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Hadronization conditions in relativistic nuclear collisions and the QCD pseudo-critical line

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ABSTRACT

We compare the reconstructed hadronization conditions in relativistic nuclear collisions in the nucleon–nucleon centre-of-mass energy range 4.7–2760 GeV in terms of temperature and baryon-chemical potential with lattice QCD calculations, by using hadronic multiplicities. We obtain hadronization temperatures and baryon chemical potentials with a fit to measured multiplicities by correcting for the effect of post-hadronization rescattering. The post-hadronization modification factors are calculated by means of a coupled hydrodynamical-transport model simulation under the same conditions of approximate isothermal and isochemical decoupling as assumed in the statistical hadronization model fits to the data. The fit quality is considerably better than without rescattering corrections, as already found in previous work. The curvature of the obtained "true" hadronization pseudo-critical line κ is found to be 0.0048 ± 0.0026, in agreement with lattice QCD estimates; the pseudo-critical temperature at vanishing μ_B is found to be 164.3 ± 1.8 MeV.

1. Introduction

It is the goal of Quantum Chromo-Dynamics (QCD) thermodynamics to study the phase diagram of strongly interacting matter. Its most prominent feature, the transition line between hadrons and partons, in the plane spanned by the baryon-chemical potential μ_B and the temperature T, is located in the non-perturbative sector of QCD. Here, the theory can be solved on the lattice and has recently led to calculations of the curvature of the parton–hadron boundary line [1–8]. This line can also be studied experimentally, in relativistic collisions of heavy nuclei, where apparently local thermodynamical equilibrium is achieved at a temperature well above the (pseudo-)critical QCD temperature T_c. Expansion and cooling then take the system down to the phase boundary where hadronization occurs. We have lately demonstrated [9–11] that post-hadronization inelastic rescattering, chiefly baryon–antibaryons annihilation, is an important feature of the process, which drives the system slightly out of equilibrium from the primordial hadronization equilibrium, implying an actual distinction between hadronization and chemical freeze-out. This rescattering stage is taken into account in state-of-the art simulations of the QGP expansion [12–14], where the local equilibrium particle distribution (through the so-called Cooper–Frye formula) at some critical values of T and μ_B is used to generate hadrons and resonances which subsequently undergo collisions and decay. By calculating the modification of the multiplicities brought about by the rescattering stage – the so-called afterburning – it is possible to reconstruct the hadronization point by means of a fit to the multiplicities in the framework of the Statistical Hadronization Model (SHM). Strictly speaking, this method allows to pin down the *latest chemical equilibrium point* [11] henceforth denoted as LCEP – i.e. the point when the primordial chemical equilibrium starts being distorted by the afterburning. As equilibrium is an intrinsic feature of hadronization [15–17] – as shown by the analysis of elementary collisions – most likely LCEP coincides with hadronization itself, as the maintaining of full chemical equilibrium in a rapidly expanding hadronic system, for the time needed to produce a measurable temperature shift, is highly unlikely.

As the primordial system temperature (baryon-chemical potential) shifts upward (downward) with increasing collision energy, an ascending sequence of experimental energies can, thus, map a sequence of LCEPs or hadronization points along the QCD transition line. This was the main point of ref. [10] where we showed that,

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indeed, the reconstructed LCEPs seem to follow the extrapolated lattice QCD pseudo-critical line in the (μ_B, T) plane as determined in, e.g., ref. [3]. The agreement between lattice QCD calculations and the reconstructed hadronization points in relativistic heavy ion collisions seem to imply that, in the examined energy range ($\sqrt{s}_{\rm NN} > 7$ GeV), the pseudo-critical line has indeed been crossed, and, thus, those energies lie above the so-called "onset of deconfinement" [18].

This conclusion is less straightforward than it may seem at a glance because, as has been mentioned, hadron formation is evidently a universal statistical process [15–17] in all kinds of collisions at the same hadronization temperature, with a difference in the strangeness sector, whose phase space appears to be only partially filled in elementary collisions [19–23].[1] Indeed, even if the strangeness phase space was fully saturated in elementary collisions, if hadron production process in a nuclear collision was fully consistent with a picture of subsequent and independent elementary hadronic reactions, strange particle production would be strongly suppressed by the exact strangeness conservation over the typical small volumes of an elementary collision (canonical suppression) and subsequent hadronic inelastic collisions would not be able to raise multi-strange particle abundance to the measured one, as it is shown by transport calculations [24–26]. Hence, the observation of a strange particle production in agreement with the prediction of the SHM for a coherent, large volume, and the agreement between lattice QCD extrapolations of the pseudo-critical line and the reconstructed hadronization point is a strong evidence that the pseudo-critical line has been overcome. However, this must cease to happen at some sufficiently low centre-of-mass energy, implying the failure of at least one of the above conditions. Estimates remain uncertain at present, pointing to a region between 4 and 8 GeV.

