Physics Letters B 726 (2013) 422–426

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Phase evolution and freeze-out within alternative scenarios of relativistic heavy-ion collisions

Yu.B. Ivanov

Kurchatov Institute, Moscow RU-123182, Russia

ARTICLE INFO

Article history:
Received 11 June 2013
Received in revised form 12 August 2013
Accepted 13 August 2013
Available online 22 August 2013
Editor: J.-P. Blaizot

Keywords:
Relativistic heavy-ion collisions
Phase evolution
Hydrodynamics
Freeze-out
Deconfinement

ABSTRACT

Global evolution of the matter in relativistic collisions of heavy nuclei and the resulting global freeze-out parameters are analyzed in a wide range of incident energies 2.7 GeV $\leqslant \sqrt{s_{NN}} \leqslant$ 39 GeV. The analysis is performed within the three-fluid model employing three different equations of state (EoS): a purely hadronic EoS, an EoS with the first-order phase transition and that with a smooth crossover transition. Global freeze-out parameters deduced from experimental data within the statistical model are well reproduced within the crossover scenario. The 1st-order-transition scenario is slightly less successful. The worst reproduction is found within the purely hadronic scenario. These findings make a link between the EoS and results of the statistical model, and indicate that deconfinement onset occurs at $\sqrt{s_{NN}} \gtrsim 5$ GeV.

1. Introduction

Extensive simulations of relativistic heavy-ion collisions were performed within a model of the three-fluid dynamics (3FD) [1] employing three different equations of state (EoS): a purely hadronic EoS [2] (hadr. EoS), which was used in the major part of the 3FD simulations so far [1,3], and two versions of EoS involving the deconfinement transition [4]. These two versions are an EoS with the first-order phase transition and that with a smooth crossover transition. These simulations cover the energy range from 2.7 GeV to 39 GeV in terms of center-of-mass energy, $\sqrt{s_{NN}}$. Details of the calculations are described in Ref. [5] dedicated to analysis of the baryon stopping. With these EoS's, onset of the deconfinement transition occurs at top AGS energies, i.e. $\sqrt{s_{NN}} \gtrsim 5$ GeV, as shown in Refs. [5,6]. The results [5–8] obtained so far indicate preference of deconfinement-transition scenarios in reproducing the available experimental data.

In particular, it was found [7] that the hadronic scenario fails to reproduce experimental yields of antibaryons (strange and non-strange), starting already from lower SPS energies, i.e. $\sqrt{s_{NN}} \geqslant$ 6.4 GeV, and yields of all other species at energies above the top SPS one, i.e. $\sqrt{s_{NN}} > 17.3$ GeV, while the deconfinement-transition scenarios reasonably agree (to a various extent) with all the data. It is naturally to search for a reason of this fact in differences of the final freeze-out states produced by different scenarios. Indeed, the statistical model (SM) needs only two parameters, temperature (T) and baryon chemical potential (μ_B), to describe ratios of (total and mid-rapidity) yields of all the produced species [9–17]. If the 3FD evolution drives the system to a final freeze-out state characterized by proper T and μ_B (somehow averaged over the system), then the experimental hadron yields are reproduced. Of course, the 3FD freeze-out state is characterized by 3D fields of T and μ_B. The (T,μ_B) point in question is formed by values around which these fields are centered.

In fact, the same procedure of the freeze-out with the same freeze-out energy density [1,18,19] was used in all considered scenarios of nuclear collisions. Nevertheless, the final states in different scenarios turn out to be different because the phase evolution of the system is determined by the specific EoS. Of course, these final states are also characterized by fields of collective flows rather than only the temperature and baryon chemical potential, and hence the 3FD model pretends to describe not only hadron yields. However, for the particular case of the hadron yields the position of the final freeze-out state in the (T,μ_B) phase space is of prime importance.

Therefore, in this Letter I analyze the 3FD final freeze-out state in terms of its position in the (T,μ_B) phase space. This analysis extends to relativistic heavy-ion collisions in the energy range from 2.7 GeV to 39 GeV in terms of $\sqrt{s_{NN}}$. This domain covers the energy range of the beam-energy scan program at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), low-energy-scan program at Super Proton Synchrotron (SPS) at CERN and the Alternating Gradient Synchrotron (AGS) at BNL, as

E-mail address: Y.Ivanov@gsi.de.

0370-2693/$ – see front matter
http://dx.doi.org/10.1016/j.physletb.2013.08.031

well as newly constructed Facility for Antiproton and Ion Research (FAIR) in Darmstadt and the Nuclotron-based Ion Collider Facility (NICA) in Dubna.

2. Freeze-out in 3FD model

The 3-fluid approximation is a minimal way to simulate the finite stopping power at high incident energies. Within the 3-fluid approximation a generally nonequilibrium distribution of baryon-rich matter is simulated by counter-streaming baryon-rich fluids initially associated with constituent nucleons of the projectile (p) and target (t) nuclei. In addition, newly produced particles, populating the mid-rapidity region, are associated with a fireball (f) fluid. Each of these fluids is governed by conventional hydrodynamic equations which contain interaction terms in their right-hand sides. These interaction terms describe mutual friction of the fluids and production of the fireball fluid. The friction between fluids was fitted to reproduce the stopping power observed in proton rapidity distributions for each EoS, as it is described in Ref. [5] in detail.

A conventional way of applying the fluid dynamics to heavy-ion collisions at RHIC and LHC energies is to prepare the initial state for the hydrodynamics by means of various kinetic codes, see, e.g., Refs. [20–23]. Contrary to these approaches, the 3FD model treats the collision process from the very beginning, i.e. the stage of cold nuclei, up to freeze-out within the fluid dynamics. Therefore, any tuning of initial conditions is impossible within the 3FD model.

