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## Dynamical equilibration in strongly-interacting parton-hadron matter

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**Abstract.** We study the kinetic and chemical equilibration in ‘infinite’ parton-hadron matter within the Parton-Hadron-String Dynamics transport approach, which is based on a dynamical quasiparticle model for partons matched to reproduce lattice-QCD results – including the partonic equation of state – in thermodynamic equilibrium. The ‘infinite’ matter is simulated within a cubic box with periodic boundary conditions initialized at different baryon density (or chemical potential) and energy density. The transition from initially pure partonic matter to hadronic degrees of freedom (or vice versa) occurs dynamically by interactions. Different thermodynamical distributions of the strongly-interacting quark-gluon plasma (sQGP) are addressed and discussed.

### 1 Introduction

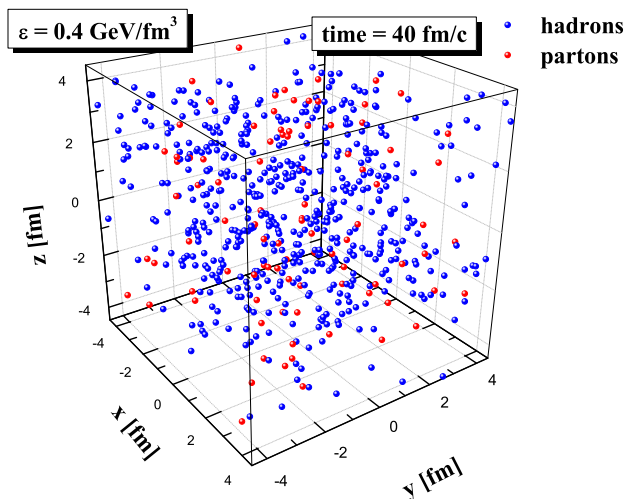
Nucleus-nucleus collisions at ultra-relativistic energies are studied experimentally and theoretically to obtain information about the properties of hadrons at high density and/or temperature as well as about the phase transition to a new state of matter, the quark-gluon plasma (QGP). Whereas the early ‘big-bang’ of the universe most likely evolved through steps of kinetic and chemical equilibrium, the laboratory ‘tiny bangs’ proceed through phase-space configurations that initially are far from an equilibrium phase and then evolve by fast expansion. On the other hand, many observables from strongly-interacting systems are dominated by many-body phase space such that spectra and abundances look ‘thermal’. It is thus tempting to characterize the experimental observables by global thermodynamical quantities like ‘temperature’, chemical potentials or entropy [1–8]. We note, that the use of macroscopic models like hydrodynamics [9–12] employs as basic assumption the concept of local thermal and chemical equilibrium. The crucial question, however, how and on what timescales a global thermodynamic equilibrium can be achieved, is presently a matter of debate. Thus non-equilibrium approaches have been used in the past to address the problem of timescales associated to global or local equilibration [13–21]. In view of the increasing ‘popularity’ of thermodynamic analyses a thorough microscopic study of the questions of thermalization and equilibration of confined and deconfined matter within a transport approach appears necessary.

### 2 The model

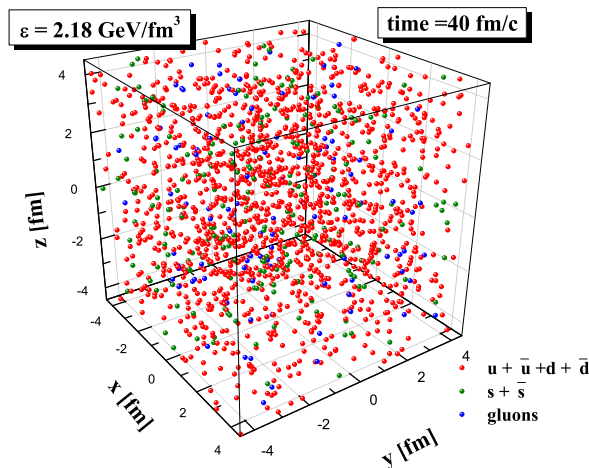
In this contribution, we study the kinetic and chemical equilibration in ‘infinite’ parton-hadron matter within the novel Parton-Hadron-String Dynamics (PHSD) transport approach [22, 23], which is based on generalized transport equations on the basis of the off-shell Kadanoff-Baym equations [24, 25] for Green’s functions in phase-space representation (in the first order gradient expansion, beyond the quasiparticle approximation). In the KB theory, the field quanta are described in terms of propagators with complex self-energies. Whereas the real part of the self-energies can be related to mean-field potentials, the imaginary parts provide information about the lifetime and/or reaction rates of time-like ‘particles’. The basis of the partonic phase description is the dynamical quasiparticle model (DQPM) [26, 27] matched to reproduce lattice QCD results – including the partonic equation of state – in thermodynamic equilibrium [24]. In fact, the DQPM allows a simple and transparent interpretation for thermodynamic quantities as well as correlators – measured on the lattice – by means of effective strongly interacting partonic quasiparticles with broad spectral functions. The transition from partonic to hadronic degrees of freedom is described by covariant transition rates for the fusion of quark-antiquark pairs or three quarks (antiquarks), obeying flavor current conservation, color neutrality as well as energy-momentum conservation.

