Equilibration of hot and dense nuclear matter

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Abstract. We perform a Monte Carlo calculation simulation for a system which resembles an equilibrated hadronic gas in a box using the microscopic transport model called the Ultra-relativistic Quantum Molecular Dynamics (UrQMD). We calculate spectra, multiplicity, and rapidity for various hadrons at fixed energy density. The particle multiplicity equilibrates after some time, rapidity distribution is isotropic and the energy spectra of the different hadronic species are fitted by a Boltzmann distribution to obtain equilibrium temperature. This indicates that the system has reached equilibrium.

1. Introduction

The assumption that strongly interacting matter known as quark gluon plasma produced in heavy-ion collisions at high energy, can reach the state of local equilibrium [1] is one of the most important topics in the relativistic heavy-ion field of research. The degree of equilibration can be checked by fitting the measured particle yields and transverse momentum spectra to that of the thermal model in order to extract the conditions of the fireball at the chemical and thermal freeze-out [2-3]. Due to the lack of a rigorous first-principle theory of nuclear reactions at relativistic energies, the approach to local equilibrium is investigated by analysing the dynamics provided by microscopic Monte Carlo simulations, i.e., microscopic string, cascade or transport models [4-5]. These models describe experimental data on hadronic and nuclear collisions in a wide energy range reasonable well, but not predict local equilibrium. For this study the microscopic transport model ultra-relativistic quantum molecular dynamics UrQMD [6] is used to simulate the equilibrated hadronic gas in a box.

2. Microscopic Transport Model for Equilibrated Infinite Matter

2.1. Description of the UrQMD Model

To investigate the equilibration of the system, our hadronic medium is simulated using UrQMD. The UrQMD is a microscopic transport model designed for the description of hadron-hadron, hadron-nucleus and nucleus-nucleus collisions for energies spanning a few hundred MeV up to hundreds of GeV per nucleon in the centre of mass system. It is a transport covariant model based upon Boltzmann equation

$$p.\partial f_i(x^\mu, p^\upsilon) = C_i,$$

where f_i is the one-particle phase-space distribution function for a given species i, and C_i is interaction or collision term.

Interactions in our calculations are based only upon scattering. The criterion for a collision to occur is based upon the geometric interpretation of the cross section:

$$d_{trans} \leq d_0 = \sqrt{\frac{\sigma_{tot}}{\pi}}, \qquad \sigma_{tot} = \sigma(\sqrt{s}, type)$$

where d_{trans} is the Lorentz-invariant transverse distance at closest approach between two particles and σ_{tot} is the total cross-section. The description of the UrQMD model is presented in detail in [6].

2.2. Criteria of Thermal and Chemical Equilibrium

To force our system into equilibrium, we consider a system in a cubic box and impose periodic boundary conditions in real space. Thus if a particle leaves the box, another one with the same momentum enters from the opposite side. The overall energy density, ε of the system is being fixed. The initial distributions are composed of mesons with uniform random distributions in phase space. The energy density is defined as $\varepsilon = \frac{E}{V}$, where *E* is the energy of *N* particles:

$$E = \sum_{i=1}^{N} \sqrt{m_i^2 + p_i^2}$$

The three-momenta p_i of the particles in the initial state are randomly distributed in the center of mass system of the particles:

$$\sum_{i=1}^{N} p_i = 0$$

This technique is similar to the one done in [7-8]. The input parameters of our system are as follows: volume of the box (10 x 10 x 10 fm^3), and initial particles species (π, K, η, ρ).

2.2.1. Chemical Equilibrium

The time evolution of the various particles densities at zero net baryon number density and energy densities ε = 0.3 is illustrated in Figure 1. The chemical equilibrium time for strange particles is much longer than for non-strange hadrons due to suppression of strange processes. As shown in Figure 1 the particle species saturates as a function of evolution time. The saturation of the particle densities indicates the realization of chemical equilibrium. We therefore conclude that chemical equilibrium has been reached.

