Theoretical study on the formation of high energy density states in heavy ion collisions
— PhD thesis summary —

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1 Introduction

Quantum chromodynamics (QCD), the theory of strong interaction, predicts the appearance of a "new" state of matter at high energy densities, the quark gluon plasma (QGP). The baryonic matter of the Universe existed in this form in the first 15-20 μs after the Big Bang. In today's Universe, cold, high density quark matter may exist in the core of neutron stars.

Due to the difficulties of solving the QCD field equations, details of the quark-hadron transition (*confinement*) are unknown, so experiments have special significance. For the experimental investigation of the phenomena, high energy heavy ion collisions provide a closer opportunity than the observation of neutron stars or the early states of the Universe. Experiments of this kind are performed in the CERN SPS and the BNL RHIC accelerators. Quark gluon plasma creation will be one of the main research topics also in CERN LHC that will start up in 2008.

From the theoretical point of view, quark-hadron transition can be approached via lattice QCD or phenomenological models. Lattice QCD provides the energy density and the pressure of the strongly interacting matter. This way we obtain the equation of state of the QCD matter. Using this equation of state, the time evolution of a heavy ion collision can be described by equilibrated hydrodynamical methods. Hydrodynamic description is important because it can provide space-time evolution and distribution of many macroscopic quantities and the characteristic times of the processes. Moreover, by following the evolution backwards in time, one can determina early states. The appearance of QGP and its equilibrium hadronization can be described well by hydrodynamic models.

However, detailed investigations of heavy ion collisions show that usually there is not enough time to reach equilibrium. Thus it is reasonable to describe the phase transition by non-equilibrium methods. Besides field theoretical modeling (e.g. Nambu-Jona-Lasinio model), another possibility is the assumption of quantum mechanical quark coalescence. A non-equilibrium description based on this assumption is my MICOR (Microscopical Coalescence Rehadronization) model.

The initial state of the hadronization described by quark coalescence is a plasma state containing massive quarks and antiquarks. The appearance of such a deconfined sate is supported by lattice QCD calculations at near-critical temperatures. The final state of hadronization is a gas of colorless "prehadrons". The applied microscopical coalescence mechanism leads to the creation of off-shell hadrons and hadron resonances. Their spectral functions given by the coalescence process is close to the Breit-Wigner distributions of known resonances. The stable, long living, experimentally detectable particles are formed from resonance decays. Predictions can be made about the final state hadron momentum spectra by neglecting secondary interactions. The best way to determine the model parameters is by fitting them to particles with short lifetime or small interaction cross sections. Examples of such particles are the purely strange hadrons; the ϕ meson and the Ω baryon. An interesting question is whether quark coalescence can also explain the creation of the heavier, charm hadrons (e.g. D and J/ψ).

For a realistic description of the momentum distribution of long living, more intensively interacting particles (e.g. pions and nucleons), secondary interactions should also be taken into account. The general approach to this problem is the numerical solution of the Boltzmann equation that describes the hadronic interactions. There are many hadron and parton transport code for modeling theoretically the heavy ion collisions. However, most of these programs are developed for special purposes. Moreover, the inner structure is usually hard to understand for anyone else than their author (e.g. RQMD). This is a general problem with the currently existing codes; there is a need for a program that is easily extendable and able to simulate any transport model, in both the hadron and the parton level.

Many problems must be solved for the development of such a universal code. One of these problems is that Lorentz invariance must be ensured. Lorentz invariance is violated by the cascade algorithm because instead of world lines, particles sweep through "world tubes" with radii depending on the cross sections. World tubes can cross each other in many spacelike separated points, so it depends on the reference frame, which event occurred first, which is the interaction that has to be taken into account from a set of possible interactions. Thus simulations with the same initial conditions may have different results when performed in different reference frames. Most of the hadron and parton cascades modeling high energy heavy ion collisions neglect Lorentz invariance violation. The code developed with my contribution also had to handle this problem.

