Chemical Equilibration and the Hadron-QGP Phase Transition

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We discuss recent experimental results on hadron multiplicities in ultra-relativistic nuclear collisions. The data for central collisions are in quantitative agreement with predictions of a thermal model assuming full chemical equilibration. It is argued that this provides strong, albeit indirect, evidence for the formation of a partonic phase in the collision prior to hadron production.

1. Introduction

Experiments with ultra-relativistic nuclei are performed to produce and study the quark-gluon plasma. This new state of matter is predicted to exist at high temperatures and/or high baryon densities. Numerical solutions of QCD using lattice techniques imply that the critical temperature (at zero baryon density) is about 170 MeV [1]. Comprehensive surveys of the various experimental approaches on how to produce such matter in nucleus-nucleus collisions have been given recently [2–5]. Here we focus exclusively on hadron production, its interpretation in terms of a thermal model, and the resulting consequences for the quark-hadron phase transition.

2. Thermal Model, Strangeness Enhancement and Equilibration

The statistical model used here is presented in detail in [6]. Like its predecessors presented in [7,8] it is based on the use of a grand canonical ensemble to describe the partition function and hence the density of the particles of species i in an equilibrated fireball:

$$n_i = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2\,\mathrm{d}p}{e^{(E_i(p)-\mu_i)/T} \pm 1} \tag{1}$$

with n_i = particle density, g_i = spin degeneracy, $\hbar$ = c = 1, p = momentum, E = total energy and chemical potential $\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$. The quantities B_i, S_i and I_i^3 are the baryon, strangeness and three-component of the isospin quantum numbers of the particle of species i. The temperature T and the baryochemical potential μ_B are the two independent parameters of the model, while the volume of the fireball V, the strangeness chemical potential μ_S, and the isospin chemical potential μ_{I_3} are fixed by the three conservation laws for baryon number, strangeness, and charge. Interactions among hadrons are taken into account via an excluded volume correction. For details see [6].

The aim of this approach is to determine whether or not the observed hadron yields can be described in a model assuming complete chemical equilibration. Note that temperature and baryon chemical potential are fixed by the pion/baryon and the anti-nucleon/nucleon ratios, and hence no information about the yields of strange particles is used to determine the two parameters of the model. The production yields of strange hadrons are, however, significantly increased in ultra-relativistic nuclear collisions compared to what is expected from a superposition of nucleon-nucleon collisions. This has been observed by several experiments both at the AGS and at the SPS [9]. Nevertheless, all hadron yields including those for multi-strange baryons, where enhancement factors of more than 1 order of magnitude are observed, can be described consistently [6] if one assumes a fireball with temperature T=168 Mev and baryon chemical potential $\mu_b = 266$ MeV. This is demonstrated in Fig. 1. On the other hand, the observed enhancement, especialy for multistrange hadrons, cannot currently be understood within any of the hadronic event generators [9]

