Particle production at energies available at the CERN Large Hadron Collider within evolutionary model

Yu. M. Sinyukov\textsuperscript{1} and V. M. Shapoval\textsuperscript{1}

\textsuperscript{1}Bogolyubov Institute for Theoretical Physics, Metrolohichna 14b, Kiev 03680 Ukraine

Abstract

The particle yields and particle number ratios in Pb+Pb collisions at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV are described within the integrated hydrokinetic model (iHKM) at the two different equations of state (EoS) for the quark-gluon matter and the two corresponding hadronization temperatures, $T = 165$ MeV and $T = 156$ MeV. The role of particle interactions at the final afterburner stage of the collision in the particle production is investigated by means of comparison of the results of full iHKM simulations with those where the annihilation and other inelastic processes (except for resonance decays) are switched off after hadronization/particlization, similarly as in the thermal models. An analysis supports the picture of continuous chemical freeze-out in the sense that the corrections to the sudden chemical freeze-out results, which arise because of the inelastic reactions at the subsequent evolution times, are noticeable and improve the description of particle number ratios. An important observation is that although the particle number ratios with switched-off inelastic reactions are quite different at different particlization temperatures which are adopted for different equations of state to reproduce experimental data, the complete iHKM calculations bring very close results in both cases.

PACS numbers: 13.85.Hd, 25.75.Gz
Keywords: lead-lead collisions, LHC, particle yield, particle number ratio, freeze-out

I. INTRODUCTION

The analysis of the particle number ratios is carried out successfully in thermal models for different energies of $A + A$ collisions, from the AGS to the LHC energies \[1–7\]. The thermal models suppose that at some hypersurface characterized by uniform temperature and baryon chemical potential, the chemical composition of the hadron matter is frozen out, and in subsequent evolution of the hadron matter the particle yield is changed only because of the resonance decays. At the LHC energies the afterburner “post-freeze-out” stage is the longest, and so there is a special interest to check the chemical freeze-out hypotheses within the dynamical models for these energies. The ALICE Collaboration has already noted \[8, 9\] that annihilation processes at the afterburner stage, which are taken into account in HKM model \[10\] noticeably improve agreement with (anti)proton spectra/yield at the LHC. The analysis of the role of inelastic processes at post-hydrodynamic stage in formation of the particle yield is continuous (see, e.g., \[11\]).

It seems that continuous chemical freeze-out as well as kinetic freeze-out is an inevitable feature of the dynamical models of $A + A$ collisions since sudden chemical freeze-out means instant transition from extremely fast chemically equilibrated expansion (presupposing a very intensive inelastic reactions) to the evolution with totally forbidden inelastic reactions. Sudden kinetic freeze-out means an instant change of hadron cross-section from a very large one (typical for near perfect hydrodynamics) to zero cross-section (free streaming particles). Such sudden transitions are not typical for realistic dynamical models\[1\]. In our very recent note \[12\] we found, using $K^*(892)$ probe, that at the LHC energies a good agreement with the experimental data for these resonances requires a relatively long kinetic freeze-out, near 5 fm/$c$ after particlization/hadronization. This is worth noting that continuous thermal freeze-out means not only successive freeze-out for different hadrons (as in, e.g., Ref. \[13\]), but continuous particle emission for each species, see new important details in Ref. \[12\].

In this study we calculate the particle number ratios in the integrated hydrokinetic model (iHKM) and compare the results with the ones obtained in thermal models. Also we calculate\[1\] Note also that neither first order phase transition, nor crossover are sudden in time in the process of system expansion.
the particle $p_T$ spectra in iHKM. We analyze the situation at different equations of state for quark-gluon and hadron matter and correspondingly, at different temperatures of the so-called chemical freeze-out.

II. MODEL DESCRIPTION

The current study is carried out within the ‘Integrated Hydrokinetic Model’ (iHKM) of relativistic nuclear collisions. This model includes the five stages of the matter evolution and observable formation in $A+A$ collisions: the initial state formation, the pre-thermal matter evolution, the hydrodynamic stage, the particlization and the hadronic cascade stages.