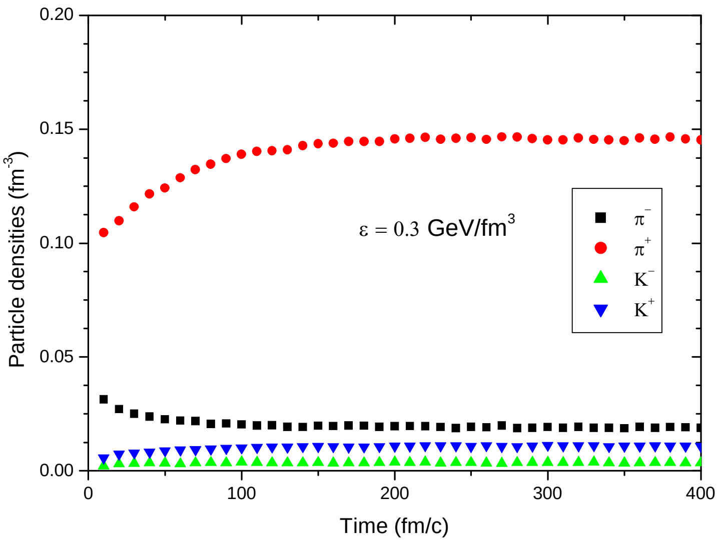


Figure 1. The time evolution of particle densities for an equilibrated system of hadron gas at a zero net baryon density, V = 1000 fm^3,T = 172 MeV and ε = 0.3 GeV/fm^3.

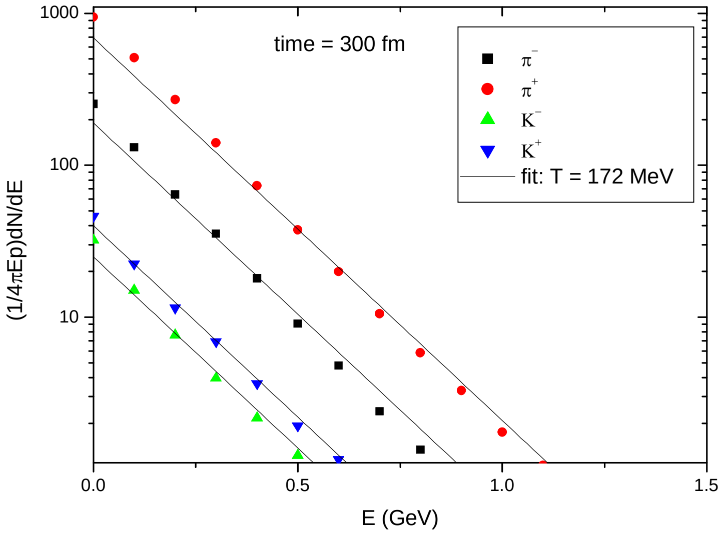
2.2.2. Thermal Equilibrium

After investigating whether the chemical equilibrium is attained, we then examine the energy distributions at that particular evolution time-step in order to verify that thermal equilibrium has been reached. A system which has attained thermal equilibrium should have its energy distributions following a Boltzmann distribution:

$$\frac{dN_i}{d^3p} = \frac{dN}{4\pi EpdE} \propto \exp\left(-\frac{E_i}{T}\right),$$

where $1/T$ is the slope parameter of the distribution and $E_i = \sqrt{p_i^2 + m_i^2}$ is the energy of particle species i. Figure 2 show the energy spectra for different particle species at energy density ε = 0.3 GeV/fm^3. The solid lines are the fitted results obtained from Boltzmann distributions. The thermal temperature is determined from the slope of individual fits of the particle species. The small temperature deviation is due to the distortion of particle spectra from resonance effects, and statistical fluctuations. We therefore conclude that the system attained thermal equilibrium.

