Hydrodynamic approach to p-Pb

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Abstract

The formation and collective expansion of the fireball formed in ultrarelativistic p-A and d-A collisions is discussed. Predictions of the hydrodynamic model are compared to recent experimental results. The presence of strong final state interaction effects in the small dense systems is consistent with the observed azimuthal anisotropy of the flow and with the mass dependence of the average transverse momentum and of the elliptic flow. This raises the question of the mechanism explaining such a rapid build up of the collective flow and the large degree of local equilibration needed to justify this scenario.

1. Introduction

Experiments on heavy-ion collisions are performed to study the properties of matter at extreme densities. In the interaction region a droplet of hot and dense matter is formed. If the matter evolves close to thermal equilibrium, its properties can be deduced from a careful comparison to hydrodynamic model calculations. Hydrodynamic expansion of the fireball forms the collective flow. The azimuthally asymmetric collective flow is evidenced in the flow coefficients of final particle distributions. The study of jet quenching and heavy quark dynamics in the quark gluon plasma is based on reference data that can be obtained in p-A interactions \cite{1}. Assuming that final state interactions are negligible in p-A interaction, differences between particle production in A-A and p-A that cannot be accounted for by a simple superposition of nucleon-nucleon interactions could serve as probes of the high density quark-gluon plasma.

On the other hand, an estimate of the expected particle multiplicity in central p-Pb interactions at the LHC gave a value similar as in peripheral Pb-Pb collisions \cite{2}. The density of matter created in violent p-Pb interactions at the LHC is sufficient for the creation of the quark-gluon plasma. The expansion of this small fireball leads to noticeable collective flow. The size and the shape of the initial source formed in a p-Pb interaction can be estimated in the Glauber Monte Carlo model. Fluctuations in the distribution of participant nucleons yield a large eccentricity and triangularity (Fig. 1, left panel). The expansion of the fireball is modeled using 3+1-dimensional viscous

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hydrodynamics [3, 4]. It has been has been predicted that the elliptic and triangular flow of particles emitted in central p-Pb collisions is large and could be directly measured [2].

An interesting possibility is to study the d-A interactions [2]. This is a small dense system, similar as for the p-A case, but the shape of the interaction region is very much deformed (Fig. 2, right panel). The most violent collisions, corresponding to a large number of participants, happen when the deuteron hits the large nucleus side-wise. The eccentricity of the fireball can be as large as 0.5 (Fig. 2, left panel). Moreover, large value of the initial eccentricity is defined by the geometry of the projectile and is not much influenced by the fluctuations. Experimentally, such configurations can be triggered on by choosing events with high multiplicity (transverse energy). The prediction is that in the most violent d-A collisions the elliptic flow is very large [2], and could be larger than in p-A or peripheral A-A collisions (Fig. 1, right panel).
2. Hydrodynamic flow in p-Pb

The analysis of two-particle correlations in the relative azimuthal angle and relative pseudorapidity for p-Pb collisions at the LHC revealed the presence of long-range ridge-like structures for particle pairs emitted in the same ($\Delta \phi \simeq 0$) and away side ($\Delta \phi \simeq \pi$) directions [5, 6, 7]. The ridge-like structures are very similar as observed in A-A and in high multiplicity p-p collisions [8, 9, 10, 11]. In heavy-ion collisions, but also in p-p interactions, such structures can be interpreted as due to collective flow harmonics $v_2$, $v_3$, and to momentum conservation effects [12, 13, 14]. The two-hadron correlation function projected on the relative angle can be decomposed in successive harmonics

$$C(\Delta \phi) \propto 1 + C_1 \cos(\Delta \phi) + 2v_2^2 \cos(2\Delta \phi) + 2v_3^2 \cos(3\Delta \phi) + \ldots .$$

(1)

For p-Pb collisions, in the hydrodynamic scenario the coefficients $v_2$ and $v_3$ are the elliptic and triangular flow coefficients, while $C_1 < 0$ is due mainly to transverse momentum conservation effects at finite multiplicity. In Fig. 3 the two-hadron correlation function measured by the CMS Collaboration [5] is compared to hydrodynamic calculations [15]. The collective expansion scenario can explain semi-quantitatively the observed structures. The same-side ridge in the correlation function normalized by the number of trigger particles increases with multiplicity. This dependence is natural for collective flow correlations which correlate all the particles in the event.
We note, that angular correlations between emitted hadrons can arise from interference diagrams between gluons in the initial state [16, 17, 18, 19]. Such effects are expected in the color glass condensate regime and explain the observed small angle enhancement of the two-hadron correlation function in p-p and p-Pb collisions, as well as its $p_{\perp}$ dependence.

In the hydrodynamic picture the transverse momentum of an emitted particle has a component from the collective flow of the fluid. The stronger is the generated transverse flow, the larger is $\langle p_{\perp} \rangle$. Another effect of the collective transverse flow is the mass hierarchy of the transverse momenta, i.e., $\langle p_{\perp} \rangle$ increases with the particle mass. Both effects are observed in p-p, p-Pb and Pb-Pb collisions [21, 20, 22]. The increase of the average transverse momentum with the event multiplicity and its mass hierarchy in p-p interactions can be explained by the color reconnection mechanism [23]. However, in p-Pb collisions, $\langle p_{\perp} \rangle$ is stronger than expected from a superposition model [24]. An example of a superposition model is given by the HIJING model calculation shown in Fig. 4, where the calculated transverse momentum is smaller than observed and its dependence on the particle mass is too weak. The measured transverse momenta can be explained as due to the collective transverse flow generated in the hydrodynamic expansion of the fireball formed in p-Pb collisions (Fig. 4, left panel) [25, 26, 24, 27, 28]. An alternative scenario based on geometrical scaling leads to a mass hierarchy in $\langle p_{\perp} \rangle$ as well [29].