The initial energy-density profile in iHKM is associated with a quite early proper time, $\tau_0 \approx 0.1 \text{ fm}/c$. According to a combined method, described in [14], one presents the generally non-equilibrium boost-invariant (in the central region of rapidity) parton/gluon distribution function on the initial hypersurface $\sigma_0$: $\tau = \tau_0$ in the following factorized form

$$f(t_{\sigma_0}, r_{\sigma_0}, p) = \epsilon(b; \tau_0, r_T) f_0(p),$$

where $\epsilon(b; \tau_0, r_T)$, being the initial energy density profile, is calculated in a hybrid approach, including both wounded nucleon model and the binary collision approach. The proportion between the contributions of these two models to $\epsilon(b; \tau_0, r_T)$ is regulated by the parameter $0 \leq \alpha \leq 1$.

In iHKM simulations we obtain the distributions of numbers of wounded nucleons and binary collisions at $\tau_0$ with the help of the GLISSANDO code [15]. The weighed sum of such distributions (with the coefficients $\alpha$ and $1 - \alpha$) is then multiplied by a normalizing factor $\epsilon_0$ — the energy density at $\tau_0$ in the center of the system in central collisions. The value of $\epsilon_0$ is the main free parameter of the model, defined, together with the parameter $\alpha$, by means of fitting the observed mean charged particle multiplicity $dN_{ch}/d\eta$ dependence on centrality at given collision energy. So, both $\epsilon_0$ and $\alpha$ parameters do not depend on collision centrality. However, changing the equation of state together with the corresponding particlization temperature will require a modification of $\epsilon_0$ and $\tau_0$ parameters. They are fixed in iHKM basing on the measured multiplicity vs centrality distribution and the measured slope of the pion transverse momentum spectrum. As for the possible momentum

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2 As for the parameter $\alpha$, in the current analysis it is not changed when switching to another EoS.
anisotropy of parton/gluon initial distribution, typical for the Color-Glass-Condensate-based approaches, it is taken into account by the function $f_0(p)$ in Eq. (1) which is described in more detail in previous papers \cite{14,16}:

$$f_0(p) = g \exp \left( -\sqrt{\frac{(p \cdot U)^2 - (p \cdot V)^2}{\lambda_\perp^2 + (p \cdot V)^2}} + \frac{(p \cdot V)^2}{\lambda_\parallel^2} \right),$$

where $U^\mu = (\cosh \eta, 0, 0, \sinh \eta)$, $V^\mu = (\sinh \eta, 0, 0, \cosh \eta)$. In the rest frame of the fluid element one has $\eta = 0$, $(p \cdot U)^2 - (p \cdot V)^2 = p_\perp^2$ and $(p \cdot V)^2 = p_\parallel^2$, so that $\lambda_\parallel^2$ and $\lambda_\perp^2$ can be associated with the two effective temperatures — one along the beam axis and another along the axis, orthogonal to it. In such a case the parameter $\Lambda = \lambda_\perp^2/\lambda_\parallel^2$ defines the momentum anisotropy of the initial state.

Once we have defined the initial conditions in the form of non-thermal energy-momentum tensor, obtained from the distribution (1), we can proceed to the description of the pre-thermal matter dynamics, using the relaxation time approximation \cite{14,16,17}. This pre-thermal stage starts in iHKM at the initial time $\tau_0 \approx 0.1 \text{ fm}/c$, when the initial state is formed, and lasts till the thermalization time $\tau_{th} = 1 \text{ fm}/c$, when an approximate local thermal equilibrium is supposed to be reached by the initially non-equilibrated system.

