Phase Evolution and Freeze-out within Alternative Scenarios of Relativistic Heavy-Ion Collisions

Yu. B. Ivanov

Kurchatov Institute, Moscow RU-123182, Russia

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 $\leq \sqrt{s_{\text{NN}}} \leq 39$ 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 $\sqrt{s_{\text{NN}}} \gtrsim 5$ GeV.

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I. INTRODUCTION

Extensive simulations of relativistic heavy-ion collisions were performed within a model of the three-fluid dynamics (3FD) employing three different equations of state (EoS): a purely hadronic EoS (hadr. EoS), which was used in the major part of the 3FD simulations so far, and two versions of EoS involving the deconfinement transition. 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, $\sqrt{s_{\text{NN}}}$. Details of the calculations are described in Ref. [3] dedicated to analysis of the baryon stopping. With these EoS’s, onset of the deconfinement transition occurs at top AGS energies, i.e. $\sqrt{s_{\text{NN}}} \gtrsim 5$ GeV, as shown in Refs. [1, 2]. The results 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 nonstrange), starting already from lower SPS energies, i.e. $\sqrt{s_{\text{NN}}} \gtrsim 6.4$ GeV, and yields of all other species at energies above the top SPS one, i.e. $\sqrt{s_{\text{NN}}} \approx 17.3$ 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 ($\mu_B$), to describe ratios of (total and midrapidity) yields of all the produced species [6,17]. If the 3FD evolution drives the system to a final freeze-out state characterized by proper $T$ and $\mu_B$ (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 $\mu_B$. The $(T, \mu_B)$ 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, 12, 13] 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 $(T, \mu_B)$ phase space is of prime importance.

Therefore, in this paper I analyze the 3FD final freeze-out state in terms of its position in the $(T, \mu_B)$ phase space. This analysis extends to relativistic heavy-ion collisions in the energy range from 2.7 GeV to 39 GeV in terms of $\sqrt{s_{\text{NN}}}$. 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 well as newly constructed Facility for Antiproton and Ion Research (FAIR) in Darmstadt and the Nuclotron-based Ion Collider Facility (NICA) in Dubna.

II. 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. [3] 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. [24–23]. 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. [23]. 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 \( \varepsilon < \varepsilon_{\text{frz}} \), where \( \varepsilon \) 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 \( \varepsilon_{\text{frz}} = 0.4 \text{ GeV/fm}^3 \) 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, \( \varepsilon_{\text{frz}} \) 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 \( T_{\text{frz}} \) and baryon chemical potentials \( \mu_{\text{frz}} \) of the frozen-out matter in the system. To quantify these fields, it is useful to consider distributions of various quantities over \( T_{\text{frz}} \) and \( \mu_{\text{frz}} \). 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 \( T_{\text{frz}} \) and \( \mu_{\text{frz}} \) 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 \( \mu_{\text{frz}} \) illustrates the accuracy of this spectator cutoff.

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\(^1\) GeV. Though, even with these pa-

\( ^1 \) The results for the energy of 62.4 GeV should be taken with care, because they are not quite accurate. An accurate computation
rameters it was impossible to simultaneously fit all the desired quantities within the hadronic scenario [3, 4]. By means of the above procedure all the model parameters turn out to be determined. All other observables, except for those above mentioned, 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. [24]. 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.

The phase trajectories presented below were calculated precisely with this parameter set, without any additional tuning. The agreement of the 3FD predictions with the SM freeze-out points, discussed below, could probably be improved by means of the above-mentioned incident-energy dependent tuning of the freeze-out energy density. However, this has not been done.

