Statistical and Thermodynamical Studies of the Strongly Interacting Matter

Thesis Booklet

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1 Introduction

The focus of high-energy physics in the recent few decades were undoubtedly about the properties of the strongly interacting matter. Conclusive evidences show, that on very high energy density, the so-called quark-gluon-plasma (QGP) is formed, a state of the matter ruled completely by the strong interaction. The details of the formation, material properties and dynamics of the QGP are, however, to be revealed.

The standard theoretical framework of the strong interaction is quantum chromodynamics (QCD). A peculiar feature of QCD, that the fundamental degrees of freedom i.e. the quarks and gluons are confined, therefore the dynamics of the observables is emergent. From the theoretical point of view, it is a great challenge to develop the methodology which is capable of dealing with the non-perturbative nature of QCD. The quantitatively most accurate tool, lattice QCD, is not yet able to describe out-of-equilibrium situations. Therefore theorists construct effective models concerning the different behaviour of QCD on different energy scales.

From the experimental side, the main focus of attention is on the high-energy particle accelerator facilities. The purpose of particle accelerator experiments, putting it simply, is to make extreme conditions and to see what happens with the matter under such circumstances. Such investigations take place on extreme high energy density in the RHIC and the LHC experiments, but this can be also achieved on large nuclear density, as it is planned in the FAIR experiment. By every new experimental findings of these research projects, a further region of the phase diagram of the strongly interacting matter (SIM) is explored. We already have an approximate picture about the phases of the SIM, many details, however, still remain unknown. Is there a critical end point of the deconfinement phase boundary, as non-perturbative investigation of QCD suggests? If so, on which temperature and chemical potential? What kind of critical behaviour the SIM would show in a collision experiment? Such questions drive nowadays the investigation of heavy-ion collisions (HIC). The interpretation and the understanding of the phenomena provided by this relatively young field of physics research impose a great challenge from the point of view of phenomenological model-building.

2 Main objectives

In this thesis we discussed three separate analysis of various phenomenological aspects of HIC.

The first problem is the long-time behaviour and the thermalization of multi-component modified Boltzmann equations. This kinetic theory analysis tackles the effect of the surrounding medium to the quasi-particles. It can be also interpreted as a possible improvement of the kinetic framework for dense systems.

The analytical and numerical studies showed, that the modification leads generally to the lack of a detailed balance state. This behaviour can be treated, however, with the dynamical feedback of the average kinetic energy into the parameters characterizing the modification.

The second analysis is about the azimuthal asymmetry of the particle yields in HIC, known as the elliptic flow. We link the initial state asymmetry of a non-central event to the elliptic flow through a possible microscopic mechanism, which involves an ensemble of ordered, decelerating source-pairs (dipole-like structures). This radiation is – at least partly – induced by the surrounding plasma. The radiation pattern of such an arrangement can be responsible for a major part of the elliptic flow. We also estimate the geometric dimensions of this radiation sources. However, we was not able to clarify the microscopic origin of this effect on the level of QCD degrees of freedom. Also, a detailed analysis on the possible existence of such phenomenological objects is needed.

The third problem is the effective field theoretical description of the fluidity of spinless quantum channels. This is the question which we explored the most thoroughly in this thesis. Namely, which microscopic properties of the quasi-particle spectrum can make the matter more fluent – from the point of view of the transport coefficients. We firstly build up an EFT framework through the generalization of the concept of QP. It is followed by the analysis of model spectral functions to demonstrate that

i) not only the shortening of the QP-lifetime alone decreases the measure of fluidity η/s.

ii) The contribution of the continuum of multi-particle scattering states, and parallel to that, the weakened residue of the QP-pole causes a considerable decrease of the fluidity measure.

iii) Even this simple, basically mean-field approximation results a lower bound for η/s which is, however, not universal, but constrained by the entropy density.

The three problems we discuss in this thesis are distinct for several reasons: They are attached to different period of the time evolution of a HIC. They also use different frameworks to account for the relevant physics. However, a common feature can be outlined in all these problems: we delineated the microscopic reasons in all three cases from the presence of medium. The phenomenological picture was, in all three cases, that the QP-like microscopic degrees of freedom (DoF) propagate through some ”medium”, whose dynamical description is beyond the scope of our model. Therefore a different macroscopic behaviour emerges, as the microscopic DoF ”test” this medium during their motion. This concept of medium-modification often comes up in the theory of HIC. Thus far, neither the complete, first-principle based description of the QGP – the medium – nor its interaction with QP-objects – such as energetic partons – is known satisfactorily. The theoretical understanding is successful only in the realm of weak jet–medium coupling, where η/s is large and therefore the quasi-particle nature of the partonic DoF is not altered significantly. That is why we keep on constructing effective models on the long way we still have to pursue to understand more fundamentally the strongly interacting matter.

3 Novel scientific results

In the following I summarize the main results of the thesis. All these results are the product of the research I have carried out on my own, or I have significantly contributed to. The corresponding scientific publications are also indicated.