The ‘infinite’ matter is simulated within a cubic box with periodic boundary conditions initialized at various values for baryon density (or chemical potential) and energy density. The size of the box is fixed to  $9^3 \text{ fm}^3$ . The initialization is done by populating the box with light ( $u, d, s$ ) quarks, antiquarks and gluons with random space positions and the momenta distributed according to the Fermi-

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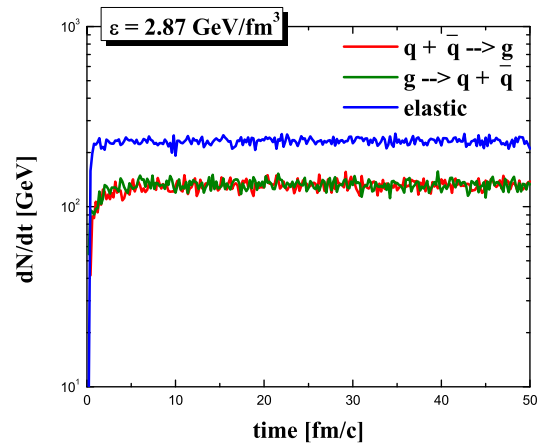
**Fig. 1.** Snapshot of the spatial distribution of hadrons (blue) and partons (red) at an evolution time of 40 fm/c after the systems was initialized by solely partons at an energy density below critical.



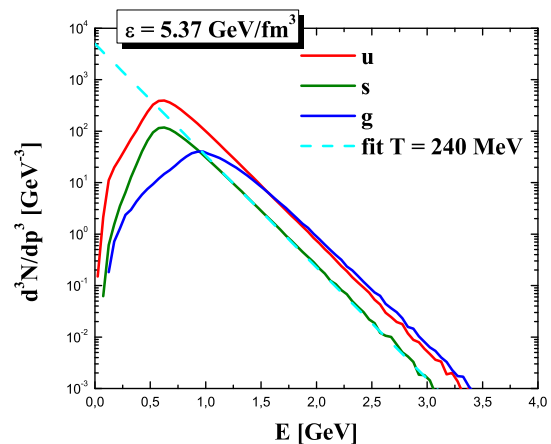
**Fig. 2.** Snapshot of the spatial distribution of light quarks and antiquarks (red), strange quarks and antiquarks (green) and gluons (blue) at a time of 40 fm/c.

Dirac distribution. The total numbers of the quarks and antiquarks are chosen so that the system with various desired values of the energy density  $\epsilon$  (the total energy of the particles divided by the size of the box) and baryon potential  $\mu$  can be studied.

In the course of the subsequent transport evolution of the system by PHSD, the numbers of gluons, quarks and antiquarks are adjusted dynamically through the inelastic collisions to equilibrium values, while the elastic collisions lead to eventual thermalization of all the particle species (e.g.  $u, d, s$  quarks and gluons, if the energy density in the system is above critical). Please note that if the energy density in a local cell drops below critical either due to the local fluctuations or because the system was initialized with a low enough number of partons, a transition from initial pure partonic matter to hadronic degrees of freedom occurs dynamically by interactions.



**Fig. 3.** The reaction rates for elastic parton scattering (blue), gluon splitting (green) and flavor neutral  $q\bar{q}$  fusion (red) as a function of time.

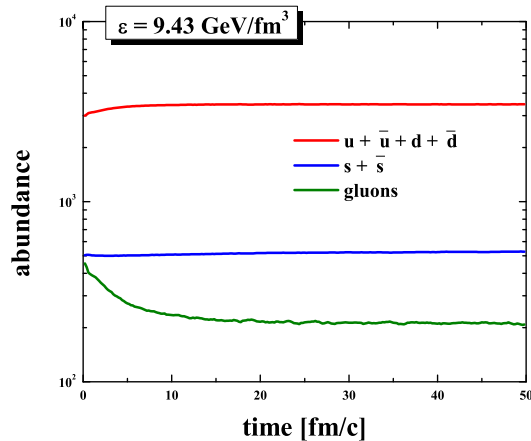


**Fig. 4.** The energy spectra for the off-shell u (red) and s quarks (green) and gluons (blue) in equilibrium for a system initialized at an energy density of  $5.37 \text{ GeV/fm}^3$ .

