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HEAVY ION PHYSICS

Particle Ratios from a Chiral SU(3) Model

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Abstract. The measured particle ratios in central heavy-ion collisions are investigated within a chemical and thermal equilibrium chiral SU(3) $\sigma - \omega$ approach. Contrary to the commonly adopted non-interacting gas calculations, the chiral SU(3) model predicts modified effective hadron masses and effective chemical potentials in the medium and a transition to a chirally restored phase at high temperatures or chemical potentials. The influence of three different types of phase transitions is investigated. We show that the deduced freeze-out values considerably depend on the underlying model while the quality of the fit is approximately the same.

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1. Introduction

Calculations of particle production in high energy collisions of elementary particles and heavy ions under the assumption of thermodynamical equilibrium have been carried out for a long time [1–11]. The experimentally determined hadron ratios can be fitted well with straightforward non-interacting gas model calculations [7–13], if a sudden breakup of a thermalized source is assumed and once the subsequent feeding of the various channels by the strongly decaying resonances is taken into account. From the χ^2 freeze-out fits one has constructed a quite narrow band of freeze-out values in the $T - \mu_B$ plane (see e.g. [12, 13]).

The extracted freeze-out parameters are fairly close to the phase transition curve for SPS and RHIC energies.

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However, when we are indeed so close to the phase transition or to a crossover as suggested by the data for T and μ_B, we cannot afford to neglect the very in-medium effects we are after — and which, after all, do produce the phase transition. Thus, since non-interacting gas models neglect any kind of possible in-medium modifications they cannot yield information about the phase transition.

Therefore, we will employ below a relativistic selfconsistent chiral model of hadrons and hadron matter developed in [14, 15]. This model can be used as a thermodynamically consistent effective theory or as a toy model, which embodies the restoration of chiral symmetry at high temperatures or densities. Therefore the model predicts temperature and density dependent hadronic masses and effective chemical potentials, which have already been proposed and considered in [4, 16–19]. Thus, using the chiral SU(3) model we can investigate, whether the freeze-out in fact takes place close to the phase transition boundary (if it exists) and if the extracted T, μ_B parameters strongly depend on the models used or the choice of particle ratios included in the fit. Depending on the chosen parameters and degrees of freedom different scenarios for the chiral phase change are predicted by the model: strong or weak first order phase transition or a crossover.

2. Particle Ratios in the Chiral Model

The chiral SU(3) model is presented in detail in [15]. In the present calculation the lowest lying baryonic octet and decuplet and the lowest lying mesonic nonets are coupled to the relativistic mean fields. Depending on the coupling of the baryon resonances (the decuplet) to the field equations, the model shows a first order phase transition or a crossover (for details see [20]). We will use three different parameter sets: Parameter set CI treats the members of the baryon decuplet as free particles, which yields a crossover behaviour. Parameter sets CII and CIII include also the (anti-)baryon decuplet as sources for the meson field equations. They differ by an additional explicit symmetry breaking for the baryon resonances along the hypercharge direction, as described in [15] for the baryon octet. This is included in CII and not used in CIII. This leads to a weak first order phase transition at $\mu = 0$ for CII and two first order phase transitions for CIII, which can be viewed as one strong first order phase transition. Heavier resonances up to $m = 2$ GeV are always included as free particles.

The density of a particle of a certain species i is then given by

$$\rho_i = \gamma_i \int \frac{d^3k}{(2\pi)^3} \left[\frac{1}{\exp[(E_i^* - \mu_i^*)/T] \pm 1} \right] , \tag{1}$$

where γ_i denotes the hadronic spin–isospin degeneracy factors. The single particle energies are $E_i^*(k) = [k_i^2 + m_i^{*2}]^{-1/2}$ and the effective chemical potentials read $\mu_i^* = \mu_i - g_{i\omega}\omega - g_{\phi i}\phi$.

Due to the medium dependent masses and chemical potentials, as predicted by the chiral model, the resulting particle ratios will change [20].

Thus, we identify combinations of temperatures and chemical potentials that fit the observed particle ratios. That is, we are looking for a minimum of χ^2 with

$$\chi^2 = \sum_i \frac{\left(r_i^{\exp} - r_i^{\text{model}}\right)^2}{\sigma_i^2} . \tag{2}$$

Here $r_i^{\exp}$ is the experimental ratio, r_i^{model} is the ratio calculated in the model and σ_i represents the error in the experimental data points.

3. Results for $A+A$ at AGS, SPS and RHIC

First, we observe that satisfactory description of the particle ratios from AGS to RHIC is possible within the chiral SU(3) model. As an example Fig. 1 shows the experimental ratios as well as the fitted ratios from the model for all three different scenarios for $E_{\text{lab}} = 160A$ GeV at SPS. Comparable good agreement is obtained for different energies from AGS, SPS to RHIC [21].