I. Analysis of the detailed balance in multi-component modified kinetic equations. In case of two component there is no detailed balance solution in general.
I analysed the conditions of the existence of a detailed balance solution in a non-extensive modification of the Boltzmann kinetic equation, motivated by medium effects. Such a solution balances the gain and loss processes perfectly.
With one component, a detailed balance solution always exists compatible with the Jaynes principle. The modification I used alters the kinetic energy constraint of a two-particle collision by adding an "interaction" term to the total kinetic energy, i.e.: $E_1 + E_2 + aE_1E_2 = \text{const}$.
In the case of two components, there are three different types of processes need to be balanced in equilibrium. For example, for particle species A and B there are collisions involving two A-type, two B-type or an A- and a B-type particle as well. I showed that

for non-equal modification parameters a_{AA}, a_{BB} and a_{AB} no detailed balance solution exists. Only a dynamical feedback of the modification parameters can maintain balance between the gain and loss terms, in which these parameters become equal. Thus, an effectively one-component system emerges. The corresponding publication is Ref. [1].

II. Numerical analysis of two-component plasma with linearly modified kinetic energy addition constraint. Scaling behaviour, thermodynamic interpretation.

To verify the findings mentioned in I, I also investigated the multi-component kinetic equation by numerical methods. Throughout the numerical analysis of the two-component case, I found a scaling family of solutions with stationary shape. After a short time of isotropisation, each gas component is characterized by an energy distribution depending on time only through the average of the total kinetic energy (which is not conserved in this model).

I also showed analytically the existence of such solutions. The stationary shape of the distributions, i.e. $f(E,t) = \frac{1}{\langle E\rangle(t)}\phi(E/\langle E\rangle)$ suggest that the system is in a pre-thermalized state. Therefore, the gas components can be interpreted as cooling or warming thermodynamical bodies, being in thermal contact with the environment through a medium in which the gas particles are propagating through. The corresponding publication is Ref. [1].

III. Phenomenological model for elliptic flow in non-central heavy-ion collisions.

My colleagues and I constructed a phenomenological model for the description of the azimuthal asymmetry (the so-called elliptic flow) of the non-central heavy-ion collisions. The key element of this model is the observation, that two charged particles decelerating towards each other can produce photon emission spectra similar to those of observed in proton-proton and proton-nucleon experiments.

Using a statistical ensemble of decelerating particle pairs as sources of photon or light particle emission, I was able to deduce a fairly simple formula for the elliptic flow, simple enough to fit the experimental data with three independent parameters. I analysed the elliptic flow of photons and also of charged hadrons using this phenomenological formula.

I estimated the geometrical parameters of the emission region, belonging to such bremsstrahlung-induced elliptic flow patterns. Our findings have been published in Ref. [2].

IV. Transport coefficients in the linear response derived in an effective field theory framework.

I derived the transport coefficients in the linear response approximation using Kubo's formula in an effective field theory framework. This kind of phenomenological description is motivated by the medium-modified dynamics of a many-body system. It can be also useful to describe the long-wavelength excitations in the vicinity of a critical end point on the phase diagram.

The description is parametrized fully by the two-particle correlation functions. Using the Keldysh formalism, I gave closed formulae for the thermodynamical quantities and the transport coefficients. The corresponding publication is Ref. [3].

V. Liquid–gas crossover within an extended quasi-particle picture.

I analysed the ratio of the shear viscosity η and the entropy density s using the formulae mentioned in point IV. η/s characterizes the relaxation of shear deformations to the local equilibrium state of the fluid, therefore it measures the fluidity of the material under consideration.

I constructed model spectral functions for investigating the liquid–gas crossover parametrically in the previously mentioned effective field theory framework. I found that the continuum part of the spectral function, besides the quasi-particle pole, plays a crucial role in the phenomenology of the fluidity of the system. Namely, making the spectral function to be less dominated by the quasi-particle pole (by increasing the relative weight of the continuum part) results increased fluidity (decreased value of η/s). The corresponding publication is Ref. [3].

VI. Thermodynamical lower bound for the shear viscosity in the EQP.
Using the effective field theory framework mentioned in V., I examined the lower bound of the shear viscosity η with fixed value of the entropy density s. I also analysed the spectral density of states, which minimizes the ratio η/s. In the spinless case the accessible states seems to accumulate near zero momentum. The findings of IV, V and VI have been published in Ref. [3].

List of publications

[1] M. Horváth and T. S. Biró,
"Multicomponent Modified Boltzmann Equation and Thermalization," Eur. Phys. J. Plus **129**, 165 (2014).

[2] M. Horváth, T. S. Biró, and Z. Schram,
"Elliptic flow due to radiation in heavy-ion collisions,"
Eur. Phys. J. A **51**, 75 (2015).

[3] M. Horváth and A. Jakovác,
"Shear viscosity over entropy density ratio with extended quasi-particles," Phys. Rev. D **93**, 056010 (2016).