The freeze-out is performed accordingly to the procedure described in Ref. [1] and in more detail in Refs. [18,19]. This is a modified Milekhin version of the freeze-out that possesses exact conservation of the energy, momentum and baryon number. Contrary to the conventional Cooper–Frye approach [24], the modified Milekhin method has no problem associated with negative contributions to particle spectra. This method of freeze-out can be called dynamical, since the freeze-out process here is integrated into fluid dynamics. This kind of freeze-out is similar to the model of "continuous emission" proposed in Ref. [25]. There the particle emission occurs from a surface layer of the mean-free-path width. In the 3FD case the physical pattern is similar, only the mean free path is shrunk to zero.

The freeze-out criterion is $\varepsilon < \varepsilon_{\rm frz}$, where ε is the total energy density of all three fluids in the proper reference frame, where the composed matter is at rest. The freeze-out energy density $\varepsilon_{\rm frz} = 0.4$ GeV/fm^3 was chosen mostly on the condition of the best reproduction of secondary particles yields (more precisely, mid-rapidity pion densities) for all considered scenarios. However, the freeze-out front is not defined just "geometrically" on the condition of the freeze-out criterion met but rather is a subject the fluid evolution. It competes with the fluid flow and not always reaches the place where the freeze-out criterion is first met. Therefore, $\varepsilon_{\rm frz}$ can be called a "trigger" value of the freeze-out energy density, whereas the actual thermodynamical parameters of the frozen out matter are jointly determined by this "trigger" value and the fluid dynamics and thus depend on the EoS.

Thus, the freeze-out procedure fixes a single parameter of the matter, i.e. the total energy density, that is additionally varied due to interference with the fluid dynamics. This results in a whole field of temperatures ($T_{\rm frz}$) and baryon chemical potentials ($\mu_{\rm frz}$) of the frozen-out matter in the system. To quantify these fields, it is useful to consider distributions of various quantities over $T_{\rm frz}$ and $\mu_{\rm frz}$. In Fig. 1 this is done at the example of the baryon-charge distribution over the temperature and baryon chemical potential of the frozen-out baryon-rich fluids in central collisions at two incident energies, $\sqrt{s_{NN}} = 4.9$ and 17.3 GeV, calculated in the crossover scenario. As seen, the regions of $T_{\rm frz}$ and $\mu_{\rm frz}$ are nevertheless well localized rather than extend to the whole available range. It should be mentioned that the contribution of rather cold spectator parts of the evolving system is excluded in Fig. 1. A weak noise at high $\mu_{\rm frz}$ illustrates the accuracy of this spectator cut-off.

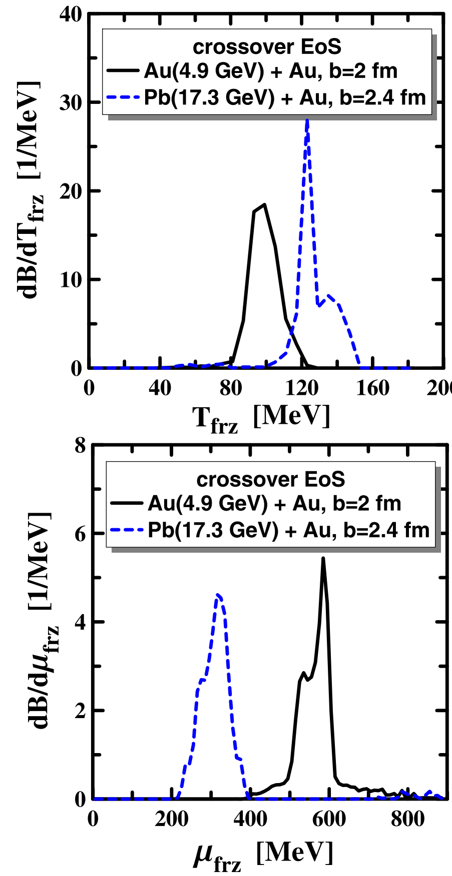

Fig. 1. Distributions of the frozen-out baryon charge over temperature (upper panel) and baryon chemical potential (lower panel) of the frozen-out matter in central collisions of Au + Au at 4.9 GeV energies ($b = 2$ fm) and Pb + Pb at 17.3 GeV ($b = 2.4$ fm) calculated with the crossover EoS.

As has been already mentioned, the model parameters (the friction, the freeze-out energy density and the formation time of the fireball fluid) were fitted to reproduce the (net)proton rapidity distributions and mid-rapidity pion densities basically at three incident energies $\sqrt{s_{NN}} = 4.9$, 17.3 and 62.4 GeV.[1] Though, even with these parameters it was impossible to simultaneously fit all the desired quantities within the hadronic scenario [5,7]. By means of the above procedure all the model parameters turn out to be determined. All other observables, except for those mentioned above, are subjects for predictions of the 3FD model. It should be mentioned that within the deconfinement scenarios the friction in the hadronic phase is not a varied quantity but is rather taken from a microscopic estimate of Ref. [26]. In fact, there is no need to vary it because simulations with the microscopic estimate quite accurately reproduce the data at lower AGS energies. In principle, the freeze-out energy density could be fitted separately at each incident energy. However, this gives only a tiny improvement of the data reproduction. Therefore, the freeze-out energy density is kept incident-energy independent.

[1] The results for the energy of 62.4 GeV should be taken with care, because they are not quite accurate. An accurate computation requires unreasonably high memory and CPU time.