The subsequent matter evolution is described within a relativistic viscous hydrodynamics formalism, with the relativistic current and energy-momentum tensor in the Israel-Stewart form. We neglect there the bulk viscosity and heat conductivity terms. Since at the LHC energies the baryonic chemical potential in the spatiotemporal region, where the midrapidity observables are formed, is negligibly small, we put it to be just zero. According to the iHKM results \cite{14} for identified hadron multiplicities, spectra, elliptic flow and femtoscopy data we put the minimal possible ratio of the shear viscosity coefficient to the entropy density, $\frac{\eta}{s} = \frac{1}{4\pi}$ for the quark-gluon matter. The hydrodynamic approximation is justified as long as the matter can be considered remaining close to local chemical and thermal equilibrium. But at some temperature $T_p$ both such quasi-equilibrium descriptions get destroyed, and the further system’s evolution should be described in terms of particles. A switching to such a description can be done either gradually or suddenly at $T_p$ isotherm hypersurface. In this paper we utilize the latter mode of sharp particlization, comparing the simulation results in the two cases of two different $T_p$ values.\footnote{In fact, we suppose that the particlization temperature $T_p$ coincides with the temperature when the hadronization process is (almost) completed.} The construction and treatment of the
particlization hypersurface in iHKM is realized through the Cornelius routine [18].

The last stage of system’s evolution within iHKM is a hadronic cascade stage, described with the help of UrQMD model [19]. At this stage all the particles, previously produced at the particlization stage, collide and interact with each other, that includes both elastic scatterings and inelastic processes, such as baryon-antibaryon annihilation. The unstable particles and resonance states decay (and re-combine) at this stage as well.

III. RESULTS AND DISCUSSION

In the current paper we present the results for different particle number ratios and spectra, calculated in iHKM at the two different particlization temperatures, \( T_p = 165 \) MeV and \( T_p = 156 \) MeV, with two corresponding equations of state (EoS) for quark-gluon matter — Laine-Schröder [20] and HotQCD Collaboration — “HotQCD” EoS [21]. Using the two equations of state we investigate also whether the form of EoS is significant for the description of particle number ratios in the evolutionary model with initial energy density \( \epsilon(\tau_0) \) as a free parameter. Such a study is important since the extremely high rate of the fireball expansion, much larger than in the Early Universe, would lead to modification of effective equation of state as compared to the lattice QCD calculations for static system.

The ratios are calculated for the central \((c = 0 - 10\%)\) Pb+Pb collisions at the LHC energy \( \sqrt{s_{NN}} = 2.76 \) TeV. The results on particle \( p_T \) spectra are demonstrated for the collisions with \( c = 0 - 5\% \) and serve as an additional justification of the choice of model parameters (which do not depend on centrality). The Laine-Schröder equation of state was previously used in HKM model, the predecessor of iHKM, as the lattice QCD inspired EoS, ensuring that the description of dense quark-gluon matter and its cross-over type transition to the hadron resonance gas pass without gaps in pressure and energy density. The corresponding particlization temperature \( T_p = 165 \) MeV was used in HKM calculations, that resulted in a successful simultaneous description of a variety of observables in heavy ion collision experiments at RHIC and LHC (spectra, interferometry radii, \( v_2 \) coefficients, source functions, etc. [10, 22–25]). The “HotQCD” EoS corresponds to the recent HotQCD Collaboration results on lattice QCD simulations devoted to the quark-gluon matter state description. The respective particlization temperature, \( T_p = 156 \) MeV, is in agreement with the most recent estimates of the chemical freeze-out temperature obtained in thermal model,
FIG. 1. The comparison of two equations of state for quark-gluon matter: the Laine-Schröder EoS \[20\], corresponding to the partcilation temperature \( T_p = 165 \) MeV and the HotQCD Collaboration “HotQCD” EoS \[21\], corresponding to the partcilation temperature \( T_p = 156 \) MeV.

\[ T_{ch} = 156 \pm 1.5 \text{ MeV}\] \[26\]. In Fig. 1 one can see the comparison of the two EoS on the plot in the coordinates \((\epsilon, T)\). The Laine-Schröder EoS corresponds to more rapidly growing energy density at the high temperatures.