Another important problem is the application of a hadronization model (the MICOR model in my case) and the hadron cascade (GROMIT) together; the determination of the initial quark matter properties from the experimental final state hadron spectra.

2 Methods

1. By assuming Jüttner distribution, longitudinal Bjorken flow, constant transverse flow and the cross section of the "pick up" type two-particle coalescence process, I determined the total and the momentum dependent rate of composite particle creation in the form of an integral consisting of phase space distribution functions.
2. I calculated the integrals by Monte Carlo simulations, using a C++ program that I developed.
3. I performed the secondary interaction simulations using a numerical method for solving the Boltzmann equations, the cascade algorithm.
4. I studied the effects of the particle subdivision method (the λ parameter) of Lorentz invariance correction, on the momentum spectra.
5. I created the basic structure of the cascade program, many interaction and analysis routines and other modules. For example, the resonance formation channel in which the incoming particles can also be resonances, the nucleon-nucleon and nucleon-kaon cross sections, the modules that create histograms containing spectra, a module for counting and tracking interactions (also in inelastic cases), etc.
6. I wrote a program for fitting functions to momentum spectrum data.

3 Results

My PhD work has the following results:

1. I studied the hydrodynamic description of the space-time evolution of matter created in heavy ion collisions. We have found a new analytic solution to the hydrodynamic equations of fireball expansion. I calculated the scale factor and the entropy [1]. Our new solution can have many applications in heavy ion physics.
2. I developed a non-equilibrium model of the hadronization of quark matter created in heavy ion collisions (MICOR). I compared its predictions to other models [2]. By extracting the model parameters from the momentum spectra of the ϕ and Ω particles, I got a prediction to the ρ meson that matches the experimental results [3]. However, to describe long living, intensively interacting particles (e.g. nucleons), it proved to be necessary to simulate the secondary interactions. I also applied the model for the description of charm meson creation (D and J/ψ). It turned out that the initial state cannot be described with one collective flow, the heavier charm quarks "lag behind" light and strange quarks, their transverse flow velocity remains smaller [4].

3. I developed a particle cascade program to solve the Boltzmann equation of the secondary interactions between hadrons [5, 6, 7]. It became more general than the problems I studied, it is able to simulate any transport model, it can be used as a parton cascade, moreover it supports the subdivision method for the correction of Lorentz invariance violation. With the GROMIT program I solved the following problems:

    - In the "pion wind" problem I found that for large cross sections or large initial densities, the final momentum spectra has a strong dependence on the λ subdivision. Using constant 40 mb cross sections, the inverse slope of the transverse momentum spectra of nucleons is 20% smaller in the naive, $\lambda = 1$ case than the "real" value that we would get from the exact solution of the Boltzmann equation, in the Lorentz invariant limit. By increasing the subdivision to $\lambda = 16$, we get a good approximation.
    - Secondary interaction simulation of the resonance gas generated by the MICOR hadronization model. The coalescence model completed with the secondary hadronic interactions was also able to describe the pion and proton spectra. Another result is that in the resonance gas created by quark coalescence, collisions are rare enough and most cross sections are small enough for the Lorentz invariance violation of the cascade algorithm to be negligible. Thus subdivision is not necessary in this problem.
    - Study of parton energy loss in RHIC Au+Au collisions, at $\sqrt{s_{NN}} = 130\,\mathrm{GeV}$ energy. $2 \to 2$ scattering and $2 \to 2 +$ *final state radiation* processes of quarks and gluons have been performed. As a consequence of these processes, the particle momentum distributions has changed, the high momentum component has decreased ("quenching"). The transverse energy is decreased with an amount depending on the cross sections. Two different hadronization mechanisms have been compared that lead to different final state hadron distributions. The Lund string fragmentation model needed larger parton cross sections to reproduce the experimental pion spectra than the independent fragmentation model [7].

    I performed these studies as a member of the RHIC Transport Theory Collaboration (RTTC). Our aim is to develop transport models describing high energy heavy ion collisions, using our universal code.

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