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COLLECTIVE DYNAMICS IN SMALL SYSTEMS*

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Signatures of collective expansion in relativistic collisions involving small projectiles are presented. The observed phenomena can be described in the framework of relativistic hydrodynamic models. Limits of applicability of hydrodynamics in small systems are discussed.

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1. Introduction

In relativistic heavy-ion collisions, a region of strongly interacting, dense, and hot matter is created. The fireball of dense matter expands and collective flow builds up. It was generally expected that such phenomena do not occur in small system collisions, proton–proton or proton–nucleus. Nevertheless, several calculations applied concepts based on collective expansion to the dynamics of small systems, *e.g.* an estimate of the elliptic and triangular flow in p+Pb collisions predicted a sizable and measurable effect [1].

Qualitatively, new experimental results in small collision systems appeared from measurements of two-particle correlations in pseudorapidity and azimuthal angle, first in $p + p$ [2], and latter in p+Pb [3] collisions.

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The two-dimensional correlation function shows an enhancement for two particles emitted with small relative angle. This could be interpreted as a consequence of azimuthally asymmetric collective flow or, alternatively, as due to initial state correlations [4–6]. In the following, we list arguments in favor of the interpretation involving collective expansion. We discuss also the applicability of relativistic hydrodynamics, the most popular model of collective expansion, to small system collisions.

2. Collectivity in small systems

We list the basic phenomenological and experimental observations indicating the presence of collective expansion in small system collisions.

1. Elliptic and triangular flow.
   Elliptic and triangular asymmetry in the spectra of particles emitted in p+Pb collisions has been observed at the LHC [3, 7, 8]. The measured flow coefficients are in a good agreement with results of hydrodynamic calculations [1, 9–17]. The calculations agree with the experiment in the range of transverse momenta, where hydrodynamics is applicable (Fig. 1).

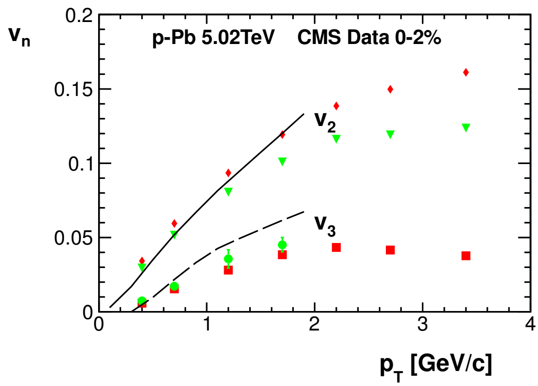

Fig. 1. Elliptic and triangular flow of charged particles, data from the CMS Collaboration [18] compared to hydrodynamic model results (from [19]).

2. Flow in p–A, d–A, ^{3}He–A collisions.
   The initial deformation of the fireball in p+Pb collisions is determined by fluctuations. The model uncertainty of that parameter can be reduced significantly when using a deuteron projectile [1]. In that case, the elliptic deformation stems from the intrinsic deformation of the deuteron wave function. Experiments at RHIC energies have compared p+Au, d+Au, and ^{3}He–Au collisions at the same energies. The

measured elliptic and triangular flows [20] are well-reproduced in hydrodynamic calculations [12, 21]. This demonstrates that the observed azimuthal asymmetry reflects the collective response of the dynamics to the deformation of the initial fireball.

3. Flow from higher cumulants.
   The contribution of non-flow effects can be reduced using higher order cumulants. The observed hierarchy of cumulants of different order [18, 22–24] is similar as expected in the Glauber model [25].

4. Interferometry radii.
   Experimentally measured interferometry radii in p–Pb collisions are in between the radii in p–p and Pb–Pb systems [26, 27]. The three interferometry radii can be calculated in hydrodynamic models [15, 28–30]. Good agreement with experiment is obtained, both for p–Pb and d–Au [31] collisions.

5. Factorization of flow correlations.
   The collective flow interpretation requires an approximate factorization of two-particle azimuthal correlations in transverse momentum and rapidity [32, 33]. Experiments confirm that factorization is approximately fulfilled for $p_\perp < 3$ GeV [34]. The small breaking of factorization (possible due to fluctuations in the initial state) is also well-reproduced in the hydrodynamic model [14].

6. Mass splitting of elliptic flow.
   A generic prediction of hydrodynamics is that the elliptic flow depends on the particle mass. A mass splitting in the elliptic flow coefficient is observed in p–Pb [35] and d–Au collisions [31].

7. Transverse flow.
   The transverse flow leads to a mass hierarchy of the average transverse momenta of emitted particles. In the experimental data [36, 37], a hardening of the spectra for massive particles is visible; this effect is in line with expectations of hydrodynamic models.

3. Applicability of hydrodynamics

The experimental observations listed above show that the dynamics generates a collective component in the spectra as a response to the initial source density. Does it indicate that hydrodynamics is applicable to small systems? Explicit calculations in the hydrodynamic model reproduce a number of observations. On the other hand, strict applicability of hydrodynamics requires that the systems stays close to local thermal equilibrium during the evolution.

Velocity and density gradients in the evolution can be very large. This problem gets even more acute in small system collisions. At the early stage of the collision, longitudinal expansion causes a strong asymmetry between the longitudinal and transverse pressure [38,39]. There are two reasons why viscous hydrodynamics remains applicable even if the pressure asymmetry is large. Firstly, numerical simulations in solvable cases show that viscous hydrodynamics becomes applicable even if the longitudinal pressure is about 50% of the equilibrium one [40,41]. Secondly, even if the pressure asymmetry is drastically changed in a given scenario, it has almost no effect on the transverse flow and its asymmetry [42,43]. It means that viscous hydrodynamics describes the dynamics even far from equilibration (or isotropization). Moreover, even if the true, dynamical pressure deviates from the predictions of viscous hydrodynamics, it has no effect on most of the observables.

Numerical simulations in strongly interacting theories show that hydrodynamics remains applicable when the size is larger than the inverse temperature [44]. It translates into a minimal charged particle multiplicity per unit rapidity $\mathrm{d}N/\mathrm{d}y \simeq 2$–$3$. Quantitatively, hydrodynamics can be trusted when non-hydrodynamic modes are subdominant. This leads to a similar estimate as quoted above for a fluid with minimal viscosity [45]. Using estimates of viscosity from heavy-ion experiments gives a minimal multiplicity for hydrodynamics $\mathrm{d}N/\mathrm{d}y \simeq 6$–$10$.

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