論文の内容の要旨

論文題目　Relativistic dissipative hydrodynamic description of the quark-gluon plasma
（クォークグルーオンプラズマにおける相対論的な散逸流体ダイナミクス）

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Quarks and gluons are considered to be fundamental elements of matter and are governed by quantum chromodynamics (QCD), the description of the strong interaction. It is known that the many-body system of the elementary particles has a lot of non-trivial properties, making it one of the biggest challenges in hadron physics to explicate them by interdisciplinarily bridging particle physics, nuclear physics and non-equilibrium statistical physics. First principle calculations suggest that quarks are deconfined from hadrons at extremely high temperatures (above two hundred MeV) and a new phase called the quark-gluon plasma (QGP) appears. The QGP is believed to have filled the early universe just after the Big Bang since it is a universal form of matter at high energies with small chemical potential. Precise properties of the QGP were not known until its experimental creation in high-energy heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC), which is a remarkable achievement since it provides unique opportunities to construct theoretical models with experimental feedbacks. One of the intriguing results revealed in the experiments is that the QGP needs to behave as a near-perfect fluid for a certain period of its lifetime to explain the large momentum anisotropy observed in hadronic yields. This indicates that the QGP is strongly coupled, much to the contrary of most predictions that the medium would be weakly coupled for asymptotic freedom, an important characteristics of QCD. It motivates one to treat the hot matter as a fluid as first proposed by Landau in the context of hadron-hadron collisions many years ago, since dynamical analyses of finite temperature QCD systems are generally difficult for first principle calculations. A number of relativistic hydrodynamic studies have been performed, and viscous corrections are found essential in quantitative understandings of the observed data. It is note-worthy that viscosity cannot completely vanish from a system due to the uncertainty principle, which was pointed out in the context of kinetic theory and also of Anti-de Sitter/conformal field theory (AdS/CFT) correspondence. On the other hand, hydrodynamics with relativistic dissipative processes is still an incomplete framework by itself and there are still many unsolved issues in high-energy heavy ion physics especially since the Large Hadron Collider (LHC) has started to provide the new experimental data of the QGP at much higher energies. It would be thus very insightful to establish a relativistic dissipative hydrodynamic model of the QGP in an integrated and consistent manner.

In this thesis, formulation of relativistic dissipative hydrodynamics for the systems with conserved charges is presented with its applications to the analyses of the QGP in high-energy heavy ion collisions. Firstly, we investigate the consistent derivation of relativistic dissipative hydrodynamic equations. Relativistic ideal hydrodynamic systems are known to be described by energy-momentum conservation, charge conservations and the equation of state. When off-equilibrium processes are present, additional equations are necessary for describing the dissipative currents. Dissipative processes in relativistic systems have long had ambiguities because the naïve relativistic extension of Navier-Stokes equation is known to suffer from violation of causality and instability to perturbation from global equilibrium. One conventionally considers the second order corrections in terms of the dissipative currents in the entropy current. This introduces the time-like derivative of the dissipative current itself to the constitutive equations and promotes them to dynamical equations, limiting the speed of propagation to finite and preserving causality. We show that the Israel-Stewart theory, one of the most popular causal frameworks used for the analyses of heavy ion collisions, is applicable only for single component systems with elastic scatterings and is not suitable for analyzing the hot quark matter that involves particle creation and annihilation; it is found that one has to introduce the kinetic moment equations for charge conservation laws in addition to the conventional ones for energy-momentum conservation law in the course of formulation for the completeness of the theory. We derive full second-order dissipative hydrodynamic equations for all the dissipative currents from the law of increasing entropy based on the momentum expansion method extended for systems with conserved charges. The formalism is independent of the frame unlike the conventional formulation due to the careful treatment of conserved charges. The derived equations naturally contain relativistic linear cross terms, which are shown to satisfy Onsager reciprocal relation, a microscopic reversibility condition that requires symmetric transport coefficient matrices. Those terms induce cross-coupling effects such as Soret effect, the chemical diffusion induced by the thermal gradients, and Dufour effect, the heat conduction caused by the chemical potential, which could be important in hot and dense systems. The cross terms are also found to be important in explaining general smallness of bulk viscosity. The formalism has all the second order terms allowed and required by kinetic theory and is mostly consistent with other hydrodynamic formalisms in the single-component and elastic scattering case, with a possible exception of the vorticity-only term in an AdS/CFT formalism. The obtained equations are very generic and would be applicable not only to high-energy heavy ion physics but also to early universe and ultra-cold atoms.