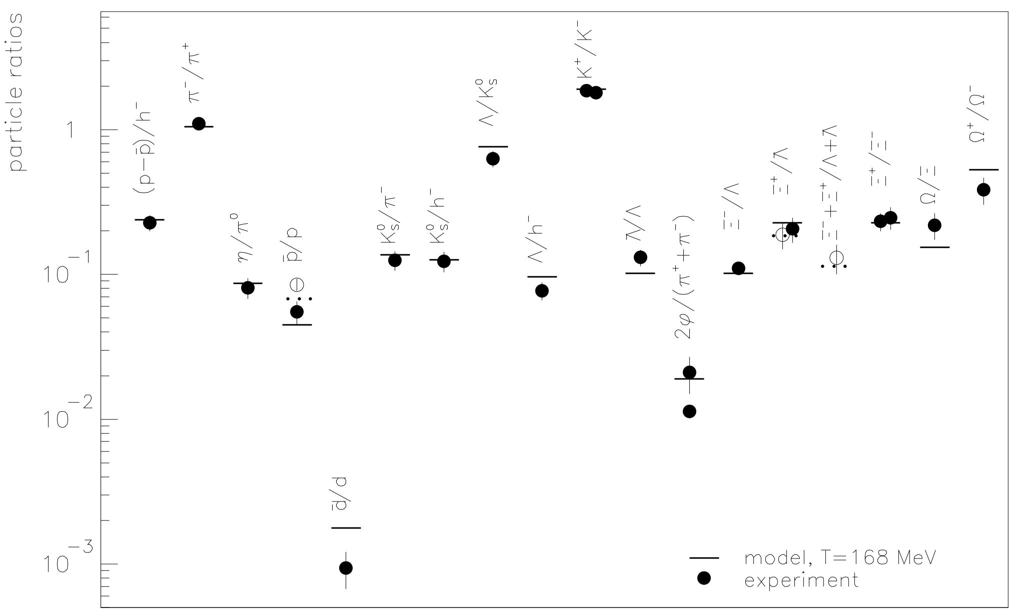

Figure 1. Comparison of measured particle ratios with predictions of the thermal model. For details see text and [6].

How chemical equilibration can be reached in a purely hadronic collision is not clear in view of the small production cross section for strange and especially multi-strange hadrons. In fact, system lifetimes of the order of 50 fm/c or more are needed for a hot hadronic system to reach full chemical equilibration [10]. Such lifetimes are at variance with lifetime values established from interferometry analyses, where upper limits of about 10 fm/c are deduced [11].

Another very interesting observation is that the chemical potentials μ_b and temperatures T resulting from the thermal analyses of [6–8] place the systems at chemical freeze-out very close to where we currently believe is the phase boundary between plasma and hadrons. This is demonstrated in Fig. 2 [1] where also results from lower energy analyses are plotted. The freeze-out trajectory (solid curve through the data points) is just to guide the eye but follows closely the empirical curve of [12].

