do not hadronize at the same time for a baryon-rich system: both the hadronic and the quark matter phases enter the strange sector, $f_s \neq 0$, of the phase diagram immediately. At the late stage of the evolution, as the strange chemical potential increases, the remaining system reaches rather large and positive f_s values $\geqslant 1$.

The changes of the chemical potentials with time will influence considerably the differential hadron production rates at the various time steps: proton and deuteron rates drop very fast due to the decreasing quark chemical potential, while the antiproton rate even increases. K^- and Ω production profits from the high strange-quark chemical potential at the late stage of evolution. Most of the ratios—the final values of which are given in figure 1—change by factors $\approx$ 2–5 in the course of the hadronization and evaporation [5].

Therefore, the thermodynamic parameters of a certain stage of the evolution, e.g. of the initial stage, cannot be deduced from the final integrated particle ratios in this model. The presented results also suggest that the observed freeze-out time will be smaller for K^+ than for K^-, and it will also be smaller for p and Λ than for $\overline{p}$ and $\bar{\Lambda}$, respectively. This might in principle be accessible by means of two-particle correlation analyses.

In conclusion, experimental particle ratios at SPS energies are considered to be compatible with the scenario of a static thermal source in chemical equilibrium [3]. A simple dynamic hadronization model, however, reproduces the numbers equally well. It yields the following conclusions: a high bag constant of $B^{1/4} \geqslant 200$ MeV seems mandatory. These values of B would exclude the existence of stable, cold strangelets, as hadronization proceeds without any cooling but with reheating. In central collisions of $\mathrm{S} + \mathrm{Au(W, Pb)}$ a specific entropy per baryon of $S/A = 35$–45 is created. Due to strangeness distillation the system moves rapidly out of the T, μ_B plane, into the μ_s-sector. The quark chemical potential drops during evolution and the strange quark chemical potential rises. Final μ_q, μ_s values of $\frac{1}{3}$ and 3 respectively of the values of the static fits are reached for $t \rightarrow t_{\mathrm{freeze\text{-}out}}$. The average freeze-out times of different hadron species differ strongly, which might be observable via two-particle correlations. Strangeness to baryon fractions of $f_\mathrm{s} \approx 1$–2 suggest that 'Λ-droplets' or even 'Ξ^--droplets' form the system at the late stage.

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