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Collective dynamics in relativistic nuclear collisions

Harri Niemi [a,b,*]

[a] *Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 University of Jyväskylä, Finland*
[b] *Helsinki Institute of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland*

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Abstract

I will review the current status of describing spacetime evolution of the relativistic nuclear collisions with fluid dynamics, and of determining the transport coefficients of strongly interacting matter. The fluid dynamical models suggest that shear viscosity to entropy density ratio of the matter is small. However, there are still considerable challenges in determining the transport coefficients, and especially their temperature dependence is still poorly constrained.

Keywords: Quark–gluon plasma; Relativistic fluid dynamics; Viscosity

1. Introduction

One of the main goals in heavy ion collision experiments at relativistic energies is to determine the properties, like viscosity, of nearly thermalized strongly interacting matter. The dynamics of the system formed in these collisions is, however, complex and the matter properties reflect into the experimental observables in a non-trivial way. Therefore, it is essential to have a good understanding of the dynamics, as well as understand how the different stages of the collisions affect the measured particle spectra. Nowadays, relativistic fluid dynamics has been established as the main tool in describing the evolution, and especially extracting the transport properties of the matter.

* Correspondence to: Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 University of Jyväskylä, Finland.

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Fluid dynamics is a natural framework to use in constraining the transport properties as the transport coefficients, like shear and bulk viscosity, are direct inputs to the models. While fluid dynamics is a convenient tool, it also has limited applicability, and for systems as small as those created in heavy ion collisions it is not at all clear whether it is strictly applicable. However, the system is also strongly interacting, and the comparisons between the experimental data and the predictions of fluid dynamical models show an extremely good agreement, suggesting that we indeed create a small droplet of fluid in these collisions. For recent reviews, see Refs. [1,2]

Constraining the transport coefficients is mostly based on the systematics of the azimuthal asymmetries of the hadron transverse momentum spectra. In the fluid dynamical picture these asymmetries originate from initially asymmetric density profiles that are then converted by the pressure gradients to the momentum space anisotropies during the evolution. The final momentum space anisotropies reflect directly to the observed particle spectra, and the magnitude of the asymmetries depends on the values of the transport coefficients.

An essential input to the fluid dynamical model is, besides equation of state and transport coefficients, an initial density distribution of the matter. The asymmetries of the final spectra depend not only on the matter properties, but also on the asymmetries of the initial state. The details of the initial profiles remains one of the largest uncertainties in extracting the transport coefficients, and it is necessary to constrain them simultaneously with the transport properties.

2. Fluid dynamics

Fluid dynamics emerges as an approximation to the evolution of the system when the microscopic scales are small compared to the macroscopic scales like the size of the system. Basic equations for fluid dynamics are the conservation laws $\partial_\mu T^{\mu\nu} = 0$, $\partial_\mu N_i^\mu = 0$, where $T^{\mu\nu}$ is the energy–momentum tensor and N_i^μ are the possible additional conserved currents (charge, baryon number, particle number, etc.). In general $T^{\mu\nu}$ can be decomposed w.r.t. fluid 4-velocity u^μ, defined in the Landau frame $e_0 u^\mu = T^{\mu\nu} u_\nu$, as $T^{\mu\nu} = e_0 u^\mu u^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu}$, where e_0 is the local energy density $P = P_0 + \Pi$ is the isotropic pressure (sum of equilibrium pressure P_0 and bulk viscous pressure Π), and $\pi^{\mu\nu}$ is the shear-stress tensor.

The conservation laws alone do not provide enough constraints to determine the evolution of the system, but in the fluid dynamical approximation the evolution of the dissipative quantities like $\pi^{\mu\nu}$ is governed by the gradients of the equilibrium fields (velocity, temperature, etc.). For example, in the simplest Navier–Stokes (NS) approximation the shear-stress tensor and bulk viscous pressure are directly proportional to the gradients of velocity, i.e. $\pi^{\mu\nu} = 2\eta(T, \{\mu_i\})\nabla^{\langle\mu} u^{\nu\rangle}$ and $\Pi = -\zeta(T, \{\mu_i\})\nabla_\mu u^\mu$. The microscopic properties of the matter are then integrated into the coefficients $\eta(T, \{\mu_i\})$ and $\zeta(T, \{\mu_i\})$, which in general depend on the temperature T and the chemical potentials $\{\mu_i\}$ associated with the conserved charges.

It is, however, known that the relativistic NS theory suffers from the instability problem [3,4], which renders the relativistic NS theory unusable at least for the full dynamical description of the system. The instability problem can be cured by using an approximation that goes beyond the first order NS theory. In the Israel–Stewart theory [5] a part of the microscopic transient dynamics is taken into account, e.g. the shear-stress tensor relaxes towards the NS values within the relaxation time τ_π and not instantaneously like in the NS theory. Transient fluid dynamics can be derived from a microscopic theory by expanding around an equilibrium state and neglecting all the microscopic time scales except the slowest one [6]. This procedure leads to relaxation type