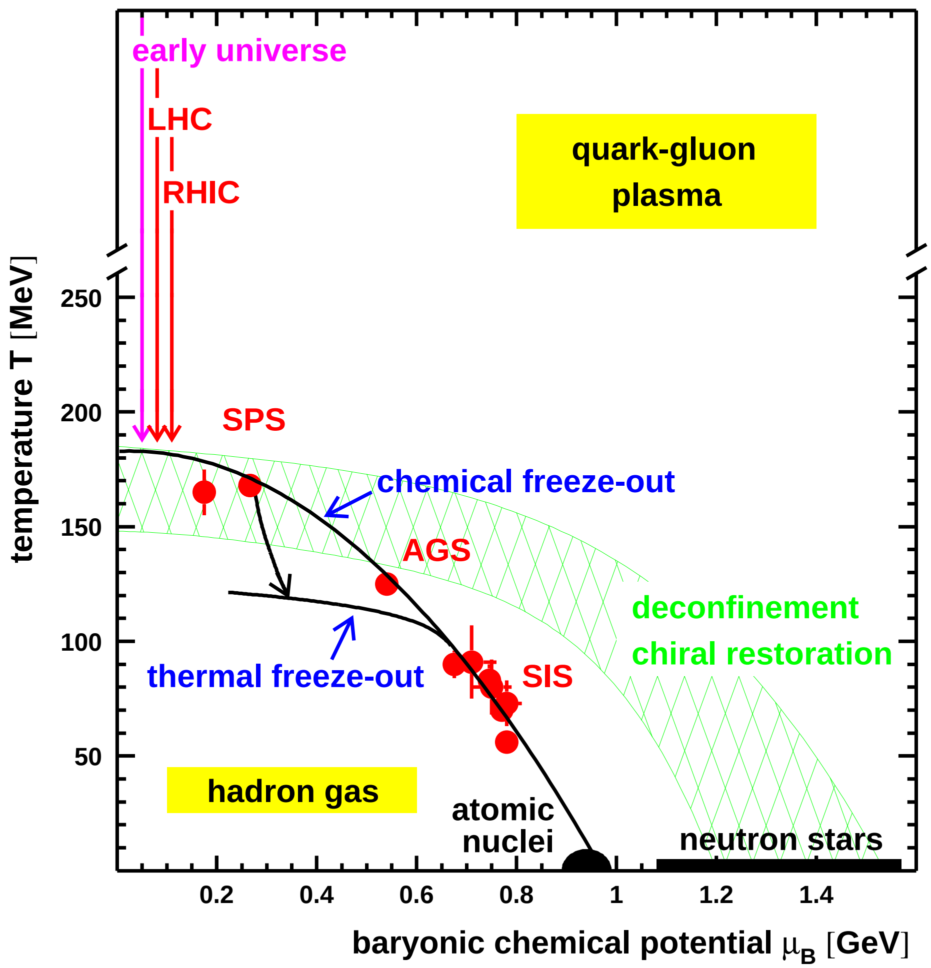

Figure 2. Phase diagram of hadronic and partonic matter. The hadrochemical freeze-out points are determined from thermal model analyses of heavy ion collision data at SIS, AGS and SPS energy. The hatched region indicates the current expectation for the phase boundary based on lattice QCD calculations at μ_b=0. The arrow from chemical to thermal freeze-out for the SPS corresponds to isentropic expansion.

The closeness of the freeze-out parameters (T,μ_b) to the phase boundary might be the clue to the apparent chemical equilibration in the hadronic phase: if the system prior to reaching freeze-out was in the partonic (plasma) phase, then strangeness production is determined by larger partonic cross sections as well as by hadronization. Slow cooking

[1]This is an updated version of the figure shown in [3,4].

in the hadronic phase is then not needed to produce the observed large abundances of strange hadrons. Early simulations of strangeness production in the plasma and during hadronization support this interpretation at least qualitatively [13].

We would like to stress, however, that it cannot be *just* the non-perturbative hadronization mechanism which brings the hadron abundances into "apparent" chemical equilibrium, as has been argued recently [14,15]. The hadronization of single quarks, as witnessed by a recent thermal analysis of hadron abundances following e^+e^- annihilation [16], leads to very drastically different distributions: as is known for many years now, hadrons with strangeness are significantly suppressed compared to purely thermal expectations. This leads in [16] to a strangeness suppression factor $\gamma_s = 0.67$, implying that Ω production is reduced by more than a factor of 3 compared to the full chemical equilibrium value reached in Pb-Pb collisions. The role of gluons is clearly important in the partonic state reached in heavy ion collisions.

Further strong support for a thermal interpretation of the observed hadron yields also arises from recent results on event-by-event fluctuations [17]. The observed distributions for the mean transverse momentum and the kaon/pion ratio look indistinguishable from reference distributions obtained by event mixing, implying only tiny[2] non-statistical components in these distributions. Since the kaon/pion ratio in the current interpretation is frozen at chemical equilibration, i.e. at the phase boundary, this result strengthens the argument for complete chemical equilibrium.

We note also that the current thermal interpretation works most convincingly for very central collisions. If the parameters T and μ_b are kept constant, all thermal yields should scale linearly with the volume and, hence, with the number of participants, implying that all particle ratios should be independent of collision centrality. This is indeed observed for the yields and ratios of multi-strange baryons in the range of participant numbers larger than 100 [18]. For pions and kaons one observes, however, a small but significant increase of yields with the number of participants [17]. Such an increase could imply a small decrease of μ_b with the number of participants. However, the observed anti-proton/proton ratios and yields of multi-strange baryons are not in support of such an interpretation. Further work is necessary to understand all finer aspects of hadron production.

3. Summary and Outlook

Hadron production results from central nucleus nucleus collisions at ultra-relativistic energies can be quantitatively understood by assuming that the fireball formed in the collision freezes out chemically very near to the phase boundary between quark-gluon plasma and hadron gas. This result cannot be explained within purely hadronic scenarios and lends strong support to the interpretation that the freeze-out state is reached via a system trajectory which crosses the phase boundary from the quark-gluon plasma side.

This interpretation leads directly to predictions for hadron production at RHIC [19] and LHC [20] which should be (at least for RHIC) testable soon.

[2]At the 90 % confidence level, nonstatistical contributions of less than 1 % to the mean transverse momentum distributions and less than 5 % to the kaon/pion ratio are excluded.

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