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Can we observe effects of early nonequilibrium dynamics using collective flow

Piotr Bożek[1,*]

[1]AGH University of Krakow, Faculty of Physics and Applied Computer Science, aleja Mickiewicza 30, 30-059 Cracow, Poland

Abstract. The rapid expansion of the fireball created in a heavy-ion collision causes strong departures from equilibrium. Such effects are especially important in the very early phase of the collision, bringing a substantial pressure asymmetry. The longitudinal pressure is much smaller than the transverse one. We investigate effects of this early stage pressure asymmetry in a kinetic model without boost-invariance. In the kinetic evolution the asymmetry results from the competion of the longitudinal expasnion rate and th erelaxation rate. Unlike the transverse flow, the directed flow is found to be very sensitive to the equilibration rate and the pressure anisotropy.

1 Introduction

The dense matter formed in the interaction region of an ultrarelativistic heavy-ion collision is expands. One of the main goals of the experimental program in ultrarelativistic heavy-ion collisions at the BNL Relativistic Heavy Ion Collider and the CERN Large Hadron Collider is to study the properties of the quark-gluon plasma formed in the collision [1, 2]. The equilibrium properties of the state of matter can be simulated in lattice quantum chromodynamics simulations. On the other hand, the strong expansion of the fireball in heavy-ion collisions generates large deviations from local thermal equilibrium. The nonequilibrium effects are important if the expansion rate dominates over the equilibration rate of the matter. Deviations from equilibrium are especially important in two instances: at the late stages when freeze-out occurs, in that case the nonequilibrium dynamics can be modeled realistically using a hadronic cascade, at the very early stages when the expansion rate is very high.

If the deviations from local equilibrium are important, the dynamics of at the very early stage cannot be described using viscous hydrodynamics [4]. On the other hand, the far from equilibrium dynamics can be described using a kinetic equation. The fast longitudinal expansion in a heavy-ion collisions gives in the kinetic description a nonisotropic momentum distribution [5]. The effective longitudinal pressure is much smaller than the transverse one. It is interesting to ask the question whether a strong deviation from equilibrium can be observed in the final collective flow observables. For collective flow observable based build on the transverse momenta of emitted particles, e.g. transverse and harmonic flow, the answer is negative. The effect of the strong pressure asymmetry on the such collective flow observables is very small [6]. On the other hand, we find that the effect of pressure asymmetry on the direct flow is important in the kinetic dynamics [3].

*e-mail: piotr.bozek@fis.agh.edu.pl

2 Kinetic dynamics

The early dynamics in a heavy-ion collision is often described with a kinetic approach (or simply a free-streaming expansion) [7–11]. At latter stages, when devaiations from local equilibrium are smaller, the viscous hydrodynamic model is appplied. In this paper we study kinetic dynamic at the very early stage of the collision. Th egoal is to find observable efefcts of this early nonequilibrium dynamics. The full solution of the kinetic equation is technically difficult. A multidimensional phase-space distribution ($f(\vec{x}, \vec{p})$) evolution equation

$$p^\mu \partial_\mu f = -\frac{u^\mu p_\mu}{\tau_R} (f - f_{iso}) \ , \tag{1}$$

must be solved. f_{iso} is an isotropic distribution, e.g. the equilibrium distribution. A simplification of the equations is possible for massless particles [12] using the moment

$$F(t, \vec{x}, \Omega_p) = \int \frac{p^3 dp}{2\pi^2} f(t, \vec{x}, \vec{p}) \ . \tag{2}$$

of the distribution function. The dimensionality of the phase-space distribution is reduced. F depends only on the spherical angles $\Omega_p = (\phi, \theta) = (\phi, v_z)$ of the particle momentum vector $\vec{p}$. It obeys the following kinetic equation

$$\partial_t F + \vec{v} \partial_{\vec{x}} F = -\frac{u^\mu v_\mu}{\tau_R} (F - F_{iso}) \ . \tag{3}$$

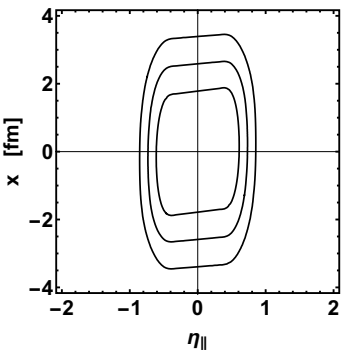

Figure 1. The initial entropy density in the transverse and longitudinal directions (x-η). From Ref. [3].