The flow coefficients $v_2$ and $v_3$ can be measured in p-Pb collisions at the LHC [32, 30, 31]. The procedure is more involved than in central A-A collisions because of significant nonflow correlations, from jets, resonance decays, or momentum conservation. Some of the nonflow correlations can be reduced using a rapidity gap between the particles or using the fourth order cumulant [33, 34]. Another possibility is to subtract the per-trigger two-particle correlation for peripheral events from the one obtained for central
events. Significant elliptic and triangular flow coefficients are measured in central p-Pb collisions. The outcomes of different methods of reducing nonflow effects vary somewhat, but correlations consistent with collective flow are observed within the uncertainty of the procedure.

In Fig. 5 the results of a hydrodynamic calculation are compared to experimental data on flow coefficients for charged and identified particles [25]. The $p_{T}$ dependent flow coefficients for charged particles for central p-Pb collisions are well reproduced by our hydrodynamic model. Qualitatively similar results are obtained for other calculations using different assumptions on the initial density and the fluid properties [35, 24, 27]. The magnitude of the predicted flow depends on the details of the model. The centrality dependence of the $v_2$ and $v_3$ coefficients cannot be fully reproduced in the hydrodynamic calculations. When varying the initial size of the fireball from peripheral to central p-Pb collisions, the collective expansion sets in. However, it is difficult to model accurately this transition using viscous hydrodynamics, which assumes almost complete equilibration. The harmonic flow coefficients have a mass hierarchy. For soft momenta, the $v_2$ coefficient for pions is larger than for protons (Fig. 5, right panel). The fluid dynamic calculations reproduce this effect [25, 28].

The d-Au at RHIC energies have been analyzed by the PHENIX Collaboration [36]. The peripheral from central events subtraction procedure has been applied to the two-hadron correlation functions. The nonflow effects are relatively more important than for p-Pb collisions at the LHC, since the average multiplicities are lower. The extracted elliptic flow coefficient is large, in line with what has been predicted in the hydrodynamic model [2]. The intrinsic deformation of the deuteron projectile leads to a very large eccentricity in the initial state, but the triangularity is determined by fluctuations. The final $v_2$ coefficient is large and $v_3$ is small [2, 24, 27]. Further insight on the collectivity in small systems could be gained from $^3$He-Au collisions, involving a projectile with triangular deformation [37]. Interestingly, deformations due to alpha clustering in small nuclei could also be studied in relativistic nuclear collisions [38].

The initial size of the fireball in p-Pb collisions is expected to be smaller than in peripheral Pb-Pb collisions. The final size of the system can be measured using the
Hanbury Brown-Twiss correlation radii. If the system undergoes as substantial collective expansion phase, its size at freeze-out would be comparable to the freeze-out radius of the fireball in peripheral Pb-Pb collisions, otherwise one expects to find somewhat smaller femtoscopic radii [39, 24]. Explicit calculations in the hydrodynamic model for p-Pb collisions show that the predicted femtoscopy radii are similar as in the A-A collisions with similar multiplicity (Fig. 6).

3. Collectivity in small systems

The hydrodynamic model describes in a satisfactory way a number of experimental observations in p-Pb collisions. This raises the question, whether for such a small and short living system the assumption of approximate local equilibration is justified. Within hydrodynamics small deviations from equilibrium can be quantified as viscosity corrections. While the local energy density in a high multiplicity p-Pb event is above the phase transition density, the small size of the fireball leads to large velocity gradients. The mean free path is not very small compared to the system size and the viscous corrections in the dynamics are large [41, 42, 24]. These arguments shows that the agreement of the hydrodynamic calculations with the data for p-Pb can be at best semi-quantitative.

At the early phase of the collision, corrections to the energy-momentum tensor of a perfect fluid amount to a strong reduction of the longitudinal pressure and an increase of the transverse pressure [43, 44]. The longitudinal pressure can be even negative. This
seems to invalidate any hydrodynamic approach. However, universal flow arguments and numerical simulations [45, 46, 47, 48] show that the transverse collective flow generated in the early, far from equilibrium evolution is almost the same as the flow generated in a perfect fluid expansion starting from the same initial time. This means that hydrodynamics acts as an effective theory for the transverse dynamics of the system even if the system is far from equilibrium.

From the arguments given above one should not conclude that any dynamical model with gradients of the energy-momentum tensor would give the observed flow. In order for the universal flow argument to apply, the system must eventually undergo a thermalization stage [45, 46]. In fact, only after an approximate local thermalization the local flow velocity and energy density are defined.

It is possible that in the short lived p-Pb system most of the evolution occurs far from equilibrium, with the thermalization happening only just before hadronization. The final transverse, elliptic and triangular flow in that scenario cannot be distinguished from the quantities obtained in a pure hydrodynamic expansion. The dynamics of small systems offers a nice laboratory to test the isotropization mechanism with probes sensitive to the pressure anisotropy. Observables involving explicitly the longitudinal pressure have been discussed in that respect, namely, the dilepton production [49], photon emission [50, 51], directed flow [47], and bottomonium suppression [52].

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