(a)



(b)

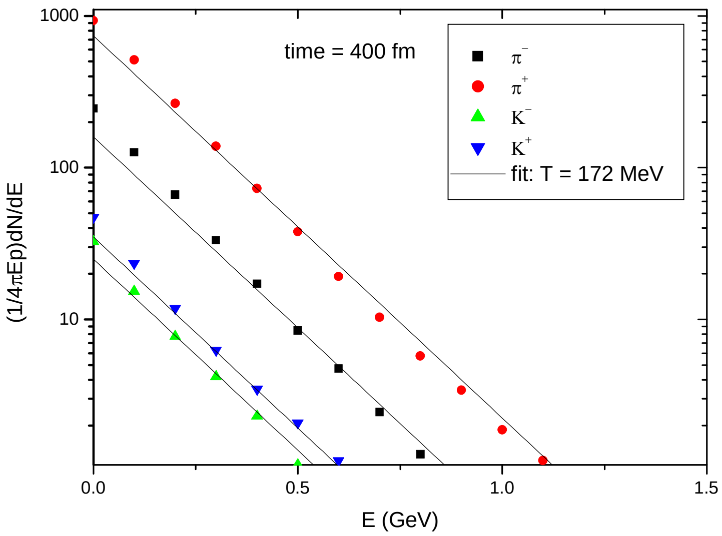


Figure 2. Energy spectra of π^+, π^-, K^+ and K^- at two different values of evolution time, (a) t = 300 fm/c, (b) t = 400 fm/c. The lines are fitted results that are given by Boltzmann distributions. The calculation was done at V = 1000 fm^3, n_B = 0.0 fm^{-3} and ε = 0.3 GeV/fm^3.

2.2.3. Rapidity and Transverse Momentum Distribution

As shown in Figure 3, the rapidity distribution for different particle species is isotropic. Figure 4 presents the transverse momentum spectra for different particle species at mid rapidity. It is described by the following exponential distribution equation:

$$\frac{d^2N}{2\pi p_T dy dp_T} \propto \exp\left(-\frac{m_T}{T}\right)$$

where m_T is the transverse mass defined as $m_T = \sqrt{p_T + m_0}$. Note that this type of fitting procedure will give the meaningful results for the temperature only at the low p_T end of the spectrum since low p_T particles are more likely to be in thermal equilibrium. Furthermore, the transverse momentum distribution also depends on centrality since more central collisions are more likely to come to thermal equilibrium.

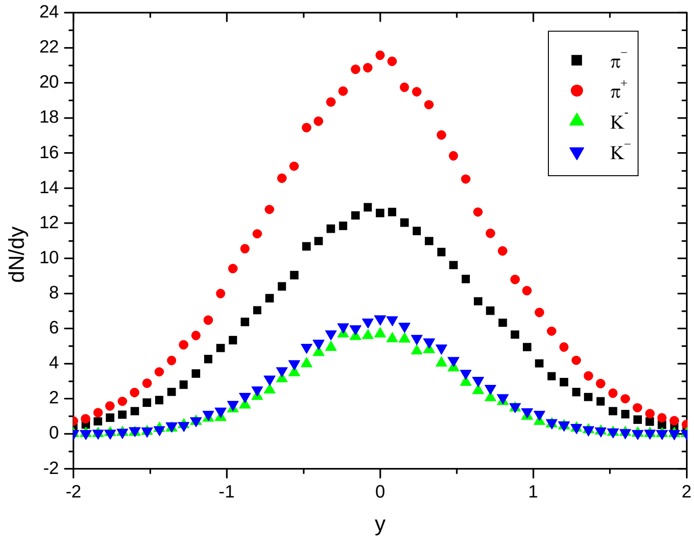


Figure 3. Rapidity distributions of π^+, π^-, K^+ and K^- at ε = 0.3 GeV/fm^3.