### III. PHASE EVOLUTION AND EFFECTIVE FREEZE-OUT

In the statistical model, mid-rapidity hadron densities are analyzed. At high incident energies, longitudinally central and peripheral regions (in space) are also well separated in the rapidity space. Therefore, only the (spatially) central part the final freeze-out state predominantly contributes to the mid-rapidity density. Thus, it is reasonable to consider evolutions of the matter in the central region of the fireball, as it was done in Ref. [27]. Similarly to that it has been done in Ref. [27], it is useful to study trajectories of the matter in the central box placed around the origin $r = (0, 0, 0)$ in the frame of equal velocities of colliding nuclei: $|x| \leq 2$ fm, $|y| \leq 2$ fm and $|z| \leq \gamma_{cm} 2$ fm, where $\gamma_{cm}$ is Lorentz factor associated with the initial nuclear motion in the c.m. frame. The size of the box was chosen to be large enough that the amount of matter in it can be representative to conclude on properties of the inner part of the system and to be small enough to consider the matter in it as a homogeneous medium. Contrary to Ref. [27], I consider these trajectories in terms of temperature ($T$) and baryon chemical potential ($\mu_B$). Only expansion stages of the fireball evolution are considered because at these stages the system is closer to equilibrium than at early stages and hence the above thermodynamic quantities are better defined.

Definition of these thermodynamic variables in terms of the 3FD model [1] needs explanations. At the expansion stage the baryon-rich fluids in the central region (i.e. those leading particles which exercised strong stopping) are already unified, i.e. mutually stopped and equilibrated, while the baryon-free fluid (i.e. the matter produced and predominantly occupying the central region) is not still equilibrated with the baryon-rich fluids. To calculate effective thermodynamic parameters of this combined fireball consisting of unified-baryon-rich and baryon-free fluids, we have to proceed from its total energy density and baryon density. When the two baryon-rich fluids are unified, the calculation of the total baryon density is straightforward because the net-baryon charge of the baryon-free fluid is zero. The problem occurs with the total energy density. In general, the unified baryon-rich fluid and the baryon-free one have different local hydro velocities. Even if the total energy density is calculated in a local common rest frame of these fluids, a part of collective energy associated with the relative hydrodynamic motion of these fluids unavoidably gets included in this energy density. This is highly undesirable. The only region, where we can safely sum the proper energy densities of two discussed fluids, is the central box discussed above. The hydro velocities of the two fluids are equal and amount to zero (in the c.m. frame of colliding nuclei) for the symmetry reasons.

Thus, because of the dominant contribution to the mid-rapidity region at high incident energies and the possibility of a consistent definition of $(T, \mu_B)$ variables of the combined matter, the phase-space trajectories of the matter contained in the central box are studied. Only central collisions of heavy nuclei are considered: Au+Au collisions at impact parameter $b = 2$ fm for AGS and RHIC energies, and Pb+Pb collisions at $b = 2.4$ fm for SPS energies.

In Fig. 2 the phase diagrams for the the 2-phase and crossover EoS's in terms of the temperature and the baryon chemical potential, and the freeze-out border deduced from experimental data within the statistical model [17] are displayed. This border and points on it corresponding to specific incident energies of central collisions of heavy nuclei are plotted accordingly to the parametrization of the the statistical-model results given in Ref. [17].

In the case of the crossover EoS, only the region of the mixed phase between the borders of the QGP fraction of $W_{QGP} = 0.1$ and $W_{QGP} = 0.5$ is displayed, because in fact the hadronic fraction survives up to very high temperatures and chemical potentials. In this respect, this version of the crossover EoS certainly contradicts results of the lattice QCD calculations, where a fast crossover, at least at zero chemical potential, was found [28]. Therefore, a true EoS is somewhere in between the crossover and 2-phase EoS's of Ref. [4].

Some examples of trajectories of the matter in the central box are also presented in Fig. 2. Only expansion stages of the fireball evolution are displayed. The hadronic trajectories are very close the crossover ones at
\[ \sqrt{S_{NN}} \leq 6.4 \text{ GeV} \ (E_{lab} \leq 20\text{ A GeV}) \]. Therefore, these are not displayed for the sake of clarity of the figure. As seen, only comparatively low chemical-potential part of the phase diagram is explored by nuclear collisions. At high incident energies, \[ \sqrt{S_{NN}} \geq 6.4 \text{ GeV} \ (E_{lab} \geq 20\text{ A GeV}) \], the trajectories quite closely hit the corresponding freeze-out points deduced within the statistical model.\[ ^{[17]} \]. The exception is the hadronic trajectory at \[ \sqrt{S_{NN}} = 17.3 \text{ GeV} \] (\[ E_{lab} = 158\text{ A GeV} \]) that ends near the freeze-out border but far from the corresponding point. As we will see below, this is a general failure of the hadronic EoS.

