Hadron production in ultra-relativistic nuclear collisions and the QCD phase boundary.

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Abstract. We update briefly our understanding of hadron production in relativistic nucleus-nucleus collisions in terms of statistical models with emphasis on the relation of the data to the QCD phase boundary and on a puzzle in the beam energy dependence.

1. Hadron yields, statistical description, and the phase boundary to the QGP.

Hadron yields or more specifically yield ratios observed in central nuclear collisions at AGS, SPS, and RHIC energies can be described with high precision within a hadro-chemical equilibrium approach [1, 2, 3, 4, 5, 6, 7, 8, 9], governed by a chemical freeze-out temperature $T_{ch}$ and baryochemical potential $\mu$. A recent review, found in [10], provides a wealth of information on the subject. The data at SPS and RHIC energy comprise multi-strange hadrons including the $\Xi$, $\Omega$ and $\Xi$ baryons. Their yields ratios (to pions, e.g.) agree particularly well with the chemical equilibrium calculation and are enhanced by more than an order of magnitude as compared to observations in pp collisions. We present as an example the results for central Au-Au collisions at RHIC energy in Fig. 1.

![Figure 1. Fit of particle ratios for Au-Au collisions measured at RHIC energies. The measurements are the symbols, the thermal model values are the lines.](image-url)
A remarkable exception is observed for strongly decaying, wide resonances. In particular, the $\Delta/p$ ratio is overpredicted while the $\rho/\pi$ ratio, both determined in (rather peripheral, though) Au-Au collisions by the STAR collaboration \cite{11, 12}, is underpredicted by the model \cite{10}. For an interesting and provocative speculation as to where this might come from see \cite{13}. Clearly, precision data for central collisions and also at other beam energies are needed to settle this issue.

![Figure 2. Phase diagram of hadronic matter and chemical freeze-out points \cite{14}. The open squares represents recent estimates \cite{15, 16} of the position of the tri-critical point (see text).](image)

The chemical parameters $T_{ch}$ and $\mu$ determined from fits to data at all available energies are plotted in the QCD phase diagram shown in Fig. 2 taken (slightly modified) from \cite{14}. The phase transition lines in this figure are obtained from recent analyses within the framework of lattice QCD \cite{15, 16} and include recent estimates \cite{15, 16} of the position of the tri-critical point. Also included in this figure are lines of constant total baryon density and lines of constant energy density, computed within the framework of the hadronic gas model of \cite{3}. The line of constant energy density $\epsilon = 500$ MeV/fm$^3$ should in our view be a reasonable phenomenological description of the phase boundary. Interestingly, it is, at $\mu > 500$ MeV, much closer to the chemical freeze-out points than to the phase lines from lattice QCD. Apparently, the phase boundary lines obtained from state-of-the-art calculations within the framework of lattice QCD are not at all lines of constant energy density. Rather, the energy density grows by more than a factor of 2 when going from 0 to 500 MeV in $\mu$. This rather surprising result deserves further attention.

An important observation, already made in\cite{1}, concerning the results of the thermal model

\footnote{Position and even the existence of such a tri-critical point are currently hotly debated. For a critical discussion see \cite{17}.}
calculations is that, for top SPS energy and above, the chemical parameters determined from the measured hadron yields coincide within the uncertainties of about ±10 MeV with the phase boundary as determined from lattice QCD calculations. A natural question arises: is this coincidence accidental and, if not, what enforces equilibration at the phase boundary? Considerations about collisional rates and timescales of the hadronic fireball expansion \[18\] imply that at SPS and RHIC energies the equilibrium cannot be established in a purely hadronic medium and that is the phase transition which drives the particles densities and ensures chemical equilibrium.