In order to study the development of the rapidity odd directed flow a system without boost invariance must be considered. For simplicity the solution i assumed to depend on two space variables, one transverse dimension x and the longitudinal space-time rapidity η. The initial density is tilted in the x-η plane away from the beam direction (Fig. 1), which generates the a non-zero directed flow, for details and discussion see [13] and [3]. For a non-boost invariant system the numerical solution is still challenging, with sharply peaked distributions in longitudinal velocity. To reduce the numerical load a rescaled phase-space distribution $\tilde{F}(\tau, x, \eta, \phi, v_z) = F(\tau, x, \eta, \phi, v_z) (\cosh(\eta) - v_z \sinh(\eta))^4$ can be used. For details of the solution see [3]. Also the full dependence on the particle longitudinal velocity in the phase-space distribution F is kept in the solution.

We compare three calculations, the free-streaming dynamics and two kinetic equation solution with two relaxation times. In Fig. 2 is shown the time evolution of the longitudinal velocity distribution. The narrowing of the distribution is fast for the free-streaming (left panel) and slower when the relaxation term is acting (right panel).

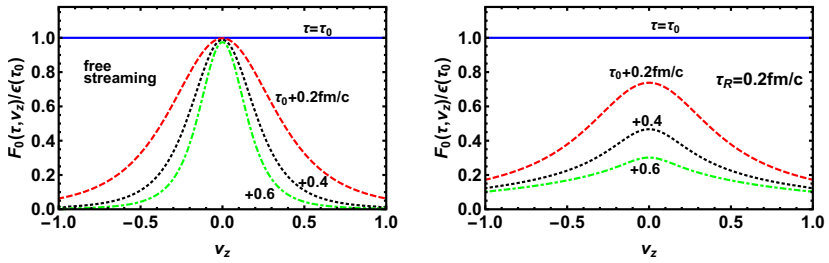

Figure 2. The distribution in the longitudinal velocity at different times of the evolution. Left panel: the free-streaming evolution, right panel: kinetic equation evolution with a finite relaxation time.

3 Results

The Bjorken expansion competes with the isotropization in the kinetic equations. As a result the the pressure in the transverse and longitudinal direction is different (Fig. 3, left panel). Even at the center of the fireball, where the density is the largest, the pressure never reaches the isotropic equilibrium limit. The effect of pressure asymmetry is dramatic for the free-streaming evolution, where no relaxation to equilibrium occurs. The pressure asymmetry is even more pronounced at the edge of the fireball, where the density is smaller and the relaxation time longer. For all of these three calculations, with very different pressure asymmetry, the resulting transverse flow almost indistinguishable (Fig. 3, right panel). It is striking that the transverse flow generated in a kinetic equation involving a relaxation to equilibrium is the same as in a free-streaming evolution. For short evolution times this lack of sensitivity to the pressure asymmetry of the transverse flow is expected [6].

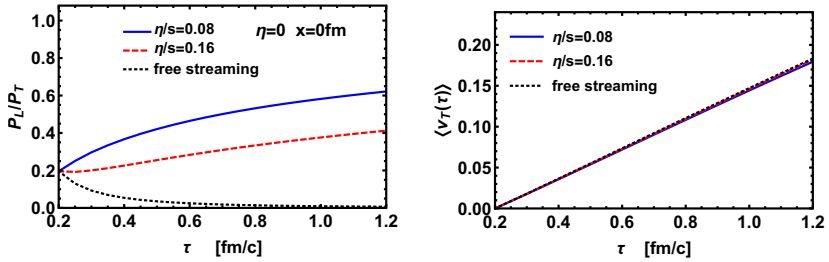

Figure 3. (Left panel) The time dependence of the ratio of the longitudinal to transverse pressure at the center of the fireball. (Right panel) The time dependence of the average transverse flow. Results are shown for two values of the relaxation time and for the free-streaming evolution. Figs. are from [3].