Though the volume of the central box is essentially smaller than that of the whole system, it is still not always negligible. At \[ \sqrt{S_{NN}} < 9 \text{ GeV} \], the freeze-out in the central box occurs practically immediately. With the energy rise above 9 GeV, this freeze-out time span becomes nonzero. At \[ \sqrt{S_{NN}} > 12 \text{ GeV} \], it is of the order of 1 fm/c in the c.m. frame of the colliding nuclei. Therefore, the fact that the deconfinement-transition trajectories slightly overshoot the SM freeze-out border at \[ \sqrt{S_{NN}} = 17.3 \text{ GeV} \] is natural because the freeze-out is not immediate.

The central-box trajectories, corresponding to energies 2.7 and 3.3 GeV, end sufficiently far from the freeze-out border and from the corresponding freeze-out points. The reason is that at low energies all spatial parts of the fireball contributes to the mid-rapidity region rather than the central part only. Fortunately, at low incident energies the baryon-free fluid is underdeveloped. Indeed, this fluid contributes less than 10% to the midrapidity value of pions at \[ \sqrt{S_{NN}} \leq 3.9 \text{ GeV} \] (\[ E_{lab} \leq 6.4 \text{ GeV} \]) for all considered scenarios, whereas at \[ \sqrt{S_{NN}} \geq 6.4 \text{ GeV} \] (\[ E_{lab} \geq 20\text{ A GeV} \]) this contribution already amounts to greater than 25%. Therefore, at \[ \sqrt{S_{NN}} \leq 4 \text{ GeV} \] it is possible to neglect the contribution of the baryon-free fluid that solves the problem of the local definition of the \((T, \mu_B)\) variables in any point of the system discussed above. Thus, it is possible to consider trajectories of the global evolution of the system formed from \((T, \mu_B)\) variables averaged over the whole system with the weight of the local baryon density of unified baryon fluids. This is done below.

In Fig. 3 it is shown a zoomed part of the 1st-order phase transition, which is explored by nuclear collisions. The freeze-out points \[ ^{[17]} \] correspond to displayed central nuclear collisions. For collisions at high incident energies the central-box trajectories are displayed, whereas for lower energies, the trajectories of the global evolution. The energy of \( \approx 5 \text{ GeV} \) is on the border between high and low ones. Therefore, both trajectories are presented
for this energy. These trajectories are very different. The reason for this is the fact that the produced excited system is highly nonhomogenous. Peripheral regions of the produced fireball are essentially less compressed and excited. As a result, the form of the trajectory strongly depends on a region over which the averaging runs. The starting point of the trajectory for \( \sqrt{s_{NN}} = 39 \) GeV is beyond the frame of Fig. 3, it is located at \( T \approx 600 \) MeV. This fact is indicated by the arrow at the top end of this trajectory (it is similarly done in Fig. 4). Symbols mark the time intervals along the trajectory, they are spaced 1 fm/c apart. The evolution proceeds from top to bottom of a trajectory.

In Fig. 3 a wiggle characteristic for the 1st-order phase transition is seen on the trajectories in the region of the transition. The length of these wiggles indicate that the central-box matter spends a considerable part of the expansion time (\( \sim 25\% \)) in the mixed phase. The trajectories, the central-box ones at high energies and the global ones at low energies, end not far from the corresponding phenomenological freeze-out points. The agreement is good while not perfect.

In Fig. 4 a zoomed part of the crossover transition with the matter-evolution trajectories is presented. Here the trajectories much closer hit the corresponding phenomenological freeze-out points than in the case of the first-order-transition scenario. Though, this fact does not significantly affect the reproduction of mid-rapidity densities of various species.

