Parton dynamics and hadronization from the sQGP

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Abstract

The hadronization of an expanding partonic fireball is studied within the Parton-Hadron-Strings Dynamics (PHSD) approach which is based on a dynamical quasiparticle model (DQPM) matched to reproduce lattice QCD results in thermodynamic equilibrium. Apart from strong parton interactions the expansion and development of collective flow is found to be driven by strong gradients in the parton mean-fields. An analysis of the elliptic flow \(v_2\) demonstrates a linear correlation with the spatial eccentricity \(\epsilon\) as in case of ideal hydrodynamics. The hadronization occurs by quark-antiquark fusion or 3 quark/3 antiquark recombination which is described by covariant transition rates. Since the dynamical quarks become very massive, the formed resonant 'pre-hadronic' color-dipole states (\(q\bar{q}\) or \(qqq\)) are of high invariant mass, too, and sequentially decay to the ground-state meson and baryon octets increasing the total entropy. This solves the entropy problem in hadronization in a natural way. Hadronic particle ratios turn out to be in line with those from a grandcanonical partition function at temperature \(T \approx 170\) MeV.

1 Introduction

The 'Big Bang' scenario implies that in the first micro-seconds of the universe the entire state has emerged from a partonic system of quarks, antiquarks and gluons – a quark-gluon plasma (QGP) – to color neutral hadronic matter consisting of interacting hadronic states (and resonances) in which the partonic degrees of freedom are confined. The nature of confinement and the dynamics of this phase transition has motivated a large community for several decades and is still an outstanding question of todays physics. