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EVOLUTION OF ENERGY DENSITY FLUCTUATIONS IN $A + A$ COLLISIONS

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Two-particle angular correlation for charged particles emitted in Au + Au collisions at the center of mass of 200 MeV measured at RHIC energies revealed novel structures commonly referred to as a near-side ridge. The ridge phenomenon in relativistic $A + A$ collisions is rooted probably in the initial conditions of the thermal evolution of the system. In this study we analyze the evolution of the bumping transverse structure of the energy density distribution caused by fluctuations of the initial density distributions that could lead to the ridge structures. We suppose that at very initial stage of collisions, the typical one-event structure of the initial energy density profile can be presented as the set of longitudinal tubes, which are boost-invariant in some space-rapidity region and are rather thin. These tubes have very high energy density as compared to smooth background density distribution. The transverse velocity and energy density profiles at different times of the evolution till the chemical freeze-out (at the temperature $T = 165$ MeV), that will be reached by the system, are calculated for sundry initial scenarios.

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INTRODUCTION

Measurements at the Relativistic Heavy Ion Collider (RHIC, Brookhaven) have revealed that the long-range structure of two-particle angular correlation functions is significantly modified by the presence of the hot and dense matter formed in relativistic heavy-ion collisions [1]. Novel correlation structures over large pseudorapidity interval Δy were observed in azimuthal correlations for the intermediate particle transverse momenta $p_T \approx 1-5$ GeV/c [2, 3]. First, the striking «ridge» events were revealed in studies of the near-side spectrum of correlated pairs of hadrons by the STAR Collaboration [4]. The spectrum of correlated pairs on the near side (defined by the trigger particle direction) extends across the entire detector acceptance in pseudorapidity interval of order $\Delta\eta \sim 2$ units and is strongly collimated for azimuthal angles. Here $\Delta\eta$ is the difference in pseudorapidity $\eta = -\ln(\tan(\theta/2))$, where θ is the polar angle relative to the beam axis, between two particles, and $\Delta\varphi$ is the difference in their azimuthal angle φ (in radians). The analyses of measurements by the PHENIX [5] and PHOBOS [6] Collaborations confirmed the STAR results.

The discovery of the ridge has aggravated quantitative theoretical analyses which propose rather different explanations [7–9]. The first, [7], treats the ridge as an initial-state effect. The authors point out that the enhanced two-particle correlations are a natural consequence of the correlations in the classical color fields responsible for multiparticle production in relativistic heavy-ion collisions. Due to fluctuations of color charges in colliding nuclei, the longitudinally boost-invariant and transversally inhomogeneous structure of the matter can be formed. When it expands hydrodynamically, it could lead to the ridges [8]. The others explore a final-state effect as the origin of the ridge [9].The evolution of the system and other later-stage effects can modify these correlations, which, in fact, are associated with fluctuations in the energy densities at the final stage. The recent measurements by CMS Collaboration [10] observed unexpected effect in proton–proton collisions at the LHC. The clear and significant «ridge»-structure emerges at $\Delta\varphi \approx 0$ extending to $|\Delta\eta|$ of at least 4 units. This novel feature of the data has never been seen in two-particle correlation functions in pp or $p\bar{p}$ collisions before. This unusually elongated structure of the ridge remains after removal of elliptic flow and ordinary jet correlations [11]. This is faced with the problem of causality which, probably, can be solved only if one supposes that the ridge phenomenon in relativistic $A + A$ collisions is rooted in the initial conditions of the thermal evolution of the system. The aim of this study is to check this hypothesis by an analysis of the developing energy density in the system which at very initial stage of collisions has transversally bumping tube-like fluctuations with boost-invariant homogeneous structure within some space-rapidity region.