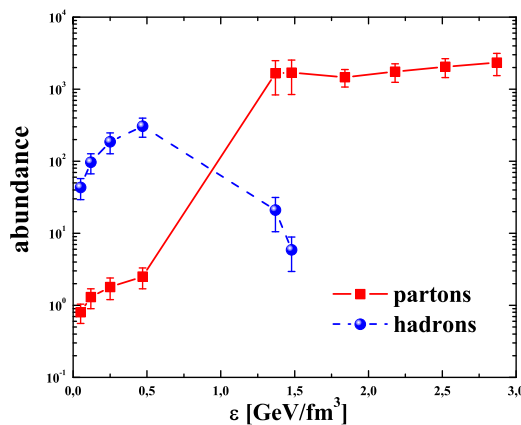
### 3 Results

We present in the Fig. 1 a snapshot of the spatial distribution of hadrons (blue) and partons (red) at an evolution time of 40 fm/c after the systems was initialized by solely partons at an energy density of  $0.4 \text{ GeV/fm}^3$ . At this energy density – slightly below the critical energy density for the deconfinement phase transition – most of the partons have already formed hadrons at this point of the evolution of the system, but a small fraction of partons have yet not hadronized. The remaining partons are approximately in the thermal equilibrium with the hadrons.

In Fig. 2, we show a snapshot of the systems that has been initialized at energy density of  $2.18 \text{ GeV/fm}^3$ , which is clearly above the critical energy density. One can see in Fig. 2 the spatial distribution of light quarks and antiquarks (red), strange quarks and antiquarks (green) and



**Fig. 5.** Abundances of the  $u, d$   $s$  quarks+antiquarks and gluons as a function of time for a system initialized at an energy density of  $9.43 \text{ GeV/fm}^3$ .



**Fig. 6.** The average abundances of hadrons (blue) and partons (red) in equilibrium as functions of the energy density  $\epsilon$ .

gluons (blue) at a time of  $40 \text{ fm/c}$ . At this energy density no hadrons are seen. The different parton species are in thermal and chemical equilibrium.

After a few  $\text{fm/c}$  the system – initialized at an energy density of  $2.87 \text{ GeV/fm}^3$  – has achieved chemical and thermal equilibrium, since the reaction rates are practically constant and obey detailed balance for gluon splitting and  $q\bar{q}$  fusion. This is shown in Fig. 3, where the reaction rates for elastic parton scattering (blue), gluon splitting (green) and flavor neutral  $q\bar{q}$  fusion (red) are presented as a function of time.

Another indication that the system has achieved the thermal equilibrium is seen in the distribution of the kinetic energy of the particles. We show in Fig. 4 the energy spectra for the off-shell  $u$  (red) and  $s$  quarks (green) and gluons (blue) in equilibrium for a system initialized at an energy density of  $5.37 \text{ GeV/fm}^3$ . The spectra may well be described by a Boltzmann distribution with tem-

perature  $T=240 \text{ MeV}$  in the high energy regime. The deviations from the Boltzmann distribution at low energy  $E$  are due to the broad spectral functions of the partons.

On the other hand, a sign of the chemical equilibration is the stabilization of the abundances of the different species. In Fig. 5, we show the particle abundances as a function of time for a system initialized at  $9.43 \text{ GeV/fm}^3$ . One can see that the chemical equilibration is reached after about  $15 \text{ fm/c}$ .

It is interesting to observe in Fig. 6 the average abundances of hadrons (blue) and partons (red) in equilibrium as functions of the energy density  $\epsilon$ . At energy densities below critical ( $\approx 0.5 \text{ GeV/fm}^3$ ) the system evolves into a state, which is dominated by hadrons and has a very small fraction of partons due to rare fluctuations of local energy density to high values. At higher energy densities, the system is in a QGP final state, with a small hadron admixture. At high enough energy (above approx.  $2 \text{ GeV/fm}^3$ ) we find that hadron fraction is negligible. In the regime of energy densities from  $0.48$  to  $1.3 \text{ GeV/fm}^3$  the calculations have provided so far no stable equilibrium over time due to large fluctuations between hadronic and partonic configurations. Further studies are on the way.

## 4 Conclusions

We have studied the kinetic and chemical equilibration in ‘infinite’ parton-hadron matter within the Parton-Hadron-String Dynamics transport approach (PHSD), which is based on a dynamical quasiparticle model for partons (DQPM) matched to reproduce lattice-QCD results – including the partonic equation of state – in thermodynamic equilibrium.

The ‘infinite’ matter has been simulated within a cubic box with periodic boundary conditions initialized at different baryon density (or chemical potential) and energy density.

Depending on the energy density, the system evolved into an ensemble of either hadrons or partons in chemical and thermal equilibrium. Abundances of the final particles depend on the energy density. The temperature of the degrees of freedom in the final state was measured by fitting the slopes of the Boltzmann-like tails of the thermal distributions of their kinetic energy.

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