The formation of the directed flow from a tilted fireball [13] involves an interplay of the transverse and longitudinal pressure. In the kinetic theory calculation it results in a strong sensitivity to differences between the transverse and longitudinal pressures throughout the evolution. The expansion of the tilted fireball in the kinetic theory generates a rapidity odd directed flow (Fig. 4, left panel). The average flow in the direction x depends on space-time rapidity. This mechanism requires a breaking of the forward-backward symmetry due to the tilt of the fireball. It is interesting to note that the resulting directed flow is very sensitive to the relaxation rate. The directed flow is very small for the free-streaming evolution and increase with increasing relaxation rate (decreasing relaxation time).

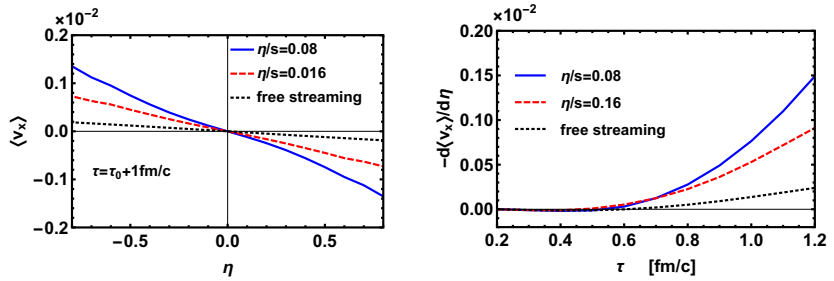

Figure 4. (Left panel) The space-time rapidity dependence of the average flow in the transverse direction x after 1fm/c of kinetic evolution. (Right panel) The time dependence of the slope of the rapidity dependence of the average flow in the transverse direction x. Figs. are from [3].

The space-time rapidity dependence of the directed flow is almost linear and can be parameterized through the sloped of this dependence. The slope of this rapidity dependence increases with the evolution time (Fig. 4, right panel). We notice a a very different rate at which the directed flow is generated depending on the relaxation time in the kinetic dynamics.

We calculate the directed flow generated in a kinetic equation dynamic sofa the fireball. The requires the solution of the equations in a system without boost-invariance. Unlike for the transverse flow, we find a a very strong dependence of the directed on the pressures asymmetry in the system. This shows that the directed flow could be used as an observable sensitive to nonequilibrium effects at the very early stage of relativistic nuclear collisions.

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References

[1] U. Heinz, R. Snellings, Ann.Rev.Nucl.Part.Sci. **63**, 123 (2013)
[2] C. Gale, S. Jeon, B. Schenke, Int.J.Mod.Phys. **A28**, 1340011 (2013)
[3] P. Bożek, Phys. Rev. C **107**, 034916 (2023)
[4] H. Niemi, G.S. Denicol (2014)
[5] W. Florkowski, R. Ryblewski, M. Strickland, Phys. Rev. C **88**, 024903 (2013)
[6] J. Vredevoogd, S. Pratt, Phys. Rev. **C79**, 044915 (2009)
[7] W. Broniowski, W. Florkowski, M. Chojnacki, A. Kisiel, Phys. Rev. **C80**, 034902 (2009)
[8] A. Kurkela, A. Mazeliauskas, J.F. Paquet, S. Schlichting, D. Teaney, Phys. Rev. C **99**, 034910 (2019)
[9] T.N. da Silva, D.D. Chinellato, A.V. Giannini, M.N. Ferreira, G.S. Denicol, M. Hippert, M. Luzum, J. Noronha, J. Takahashi (ExTrEMe), Phys. Rev. C **107**, 044901 (2023)
[10] V.E. Ambrus, S. Schlichting, C. Werthmann, Phys. Rev. D **107**, 094013 (2023)
[11] D. Liyanage, D. Everett, C. Chattopadhyay, U. Heinz, Phys. Rev. C **105**, 064908 (2022)
[12] A. Kurkela, U.A. Wiedemann, B. Wu, Phys. Lett. B **783**, 274 (2018)
[13] P. Bożek, I. Wyskiel, Phys. Rev. **C81**, 054902 (2010)