CALCULATION OF ENERGY DENSITY DISTRIBUTIONS

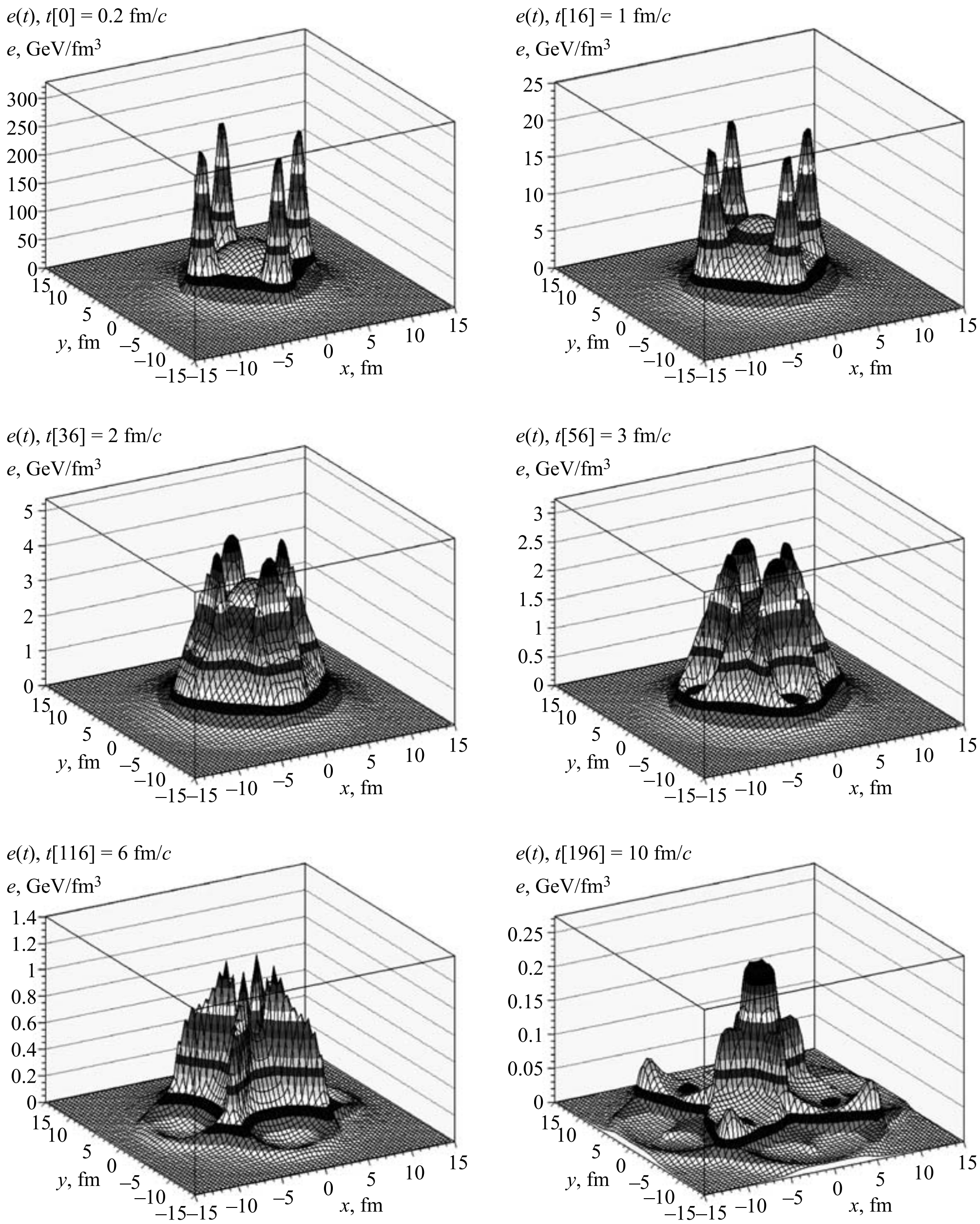
The numerical results presented in this section were obtained on the basis of original 3D ideal hydro-code, described in detail in [12]. The analysis is based on hydrodynamic approach to $A + A$ collisions and considered within the Boltzmann equations. It is consistent with conservation law and accounts for the opacity effects. The hydrodynamic evolution starts at the time τ_0. We use Bjorken-type initial conditions at τ_0: boost-invariance of the system in longitudinal direction, initial longitudinal flow $v_L = 0$ without transverse collective expansion. In present calculation we compare the transverse-velocity profile of hydrodynamic flow and energy density profile which evolve in time till the chemical freeze-out ($T = 165$ MeV) in different initial scenarios. The one of them corresponds to the smooth Gaussian profile with radius R and energy density as it was considered in [13] at $\tau_0 = 0.2$ fm/c. The other scenarios are based on transversally bumping tube-like initial conditions at τ_0. These tubes are rather thin transversally and relatively long in the direction of beam axis; with radii $a_i = 1$ fm. The general energy density distribution at τ_0 could be written as:

$$E = E_b \exp\left(-\frac{x^2 + y^2}{R^2}\right) + \sum_{i=0}^{N_t} E_i \exp\left[-\frac{(x - x_i)^2 + (y - y_i)^2}{a_i^2}\right], \tag{1}$$

$$R_i = x_i^2 = y_i^2, \tag{2}$$

where E_b is the maximum of average energy density distribution; E_i are the maxima of tube-like fluctuations; R_i are the positions of the fluctuation locations, and N_t is the number of tubes. Instead of a study of the result over very many fluctuations, that should be finally averaged over azimuthal angular (it brings symmetry), we will base here on the possible typical, or representative, initial fluctuation which is already maximally symmetric in azimuthal plane. The following initial configurations are considered:

i) The configuration without fluctuation: distribution of initial energy density corresponds to the Gauss distribution with $R = 5.4$ fm and maximum energy density at $r = 0$ is $E_b = 90$ GeV/fm^3.



