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Review

Hydrodynamic approaches in relativistic heavy ion reactions

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A B S T R A C T

We review several facets of the hydrodynamic description of the relativistic heavy ion collisions, starting from the historical motivation to the present understandings of the observed collective aspects of experimental data, especially those of the most recent RHIC and LHC results. In this report, we particularly focus on the conceptual questions and the physical foundations of the validity of the hydrodynamic approach itself. We also discuss recent efforts to clarify some of the points in this direction, such as the various forms of derivations of relativistic hydrodynamics together with the limitations intrinsic to the traditional approaches, variational approaches, known analytic solutions for special cases, and several new theoretical developments. Throughout this review, we stress the role of course-graining procedure in the hydrodynamic description and discuss its relation to the physical observables through the analysis of a hydrodynamic mapping of a microscopic transport model. Several questions to be answered to clarify the physics of collective phenomena in the relativistic heavy ion collisions are pointed out.

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1. Introduction

Hydrodynamics is a theoretical framework to describe the motion of fluids based on their local property and the conservation laws of energy and momentum, and other conserved quantities, for example mass in non-relativistic hydrodynamics. The main advantage of hydrodynamics resides in the fact that a huge number of degrees of freedom contained in the microscopic composition of the fluids is drastically reduced to a few macroscopic hydrodynamic variables which represent the local property of the fluid. We refer to this property of hydrodynamic description as "locality". The local property is usually represented by thermodynamic relations among the hydrodynamic variables frequently called as equation of state (EoS), plus transport coefficients. That is, it is assumed that the fluid is in the state of local thermal equilibrium (LTE), or very close to it (see Section 2).

Hydrodynamics is one of the oldest classical phenomenological theories which has played an important role in the development of science and technology. Its relativistic form was already developed in the early stages of the theory of relativity [1,2] mainly in the context of astrophysics and cosmology. As we will report in this review, applications of hydrodynamics to the microscopic system such as nuclear collective motion and heavy ion collisions have been shown to be successful. It is amazing to observe that such a simple scheme of dynamics is able to cover various phenomena from cosmological to hadronic scales.

When we think of typical dynamics of a fluid, we immediately imagine its flow profile as we usually observe in daily life, such like waves of sea, ripples of wine in a glass, vortices in a water-sink, turbulences in winds, etc. Indeed, in most of these phenomena, the hydrodynamic picture is known to be well established since the validity of the concept of locality in describing the properties of fluids through LTE seems obvious due to the huge number ($\sim 10^{20}$) of particles involved in a visible dynamics of these fluids. In such cases, if the property of the matter is given we can study its response as an initial value problem. Sometimes we can use the hydrodynamic description to determine the initial condition which leads to the specified final state after the hydrodynamic evolution. On the other hand, if the properties of the matter is not known, then we can introduce a model to represent them in terms of a few hydrodynamic parameters, and infer them by comparing the predictions with experiments, provided that the hydrodynamic picture is in fact valid. Of course, hydrodynamic responses of the matter in principle can be nonlinear, and sometimes they are extremely complex. In such cases the above mentioned hydrodynamic modeling to deduce the initial condition or properties of the matter in question is not trivial at all. In particular, for example in the presence of turbulence, the time evolution becomes chaotic and the one-to-one correspondence of the initial and final states is lost [3].

As mentioned, the hydrodynamic picture is applicable for a vast class of different scales. However, it should be kept in mind that the meaning of the locality changes depending on the scale of the system in question. For example, if we try to study hydrodynamics of the atmosphere for weather forecasting purpose, larger-scale simulations are implemented to cover the significant area of the earth. There, the locality means that any inhomogeneity of the air is completely neglected within the volume, say, of the order of m^3, and in fact, too precise information is not required. However, this does not necessarily mean that small scale dynamics is completely neglected. For example, in the presence of turbulences in a smaller volume than the required precision, they are smeared out and counted as the internal degrees of freedom of the air in our observational scale. In these situations, the transport coefficients might be modified and some effective quantities, e.g. the so-called eddy viscosity should be used [3]. Such a situation occurs frequently when we perform numerical simulations