Dynamical equilibration of the strongly interacting parton-hadron matter

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Introduction

We study the kinetic and chemical equilibration in 'infinite' parton-hadron matter within the novel Parton-Hadron-String-Dynamics (PHSD) transport approach [1,2], which is based on generalized transport equations on the basis of the off-shell Kadanoff-Baym equations for Green's functions in phase-space representation (in the first order gradient expansion, beyond the quasiparticle approximation). The basis of the partonic phase description is the dynamical quasiparticle model (DQPM) matched to reproduce lattice QCD results – including the partonic equation of state – in thermodynamic equilibrium [3]. The transition from partonic to hadronic degrees of freedom is described by covariant transition rates for fusion of quark-antiquark pairs or three quarks (antiquarks), obeying flavor current conservation, color neutrality as well as energy-momentum conservation.

Box with periodic boundary conditions

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 transition from initial pure hadronic matter to partonic degrees of freedom (or vice verse) occurs dynamically by interactions.

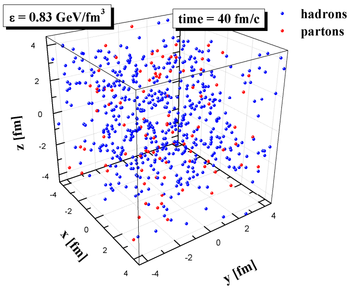


Fig.1: Snapshot of the spatial distribution of hadrons (blue) and partons (red) at an evolution time of 40 fm/c after the systems was initialized by solely partons at an energy density of 0.83 GeV/fm^3. At this energy density – close to the critical energy density – most of the partons have formed hadrons. The remaining partons are in thermal equilibrium with the hadrons.

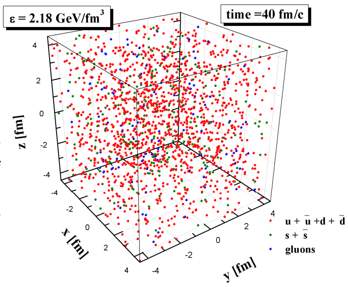


Fig. 2: Snapshot of the spatial distribution of light quarks and antiquarks (red), strange quarks and antiquarks (green) and gluons (blue) at a time of 40 fm/c. The systems has been initialized by solely partons at an energy density of 2.18 GeV/fm^3. At this energy density – clearly above the critical energy density – no hadrons are seen. The different partons are in thermal and chemical equilibrium.

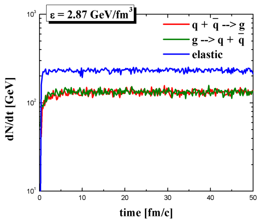
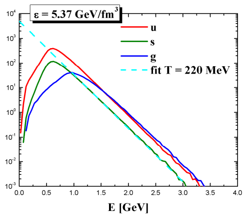


Fig. 3: The reaction rates for elastic parton scattering (blue), gluon splitting (green) and flavor neutral quark + antiquark fusion (red) as a function of time. After a few fm/c the system – initialized at an energy density of 2.87 GeV/fm^3 – has achieved chemical and thermal equilibrium, since the reactions rates are practically constant and obey detailed balance for gluon splitting and q + qbar fusion.

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 GeV/fm^3. The spectra may well be described by a Boltzmann distribution with temperature T=220 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.



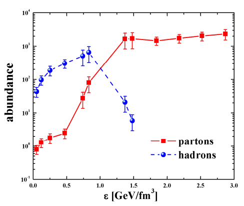


Fig. 5: The average abundances of hadrons (blue) and partons (red) in equilibrium as functions of the energy density ε. In the regime of energy densities from 0.85 to 1.3 GeV/fm^3 the calculations have provided no stable equilibrium over time due to large fluctuations between hadronic and partonic configurations.

Expanding partonic fireball

Initial conditions

We additionally present results from PHSD for the model case of an expanding partonic fireball at initial temperature T=1.7T$_C$ (T$_C$=0.185 GeV) with quasiparticle properties and four-momentum distributions determined by the DQPM [2]. The initial distribution for quarks, antiquarks and gluons in coordinate space is taken as a Gaussian ellipsoid with a spatial eccentricity

$$\epsilon = \langle y^2 - x^2 \rangle / \langle y^2 + x^2 \rangle \quad , < z^2 >=< y^2 >$$