The iHKM parameter values, used in current analysis in the case of \( T_p = 165 \) MeV, are chosen to be the same as those that have provided the optimal description of the multiple LHC bulk observables \[16\]: \( \tau_0 = 0.1 \text{ fm}/c, \tau_{th} = 1 \text{ fm}/c \), the relaxation time at the pre-thermal stage \( \tau_{rel} = 0.25 \text{ fm}/c \), \( \epsilon_0 = 680 \text{ GeV/fm}^3 \), \( \alpha = 0.24 \), the momentum anisotropy of the initial state \( \Lambda = 100 \). For the new partcilation temperature \( T_p = 156 \) MeV most parameter values remain the same, except for \( \epsilon_0 = 495 \text{ GeV/fm}^3 \) and \( \tau_0 = 0.15 \text{ fm}/c \), which are changed in order to ensure the correct charged particle multiplicity and pion \( p_T \) spectrum slope.

In Fig. 2 one can see the comparison of transverse momentum spectra calculated in
FIG. 2. The pion, kaon and proton $p_T$ spectra calculated in iHKM model at the two particlization temperatures, $T_p = 165$ MeV and $T_p = 156$ MeV, and corresponding equations of state, [20] and [21] compared with the ALICE experimental data [9] for central ($c = 0 − 5\%$) Pb+Pb collisions at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV.

iHKM for $c = 0 − 5\%$ Pb+Pb collisions at two mentioned regimes ($T_p = 165$ MeV and $T_p = 156$ MeV) together with the experimental points. At both particlization temperatures the model gives a sufficiently good description of the data, which confirms that the model parameters are chosen correctly.

In Figs. 3, 4 we demonstrate the iHKM results for a set of particle number ratios and compare it with the experimental results and those obtained from the thermal model [26, 27]. Here the iHKM simulations are performed in two regimes: full calculation and the mode with the inelastic processes switched off (except for resonance decays). It is worth noting that the calculations without inelastic reactions but with the initial conditions adjusted to provide right description of the charged hadron multiplicities, give the same particle number ratios as without such an adjusting. This effect is clear: when we switch off the inelastic reactions (except for the resonance decays), then all the particle numbers on the hypersurface of the
chemical freeze-out are proportional to the effective volume, \( N_i = n_i(T, \mu)V_{\text{eff}}, \) \([29]\), which absorbs the hydro-velocities and space-time characteristics at the chemical freeze-out: \( V_{\text{eff}} = \int_{\sigma_{\text{ch}}} u^\mu(x) d\sigma_\mu(x) \). The same happens with the similarly defined effective volume, related to the unity of rapidity in the case of boost invariance in the midrapidity region \([29]\). Therefore, when one fits the initial energy density (and the related initial time) in order to adjust multiplicity distribution at the artificially truncated “switched-off-inelastic” dynamics at the afterburner stage, the only common factor \( V_{\text{eff}} \) will be modified (EoS and corresponding particlization temperature are fixed). So, the particle number ratios will not change, no matter whether the initial conditions are re-tuned or not.

As one can see from the figures, the thermal model and the iHKM results, related to the case when the inelastic scatterings are switched off \([4]\), are modified noticeably when the temperature \( T_p \) (or \( T_{\text{ch}} \) in thermal models) is changing, and describe the data worse than the full iHKM calculations. As for the latter, they give very close results at both particlization temperatures and equations of state!

In a very recent paper \([12]\), an essential influence of the particle rescatterings at the afterburner stage of the collision on the \( K^*(892) \) resonance observability was shown. It means that the so-called thermal freeze-out is not sharp/sudden, but continuous. Our current study points out to the dynamical continuous character of the so-called chemical freeze-out in the relativistic heavy ion collisions. It demonstrates that the account for inelastic processes at the afterburner stage of the collision plays more important role in the correct description of experimental observables, than the specific choice of the supposed particlization/hadronization temperature.

\[^4\] Note that some deviation of iHKM results in this truncated case from those of the thermal model should be connected with the number of resonances taken into account. In iHKM case we consider 329 types of resonances. As for the large deviation in the case of \( K^*/K^{\text{ch}} \) ratio, it can be explained by different definition of \( K^*/K^{\text{ch}} \) ratio in the experiment and iHKM from the one side and the thermal model calculations from the other side. As follows from the experimental papers, e. g. \([30]\), the \( K^{*0}(892) \) resonances are reconstructed via the products of their decay into \( K^+\pi^- \) pairs with branching ratio 0.66 (while the \( K^{*0} \)’s decaying through a channel \( K^{*0} \rightarrow K^0\pi^0 \) are excluded from the analysis). The same reconstruction procedure is applied in the iHKM study. Hence, the number of \( K^* \)s, identified in such a way is about 2/3 of the full \( K^* \) number. In contrast, the thermal model describes the full \( K^* \) number and therefore gives higher \( K^*/K^{\text{ch}} \) ratio.
FIG. 3. The comparison of particle number ratios, calculated in iHKM (blue markers) at the particlization temperature $T_p = 156$ MeV and HotQCD Collaboration equation of state with the ALICE experimental data [28] and the thermal model results at $T = 156$ MeV [26]. The iHKM simulations are performed in two regimes: full calculation and the mode with inelastic reactions (except for resonance decays) are switched off. The $\chi^2$ values for these two regimes are 2.2 and 14.9 respectively.

IV. CONCLUSIONS

The particle $p_T$ spectra and particle number ratios calculated in iHKM at the two different thermodynamic equations of state and corresponding particlization/hadronization temperatures demonstrate that the satisfactory description of the experimental data can be achieved at both $T_p$ values if the initial energy density $\epsilon(\tau_0)$ is the free parameter. In this sense the results practically do not depend on the equation of state in complete dynamics of rapidly expanding fireballs formed in A+A collision. However, the situation is different when one truncates the post hydrodynamic stage, the description is better for lower temperature of chemical freeze-out, $T = 156$ Mev. But even in this case — when annihilation and other in-
elastic processes (except for the resonance decays) at the afterburner stage are neglected — the theoretical results get worse as compared to the full calculations. One can conclude that neither thermal nor chemical freeze-out can be considered as sudden at some corresponding temperatures. Our analysis shows that even at the minimal hadronization temperature near 155 MeV, the annihilation and other non-elastic scattering reactions still play noticeable role in the formation of particle number ratios, especially those where protons and pions are participating.

The fact that the results of iHKM evolutionary model for small and relatively large particlization temperatures are quite similar means that inelastic processes (other than the resonance decays), which occur during the matter evolution below the corresponding temperature, play a role of the compensatory mechanism in formation of the particle number ratios.

FIG. 4. The same as in Fig. 3, but the results for iHKM calculation at $T_p = 165$ MeV and Laine-Schröder equation of state are shown. The thermal model results are demonstrated for $T = 164$ MeV [26, 27]. The $\chi^2$ values for the full and “switched-off-inelastic” iHKM simulations are 0.7 and 37.7 respectively.
Thus, the current analysis supports the picture of continuous chemical freeze-out at the LHC in the sense that the corrections to the sudden chemical freeze-out results, accounting for the inelastic reactions at the subsequent times, are important and improve the description of the experimental data.

ACKNOWLEDGMENTS

Yu.S. thanks to P. Braun-Munzinger for fruitful and stimulating discussions. The research was carried out within the scope of the EUREA: European Ultra Relativistic Energies Agreement (European Research Group: “Heavy ions at ultrarelativistic energies”, Agreement F-2018 with the National Academy of Sciences (NAS) of Ukraine. The work is partially supported by the NAS of Ukraine Targeted research program “Fundamental research on high-energy physics and nuclear physics (international cooperation)”.

