論文の内容の要旨

Causal hydrodynamic fluctuations and their effects on high-energy nuclear collisions

(相対論的流体揺らぎと高エネルギー原子核衝突反応への影響)

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The system of quarks and gluons is described by quantum chromodynamics. Under sufficiently high temperature or high density, quarks and gluons are deconfined from hadrons and form a novel state of matter called quark-gluon plasma. It may be found in extreme conditions such as in the early universe and in compact stars. Also, quark-gluon plasma states can be created in experiments of high-energy nuclear collisions. Currently, understanding of the transport properties of the quark-gluon plasma are one of the major challenges. In particular the specific shear viscosity η/s of the quark-gluon plasma from the observed event-by-event fluctuations is actively discussed. The quantitative extraction of the transport properties needs integrated dynamical models with a proper treatment of all the sources of the event-by-event fluctuations. Among them the effects of the thermal fluctuations of hydrodynamics have not yet been studied within the integrated dynamical models so far. In this thesis, we consider the thermal fluctuations of the hydrodynamics, which are called hydrodynamic fluctuations, within second-order causal dissipative hydrodynamics to investigate the effects on the experimental observables of high-energy nuclear collisions.

We first consider the properties of the hydrodynamic fluctuations in the causal dissipative hydrodynamics. In relativistic systems the Navier-Stokes theory has problems of the acausality and instabilities. Therefore second-order causal theories with non-zero relaxation times are needed. We formulate the hydrodynamic fluctuations in the causal theories with non-uniform backgrounds and find an interesting property: The hydrodynamic fluctuations become always colored in the integral form of the constitutive equations while it turns out that they become white in the differential form of the constitutive equations. This property is proved using the fluctuation-dissipation relation, the causality, the relaxation and the retardation of the memory function, and the symmetries and structure of the constitutive equations written by the derivative expansion.

To consider the hydrodynamic fluctuations in numerical calculations, we develop a new conservative scheme of the causal dissipative hydrodynamics in curved coordinates which is robust against the large gradients caused by the fluctuations. In particular, by choosing the representation of the dissipative current fields to be the components in the local rest frame, we construct a scheme with no discretization errors in the transversality constraints of the dissipative currents.

We also consider the singular behavior of the fluctuating hydrodynamics with the hydrodynamic fluctuations. With the hydrodynamic fluctuations the hydrodynamic equations become stochastic partial differential equations which have a singular behavior in the limit of spatial resolution going to zero. We propose the necessity of coarse-graining scales in the framework. The stochastic integrals in the causal dissipative hydrodynamics are also studied.

Finally to investigate the effects of the hydrodynamic fluctuations in high-energy nuclear collisions, we implement the causal fluctuating hydrodynamics in our dynamical model with initial-state models and hadronic cascades, and perform a massive number of event-by-event numerical simulations. First we consider only the hydrodynamic fluctuations as the event-by-event fluctuations to see their qualitative effects. As a result, we find increase of the charged particle multiplicity, which is stronger in high-p_T hadrons. The elliptic flow v_2 is also increased by the fluctuations. Next we consider, in addition to the hydrodynamic fluctuations, the initial-state fluctuations which is considered to be the major part of the event-by-event fluctuations. As a result, we find that the relative increase of the multiplicity is larger in peripheral collisions. Also, the increase of the integrated v_2 by the hydrodynamic fluctuations turns out to be comparable to the decrease by the shear viscosity. Those results show that the hydrodynamic fluctuations are inevitable components in integrated dynamical models of the high-energy nuclear collisions for quantitative analyses of the transport properties of the quark-gluon plasma.