With the newly derived relativistic dissipative hydrodynamic equations of motion, we next analyze the effects of space-time evolution on the quark-gluon and hadronic matter. A "standard model" of high-energy heavy ion collisions consists of several stages; collision of nuclei, early thermalization, hydrodynamic evolution, freezeout and hadronic cascade. The nuclei before the collision are described by the color glass condensate (CGC), a state of saturated gluons, rather than by the naïve valence quark picture. A latest result of Pb-Pb collisions at 2.76 TeV in the LHC experiments, however, has shown that the charged particle production at mid-rapidity is about 30% larger than that expected in pure CGC models, which had been successful in describing the particle yields of Au-Au collisions at 200 GeV in the RHIC experiments. We point out medium interactions in later stages are missing in those estimations and estimate the effects of shear and bulk viscous hydrodynamic evolution on the CGC rapidity distributions at RHIC and LHC by employing the energy distribution of the CGC as initial conditions. Here the rapidity is a hyperbolic angle in momentum space that reflects the momentum in the longitudinal direction. All the numerical viscous hydrodynamic analyses for heavy ion collisions with CGC-inspired initial conditions before this study focus on the transverse directions to the collisional axis and assume unrealistic boost-invariant solution for the longitudinal direction, even though it could be essential for qualitative discussion of mid-rapidity particle production. It is note-worthy that this would be possibly due to the complexities of second-order dissipative hydrodynamic equations and to the numerical difficulties caused by the mixing of time-like and space-like derivatives in relativistic dissipative processes. Those issues are solved in a brand new numerical algorithm by taking iterations on the variables with a time-like derivative. A state-of-art equation of state from the first principle calculation of lattice QCD is employed for the hydrodynamic simulations at the vanishing chemical potential limit. The CGC initial conditions are employed from Nara adaptation of Monte-Carlo Kharzeev-Levin-Nardi model. The numerical results show that the rapidity distributions are modified differently at RHIC and at LHC due to the interplay of entropy production in non-equilibrium processes and entropy flux toward forward rapidity region driven by non-boost invariant flow. At RHIC, the convection is effectively stronger than the viscous particle production and the distribution is flattened, suggesting that the CGC parameter for rapidity dependence would be larger than the currently accepted value. Since the effects of viscosity at LHC stood up with those of convection, the readjustment of the rapidity controlling parameter can lead to more particle production at LHC. This suggests that secondary interactions in the hydrodynamic medium could be essential for quantitative description of the multiplicity in the CGC-based models.

Finally, relativistic dissipative hydrodynamic effects on the QGP at finite baryon density are estimated. The net baryon number is neglected in most modern hydrodynamic studies of high-energy heavy ion collisions, but it can be important in the context of precision physics especially at forward rapidity where the net baryon density of valence quarks in the shattered nuclei is conserved. It would also allow one to study dissipative processes at finite density. Development of a finite-density dissipative hydrodynamic model would be able to help the theoretical efforts to locate a critical point on the QCD phase diagram considering the first principle calculations have difficulties at finite density regions due to the fermion sign problem. It should be noted that beam energy scan experiments for the QCD critical point are being performed at RHIC and planned at Nuclotron-based Ion Collider fAcility, Facility for Antiprotons and Ion Research and Japan Proton Accelerator Research Complex. We develop a novel relativistic dissipative hydrodynamic model with all the dissipative processes, *i.e.*, shear viscosity, bulk viscosity and baryon dissipation. Again the longitudinal evolution is considered because the net baryon yields are experimentally shown to be independent of the transverse geometry. The initial condition is constructed from valence quark distribution in the color glass picture and the finite-density equation of state is employed from the lattice QCD with Taylor expansion method as the baryon chemical potential is expected to be sufficiently small compared with the temperature in high-energy collisions. The results show that the hydrodynamic evolution effectively enhances the transparency of the collision. This implies that more energy is available for the production of the hot medium than it was naïvely expected from experimental data because the hydrodynamic interaction gives part of the energy back to the net baryon components from the QGP medium in later stages. This can be a candidate explanation for sudden increase in the transparency observed in the RHIC experiments compared with the extrapolation of the results from early collider experiments at the Alternating Gradient Synchrotron and the Super Proton Synchrotron. The net baryon rapidity distribution is also found sensitive to baryon dissipation as much as to shear and bulk viscosities. Viscosity enhances the baryon stopping because the longitudinal pressure is effectively reduced with the expansion of the system. Diffusion also enhances the trend as it is induced by the chemical gradient into mid-rapidity due to the geometrical positions of the remnant of shattered nuclei. The fact that those effects are visible might suggest that the net rapidity distribution has variable information on the transport coefficients at finite baryon density.