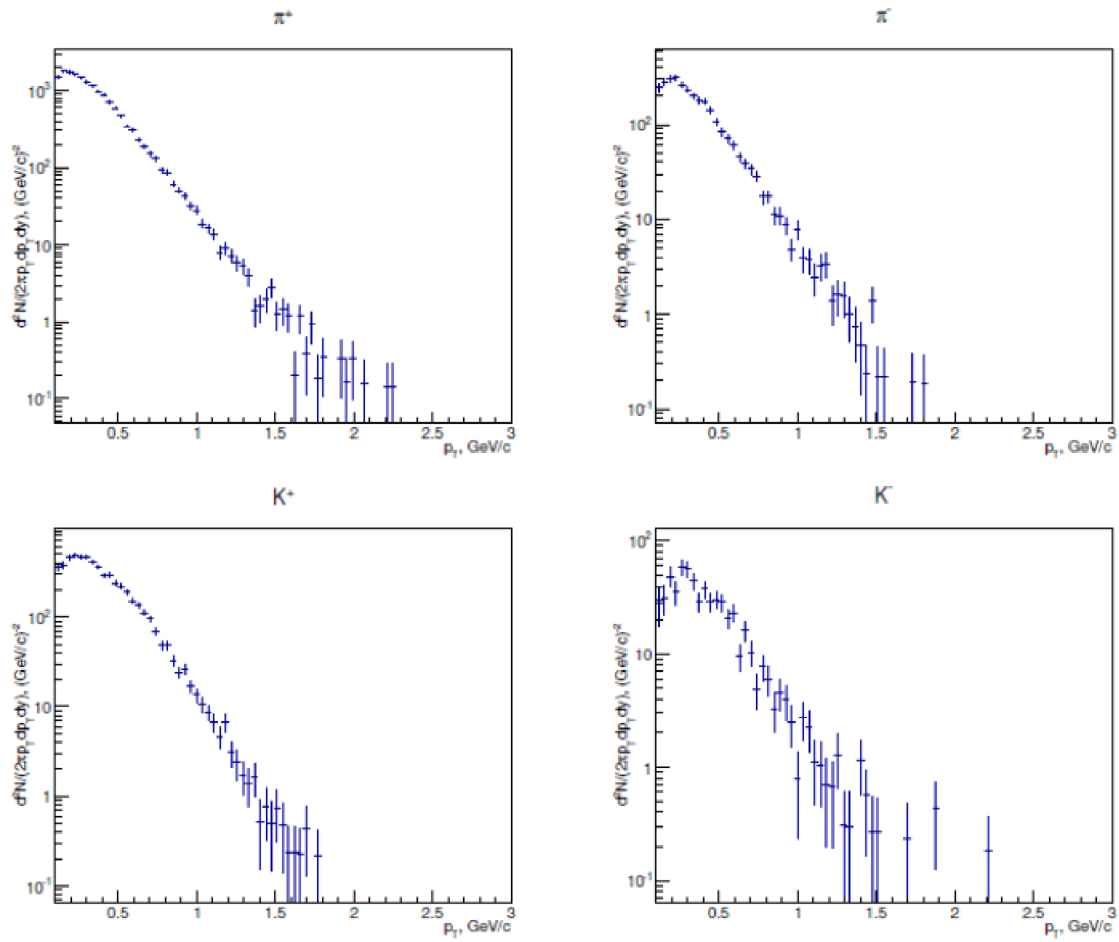


Figure 4. Transverse momentum spectra of π^+, π^-, K^+ and K^- at mid-rapidity and $\varepsilon = 0.3$ GeV/fm^3.

3. Conclusion

We have studied the space-time evolution of the strongly interacting matter formed in ultra-relativistic heavy-ion collisions. The microscopic transport UrQMD model is used to simulate the equilibrated hadronic gas in a box with periodic boundary imposed. It is shown that both chemical and thermal equilibrium is reached by the system of hadronic gas.

Acknowledgments

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