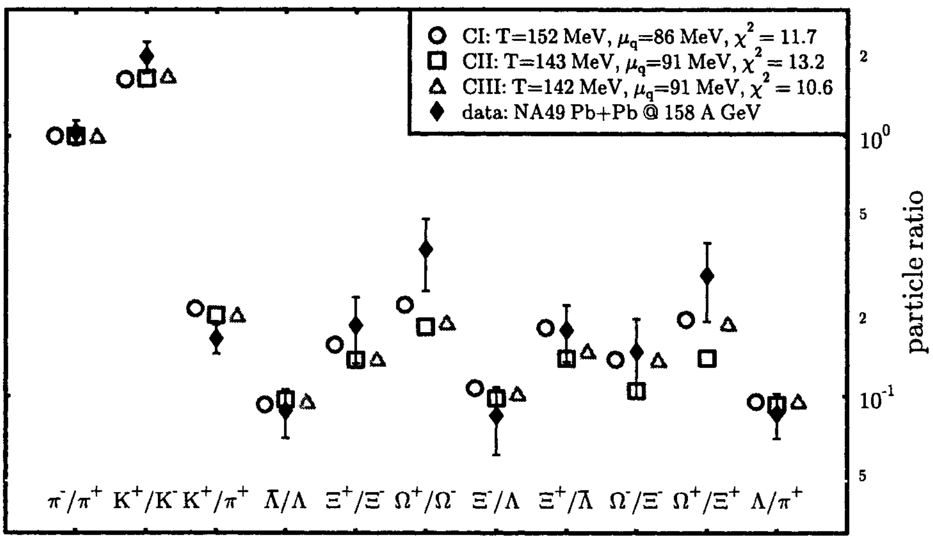

Fig. 1. Particle ratios at SPS 160 AGeV for CI, CII, and CIII compared to experimental data [22–24]

Second, the resulting freeze-out values for temperature and chemical potential strongly depend on the model employed, as can be seen in Fig. 2, experimental data is taken from [22–25], the fit values for RHIC are taken from [21]. However, for all

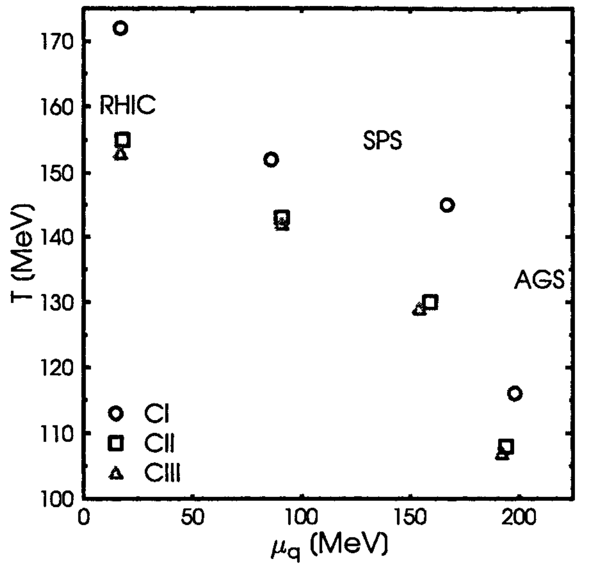

Fig. 2. Freeze-out values for temperature and quark chemical potential for AGS, SPS, and RHIC energies

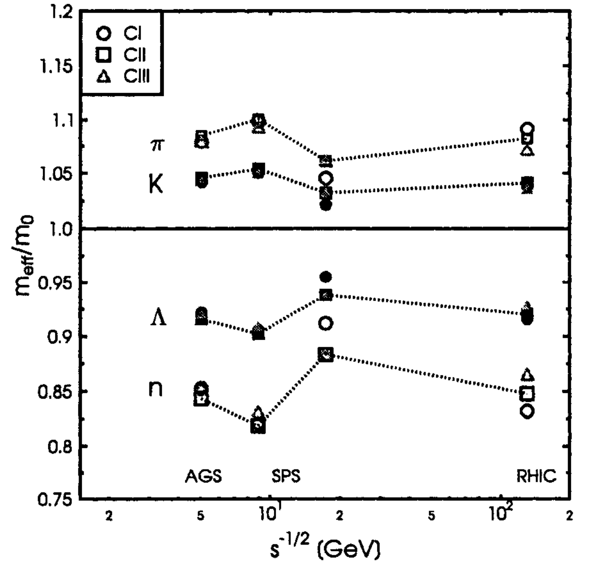

Fig. 3. Effective hadron masses at freeze-out relative to vacuum masses as a function of center of mass energy

scenarios studied in the chiral model, the deduced freeze-out points never lie above the corresponding phase transition or crossover curve, respectively. Above T_c a very steep increase of the χ^2 can be observed. Thus, the chemical composition has to change considerably within a small temperature intervall, just before freeze-out [21].

Third, as depicted in Fig. 3, the effective masses at freeze-out change up to 15%. Further more it can be seen that for a given energy the predicted mass shift for a certain particle species is weakly influenced by the different phase transition scenarios given.

4. Conclusion

Particle ratios as calculated in a chiral SU(3) $\sigma - \omega$ model are compared with data from A+A collisions at AGS, SPS and RHIC. We have shown that the current data is described well by all three different phase transition scenarios. Thus, we cannot discriminate between different equations of state on the basis of the χ^2 fit to the measured particle ratios. Since the deduced temperatures and chemical potentials vary significantly with the different approaches, there is a large uncertainty in these freeze-out values. In contrast, the predicted effective hadron masses at freeze-out do not depend strongly on the phase transition scenario employed, but they do differ from the vacuum masses used by ideal gas models.

At RHIC energy the freeze-out takes place right at the phase boundary and just below the phase boundary for SPS energy, respectively. Since in addition, the χ^2 values increase very rapidly at the phase boundary equilibration in the hadronic phase is questionable. This suggests that the extracted particle ratios are just the result of the dynamical symmetry breaking process itself.

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