[1] P. Braun-Munzinger, J. Stachel, J. P. Wessels and N. Xu, Phys. Lett. B 344 (1995) 43.
[2] P. Braun-Munzinger, J. Stachel, J. P. Wessels and N. Xu, Phys. Lett. B 365 (1996) 1.
[3] P. Braun-Munzinger, I. Heppe and J. Stachel, Phys. Lett. B 465 (1999) 15.
[4] F. Becattini, M. Gazdzicki and J. Sollfrank, Eur. J. Phys. C 5 (1998) 143.
[5] J. Cleymans and K. Redlich, Phys. Rev. C 60 (1999) 054908.
[6] P. Braun-Munzinger, D. Magestro, K. Redlich and J. Stachel, Phys. Lett. B 518 (2001) 41.
[7] P. Braun-Munzinger, V. Koch, T. Schafer, J. Stachel, Physics Reports 621 (2016) 76.
[8] B. Abelev et al. (ALICE Collaboration), Phys. Rev. Lett. 109 (2012) 252301.
[9] B. Abelev et al. (ALICE Collaboration), Phys. Rev. C 88 (2013) 044910.
[10] Iu.A. Karpenko, Yu.M. Sinyukov, K. Werner. Phys. Rev. C 87 (2013) 024914.
[11] F. Becattini, et al, in “New Horizons in Fundamental Physics”, pp.139-150, Springer, 2016.
[12] V.M. Shapoval, P. Braun-Munzinger, Yu.M. Sinyukov, Nucl.Phys. A 968 (2017) 391.
[13] S. Chatterjee, R.M. Godbole, Sourendu Gupta, Phys. Lett. B 727 (2013) 554.
[14] V.Yu. Naboka, Iu.A. Karpenko, Yu.M. Sinyukov, Phys. Rev. C 93 (2016) 024902.
[15] W. Broniowski, M. Rybczynski, P. Bozek, Comput. Phys. Commun. 180 (2009) 69.
[16] V.Yu. Naboka, S.V. Akkelin, Iu.A. Karpenko, Yu.M. Sinyukov, Phys. Rev. C 91 (2015) 014906.
[17] S.V. Akkelin, Yu.M. Sinyukov, Phys. Rev. C 81 (2010) 064901.

[18] P. Huovinen, H. Petersen, Eur. Phys. J. A 48 (2012) 171. arXiv:1206.3371; S. Pratt, Phys. Rev. C 89 (2014) 024910; D. Molnar and Z. Wolff, Phys. Rev. C 95 (2017) 024903. arXiv:1404.7850

[19] S.A. Bass et al., Prog. Part. Nucl. Phys. 41 (1998) 255; Prog. Part. Nucl. Phys. 41 (1998) 225; M. Bleicher et al., J. Phys. G 25 (1999) 1859.

[20] M. Laine and Y. Schröder, Phys. Rev. D 73 (2006) 085009.

[21] A. Bazarov et al. (The HotQCD Collaboration), Phys. Rev. D 90 (2014) 094503.

[22] V. M. Shapoval, P. Braun-Munzinger, Iu. A. Karpenko, Yu. M. Sinyukov, Nucl. Phys. A 929 (2014) 1.

[23] V. M. Shapoval, P. Braun-Munzinger, Iu. A. Karpenko, Yu. M. Sinyukov, Phys. Lett. B 725 (2013) 139.

[24] V.M. Shapoval, Yu.M. Sinyukov, and Iu.A. Karpenko, Phys. Rev. C 88 (2013) 064904.

[25] Yu. M. Sinyukov, V. M. Shapoval, V. Yu. Naboka, Nucl. Phys. A 946 (2016) 227.

[26] J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, J. Phys. Conf. Ser. 509 (2014) 012019, arXiv:1311.4662 [nucl-th].

[27] A. Andronic et al., J. Phys. G: Nucl. Part. Phys. 38 (2011) 124081.

[28] M. Floris, Nucl. Phys. A 931 (2014) 103112.

[29] S.V. Akkelin, P. Braun-Munzinger, Yu.M. Sinyukov, Nucl.Phys. A 710 (2002) 439.

[30] B.B. Abelev, et al., The ALICE Collaboration, Phys. Rev. C 91 (2015) 024609.