In \[18\] it is further shown that many body collisions become important close to \( T_c \) and provide a mechanism for rapid equilibration. Because of the strong density increase near the QCD phase transition such multi-particle collisions provide a natural explanation for the observation of chemical equilibration at RHIC energies and lead to \( T_{ch}=T_c \) within an accuracy of a few MeV. Any scenario with \( T_{ch} \) substantially smaller than \( T_c \) would require that either multi-particle interactions dominate even much below \( T_c \) or that the two-particle cross sections are larger than in the vacuum by a high factor. Both of the latter hypotheses seem unlikely in view of the rapid density decrease in the hadronic phase of the expanding fireball. The critical temperature determined from RHIC for \( T_{ch} \approx T_c \) coincides well with recent lattice estimates \[19\] for \( \mu = 0 \). The same arguments as discussed here for RHIC energy also hold for SPS energies: it is likely that also there the phase transition drives the particle densities and insures chemical equilibration.

![Figure 3](image.png)

**Figure 3.** The \( K^+/\pi^+ \) ratio from NA49 \[25\] and thermal model predictions from \[27\]. The dashed and solid lines correspond to calculations without and with account of the resonance widths.

It was alternatively proposed \[20, 22, 21\] that the observed hadron abundances arise from a direct production of strange (and non-strange) particles by hadronization. How this happens
microscopically is unclear. To escape the above argument that \(T_{ch}=T_c\) one would have to argue that the particle yields are established without hadronic rescattering. This is unlikely since the abundances are determined by hadronic properties (masses) with high precision. Second, one may question if the “chemical temperature” extracted from the abundances is a universal temperature which also governs the local kinetic aspects and can be associated with the critical temperature of a phase transition in equilibrium. Indeed, in a prethermalization process, different equilibrium properties are realized at different time scales. Nevertheless, all experience shows that kinetic equilibration occurs before chemical equilibration. It seems hard to imagine that chemical equilibrium abundances are realized at a time when the kinematic distributions are not yet close to their equilibrium values.

![Energy dependence of particle ratios involving strange baryons compared to thermal model calculations of [27].](image)

**Figure 4.** Energy dependence of particle ratios involving strange baryons compared to thermal model calculations of [27].

The chemical equilibrium curve and the QCD phase boundary as obtained from lattice QCD calculations begin to differ for baryo-chemical potential values of \(\mu > 400\) MeV. Despite that multi-strange baryons are produced with yields very close to what is obtained in a full chemical equilibration scenario (see below). This could be an indication for new, as yet unidentified equilibration processes, different from those advocated in [18] and also incompatible with the “phase space filling” scenario through hadronization put forward by [20, 21, 22], in a dense, baryon-rich medium. Considering the discussion above, a rather radical but appealing possibility is that the chemical freeze-out curve defines the phase boundary also at large \(\mu\) values up to \(\mu \approx 600\) MeV. We note in this context that the chemical freeze-out points determined from measurements at SIS energy should still be considered with caution as no multi-strange baryons have been measured there.

The relatively smooth energy dependence of the above discussed thermal parameters is to be contrasted with recent observation by the NA49 collaboration of an anomaly in the \(K^+/\pi^+\) ratio
near $\sqrt{s_{NN}} = 8$ GeV. These results look rather striking, and indeed, the narrowness of the observed structure is missed by the thermal model predictions, as is visible in Fig. 3.

We note, however, that the anomaly seems to be confined to ratios involving light mesons. For strange baryons, the situation is quite different, as is demonstrated in Fig. 4. Here, the observed energy dependence is very well reproduced by the calculations and no anomaly is visible.

The situation is even more puzzling considering that the energy averaging inherent in ultra-relativistic nucleus-nucleus collisions leads to a characteristic smearing of all possible intrinsic structures. The effect can be estimated using simple geometrical arguments and is of the order 10% of the cm. energy per nucleon at SPS energy. The corresponding width is very close to the width of the structure observed by the NA49 collaboration and would imply that the strength of the intrinsic structure is even much larger than visible in Fig. 3. Further research is necessary to shed light on this puzzle.

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