3D plots of energy density profiles with 4 tube-like initial conditions for $\tau = 0.2, 1, 2, 3, 6,$ and 10 fm/c

ii) The configuration with one tube (fluctuation) in the center: energy density profile is the Gauss distribution with $a = 1.0$ fm and the maxima value 270 GeV/fm^3.

iii) The configuration with one tube (fluctuation) shifted from the center: E_b = 90 GeV/fm^3; $R = 5.4$ fm; $E_0 = 270$ GeV/fm^3; $R_0 = 3$ fm; $a_0 = 1$ fm. The results of calculations are presented for initial time and for $\tau = 1, 2, 10$ fm/c.

iv) The configuration with four tubes (fluctuations): $E_b = 85$ GeV/fm^3; $R = 5.4$ fm; $E_i = 250$ GeV/fm^3; $R_i = 5.6$ fm; $a_i = 1$ fm; The evolution of energy density profiles is presented in the Figure.

v) The configuration with ten tubes (fluctuations): $E_b = 25$ GeV/fm^3; $R = 5.4$ fm; $R_0 = 0$ fm; $R_i(i \leqslant 3) = 2.8$ fm; $R_i(i > 3) = 4.7$ fm; $a_i = 1$ fm; $E_i = 4E_b \exp(-R_i^2/R^2)$.

For all the considered cases, the traces of the initial fluctuations — bumping final energy distributions — remain after the system evolution that should lead to a nontrivial structure in observed correlations. Besides the energy density profiles, the evolution of transverse velocity profiles of hydrodynamic flow in different scenarios was also considered. The fluctuations of the initial conditions result in the fluctuation of the transverse velocity in the system. At the supposed thermalization time $\tau = 1$ fm/c the corresponding fluctuations in the transverse velocity averaged over azimuthal angular and radius are approximately 30% between the cases when the high density fluctuation peak is just in the center and when it is shifted while at the later times ($\tau = 10$ fm/c) it is only 2–3%. This may lead to the important conclusions as for small fluctuations of the mean transverse momenta of observed particles, despite big fluctuations of transverse velocities at thermalization time.

CONCLUSIONS

The basic hydrokinetic code, proposed in [12] was modified to include the tube-like initial conditions with the aim to study how the initial correlations in the energy density evolve with time. We found that the effect of the fluctuations of the initial conditions does not wash out during the system expansion that, probably, leads to the ridges structures of the correlations, which are caused by these fluctuations. The evolution of the energy density distributions and velocity profiles are calculated in the framework of the 3D hydrodynamics. Possible physically grounded configurations of initial density profiles are proposed. The first spectra calculations were done in the framework of the hydrokinetic model (HKM) [12, 14] which allows describing all the stages of the system evolution as well as a formation of the particle momentum at the decoupling stage. The further investigations on this matter and description of correlations could be done in frames of this approach.

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REFERENCES

1. *Alver B. et al. (PHOBOS Collab.)* // Phys. Rev. C. 2010. V. 81. P. 024904.
2. *Alver B. et al. (PHOBOS Collab.)* // Phys. Rev. Lett. 2010. V. 105. P. 022301.
3. *Abelev B. I. et al. (STAR Collab.)* // Ibid. V. 104. P. 062301.

4. *Horner M. G. (for the STAR Collab.)* // J. Phys. G: Nucl. Part. Phys. 2007. V. 34. P. S995.
5. *Adare A. et al. (PHENIX Collab.)* // Phys. Rev. C. 2008. V. 78. P. 014901.
6. *Wosiek B. (for the PHOBOS Collab).* // J. Phys. G. 2008. V. 35. P. 104005.
7. *Dumitru A. et al.* // Nucl. Phys. A. 2008. V. 810. P. 91.
8. *Hama Y. et al.* arXiv:0911.0811 [hep-ph]. 2009.
9. *Schenke B. et al.* // J. Phys. G: Nucl. Part. Phys. 2008. V. 35. P. 104109.
10. *Khachatryan V. et al. (CMS Collab.).* CMS-QCD-10-002, CERN-PH-EP/2010-031.
11. *Abelev B. I. et al. (STAR Collab.)* // Phys. Rev. C. 2009. V. 80. P. 064912.
12. *Akkelin S. V. et al.* // Phys. Rev. C. 2008. V. 78. P. 034906.
13. *Sinyukov Yu. M., Karpenko Yu. A., Nazarenko. A. V.* // J. Phys. G: Nucl. Part. Phys. 2008. V. 35. P. 104071.
14. *Sinyukov Yu. M., Akkelin S. V., Hama Y.* // Phys. Rev. Lett. 2002. V. 89. P. 052301.