In this paper, we reexamine the hadronization conditions in relativistic heavy ion collisions over the energy range from low SPS (7.6 GeV) to LHC (2.76 TeV) by using hadronic multiplicities. We also include the highest AGS energy point at $\sqrt{s}_{\rm NN} = 4.5$ GeV to probe the aforementioned deconfinement conditions further down in energy. For this purpose, we take advantage of an improved initialization of the afterburning process by enforcing a particle generation stage – or hydrodynamical decoupling – in UrQMD [27–30] at fixed values of energy density corresponding to mean temperatures and chemical potentials equals to those determined in ref. [10] and show how this leads to a further remarkable improvement of the fit quality compared to the plain statistical model fits [10,11,31]. Finally, we compare the resulting curvature of the LCEP-hadronization curve in the (μ_B, T) plane with the predictions of lattice QCD, reporting a good agreement.

2. Afterburning and modification factors

As has been mentioned, we studied the effect of post-hadronization rescattering on hadron multiplicities and on the associated SHM fits in previous publications [9–11] employing a hybrid model [34,35] with a hydrodynamic expansion of the QCD plasma terminated at a predefined point where local equilibrium particle generation is assumed (hadronization), followed by a hadronic rescattering stage modelled by UrQMD [29] (afterburning). For the fluid dynamical simulation we employed an equation of state which follows from a so-called "combined hadron-quark model". It is based on a chiral hadronic model which provides a satisfactory description of nuclear matter properties. The quark phase is introduced as a PNJL type model. The transition from the hadronic to the quark phase occurs at about $T_c \approx 165$ MeV for $\mu_B = 0$, as a smooth crossover as shown in [32].

Table 1
Energy densities used to implement hydrodynamic decoupling or Cooper–Frye particlization, at the different collision energies. Also quoted are the corresponding mean temperatures and baryon-chemical potentials.

$\sqrt{s}_{\rm NN}$ (GeV)	Energy density (MeV/fm^3)	$T_{\rm CF}$ (MeV)	$\mu_{B\,CF}$ (MeV)
4.75	508	135	563
7.6	435	155	426
8.7	435	161	376
17.3	435	163	250
2760	362	165	0

For each hadronic species a so-called modification factor is extracted which is defined as the ratio between the final multiplicity after the actual chemical (and kinetic) freeze-out (which is now species-dependent) and its value without afterburning (at hadronization):

$$f_j = \frac{n_j}{n_j^{(0)}} \tag{1}$$

The modification factors are then used as additional multiplicative factors to the theoretical equilibrium multiplicity yields in the SHM fit, ready to be compared to the data. Note that in the calculation of the modification factors, all weak decays are turned off, but all strong and EM decays are turned on; this limits the data analysis to measurements of multiplicities corrected for the weak decay feed-down.

In our previous studies, the hydrodynamic decoupling procedure was inspired by the so-called "inside–outside cascade" mechanism: the transition from the fluid dynamical phase to the hadronic transport part occurs in successive transverse slices, of thickness 0.2 fm, whenever all fluid cells of that slice fall below a critical energy density, that is six times the nuclear ground state density $\epsilon \approx 850$ MeV/fm^3. In fact, in the present investigation, we have implemented an approximate isothermal termination of the hydrodynamical stage at some pre-established temperature $T_{\rm CF}$ (the subscript CF stands for Cooper–Frye). This is certainly in much better accordance with the underlying picture of a statistical hadronization as well as with the previously discussed concept of LCEP, which is determined at a fixed value of the proper temperature. For the decoupling, the hypersurface is defined by a fixed energy density – at LHC energy – of approximately 0.360 GeV/fm^3 which corresponds to a mean hadronization temperature close to 165 MeV at zero baryon-chemical potential (for the lower energies, see Table 1). The cell-to-cell temperature and chemical potential fluctuations corresponding to such a hydrodynamic decoupling procedure, at some given collision energy, are small. For instance, the dispersion of the temperature at LHC energy is $\sim$1.5 MeV, the dispersion of the chemical potential at the SPS energy is of the order of 10 MeV; these values are comparable or smaller than the parameter fit errors (see Table 5).

The UrQMD model employs the hypersurface finder outlined in ref. [30], which is used in the Cooper–Frye prescription and sampled to produce hadrons in accordance with global conservation of charge strangeness baryon number and the total energy.

It should be pointed out that the calculated modification factors do depend on the chosen temperature $T_{\rm CF}$ ending the hydrodynamical expansion [33]. Ideally, this should coincide with the actual $T_{\rm LCEP}$ at each energy, which is *a priori* unknown, except for a reasonable lower bound set by the chemical freeze-out temperature as determined in the traditional, plain, SHM fit. One may then

[1] It is worth pointing out here that the strangeness undersaturation is still observed in nuclear collisions at high energy but it can be accounted for by residual nucleon–nucleon collisions nearby the outer edge of the nuclear overlapping region, see [15] and references therein.