Fig. 5 presents the phase evolution of the matter within the hadronic scenario. The wiggle in the hadronic trajectory for \( \sqrt{s_{NN}} = 17.3 \) GeV results from the delayed production of the baryon-free fluid (i.e. newly produced particles near the mid-rapidity) \( \overline{\mu}_B \). This time delay in the hadronic scenario amounts to 2 fm/c. Therefore, the baryon-free fluid starts to contribute to the total energy density and hence to the effective temperature of the matter only after this time span. Naturally it raises the temperature. When the baryon-free fluid got completely formed, the trajectory returns to its natural behavior. Such a wiggle is absent on the trajectories related to 2-phase and crossover EoS’s because in those cases the delay time amounts to 0.17 fm/c and hence the formation of the baryon-free fluid gets completed already at the compression stage of the collision. The delay time for each scenario was chosen proceeding from the best reproduction of available experimental data. Notice that at high incident energies, when the baryon-free fluid is already well developed, the delay time essentially affects the baryon stopping, at \( \sqrt{s_{NN}} = 39 \) GeV it even becomes decisive. The earlier the baryon-free fluid is produced, the earlier it starts to interact with baryonic fluids and hence the stronger baryon stopping provides.

In the case of the hadronic scenario the agreement with the corresponding phenomenological freeze-out points is the worst among the considered scenarios even at low incident energies, where a pure hadronic dynamics takes place. Probably the latter is a byproduct of enhancement the inter-fluid friction in the hadronic phase \( \overline{\mu}_B \) as compared with its microscopic estimate of Ref. \( \overline{\mu}_B \). This enhancement has been applied in order to reproduce a major part (however not all \( \overline{\mu}_B \)) of observables up to the energy of 17.3 GeV This modification of the friction spoils the agreement in the purely hadronic domain. The advantage of deconfinement-transition scenarios is that they do not require any modification of the microscopic
friction in the hadronic phase.

IV. SUMMARY

Evolution of the matter in relativistic collisions of heavy nuclei and the resulting freeze-out parameters were analyzed in the incident energy range of 2.7 GeV ≤ √sNN ≤ 39 GeV. These simulations were performed within the 3FD model \(^1\) employing three different equations of state: a purely hadronic EoS \(^2\), and two versions of EoS involving the deconfinement transition \(^3\), i.e. an EoS with the first-order phase transition and that with a smooth crossover transition. Details of these calculations are described in Ref. \(^3\).

It is found that the freeze-out parameters deduced from experimental data within the statistical model \(^3\) are well reproduced within the crossover scenario. The 1st-order-transition scenario turns out to be slightly less successful. In the case of the hadronic scenario the agreement with the corresponding phenomenological freeze-out points is the worst among the considered scenarios even at low incident energies, where a pure hadronic dynamics takes place. Probably the latter is a byproduct of noticeable enhancement the inter-fluid friction in the hadronic phase \(^1\) as compared with its microscopic estimate of Ref. \(^2\), that was introduced in order to reproduce a major part (however not all \(^7\)) of observables up to the energy of 17.3 GeV.

In particular, these results explain why the hadronic scenario fails to reproduce experimental yields of antibaryons (strange and nonstrange), starting already from lower SPS energies, i.e. √sNN ≤ 6.4 GeV, and yields of all other species at energies above the top SPS one, i.e. √sNN > 17.3 GeV, while the deconfinement-transition scenarios reasonably agree (to a various extent) with all the data \(^3\).

The present analysis, as well as results of Ref. \(^7\) indicates a certain preference of the deconfinement-transition EoS which predict onset of the deconfinement in central collisions of heavy nuclei at top AGS energies, i.e. √sNN ≥ 5 GeV. However, it should be mentioned that the crossover transition constructed in Ref. \(^3\) is very smooth \(^3, \(7\)). In this respect, this version of the crossover EoS certainly contradicts results of the lattice QCD calculations, where a fast crossover, at least at zero chemical potential, was found \(^28\). Therefore, for better reproduction of experimental data and phenomenological freeze-out parameters a more realistic EoS is required.

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