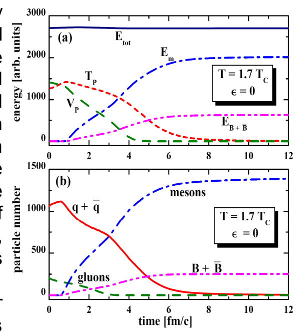
The hadronization is performed by integrating the rate equations for hadronization in space and time, which are discretized by Δt and ΔV(t) :

$$\frac{1}{\Delta V}\int_{\Delta V} d^3x \int \frac{d\omega_q}{2\pi}\omega_q \int \frac{d^3p_q}{(2\pi)^3}\, \rho_q(\omega_q,p_q)\, N_q(x,p_q) = \frac{1}{\Delta V}\sum_{J_q \epsilon \Delta V} 1 \;=\; \rho_q(\Delta V)\;,$$

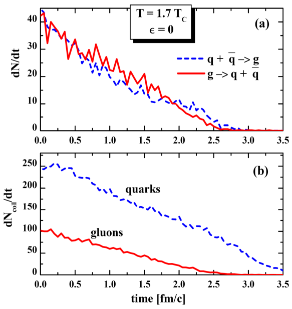
where the sum over J$_q$ implies a sum over all test particles of type q (here quarks) in the local volume ΔV in each parallel run.

Dynamical evolution

In upper part of Fig. 6 we show the energy balance for the expanding system at initial temperature T=1.7T$_C$ and eccentricity ε=0. The total energy E$_{tot}$ (upper part) is conserved within 3% throughout the partonic expansion and hadronization phase, for t>8 fm/c it is given essentially by the energy contribution from mesons and baryons (+antibaryons). The hadronization mainly proceeds during the time interval 1 fm/c < t < 7 fm/c (cf. the lower part of Fig. 6 where the time evolution of the q, qbar, g, meson, baryon (+antibaryon) numbers is displayed).



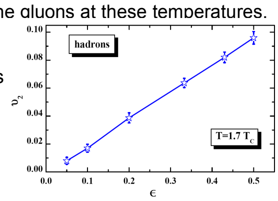
As one observes in Fig. 6, on average the number of hadrons from the resonance or 'string' decays is larger then the initial number of fusing partons.

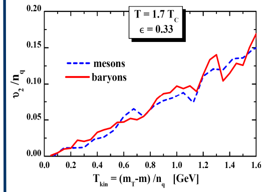


The interaction rates for the channels $q+\bar{q}\rightarrow g$ and $g\rightarrow q+\bar{q}$ are displayed in Fig. 7 (upper part) by the dashed line and solid line, respectively, for the expanding partonic fireball at initial temperature T=1.7T$_C$ and initial eccentricity ε=0. Within statistics the numerical result shows that detailed balance actually is fulfilled for the expanding partonic system, which was initialized in thermal equilibrium. The lower part of Fig. 7 shows the total number of collisions per time for gluons (solid line) and quarks or antiquarks (dashed line); the number of collisions is higher for the fermions, since they are much more frequent than the gluons at these temperatures.

Elliptic flow scaling

Fig. 8 shows the final hadron elliptic flow υ_2 versus the initial eccentricity ε and indicates that the ratio υ_2/ε is practically constant (~0.2) as in ideal hydrodynamics. Accordingly, the parton dynamics in PHSD is close to that of ideal hydrodynamics.





A further test of the PHSD hadronization approach is provided by the 'constituent quark number scaling' of the elliptic flow υ_2. Thus we plot υ_2/n_q versus the transverse kinetic energy per constituent parton,

$$T_{kin} = \frac{m_T - m}{n_q}\;,$$

with m$_T$ and m denoting the transverse mass and actual mass, respectively. The results for the quark-number-scaled elliptic flow are shown in Fig. 9 for mesons (dashed line) and for baryons (solid line) and suggest an approximate scaling (in agreement with

References

[1]. W.Cassing and E.L.Bratkovskaya, *Parton-Hadron-String-Dynamics: an off-shell transport approach for relativistic energies*, Nucl. Phys. A 831: 215-242, 2009. e-Print: arXiv: 0907.5331 [nucl-th].

[2]. W.Cassing and E.L.Bratkovskaya, *Parton transport and hadronization from the dynamical quasiparticle point of view*, Phys. Rev. C 78: 034919, 2008. e-Print: arXiv: 0808.0022 [hep-th].

[3]. W.Cassing, *QCD thermodynamics and confinement from a dynamical quasiparticle point of view*, Nucl. Phys. A791: 365-381, 2007. e-Print: arXiv:0704.1410 [nucl-th].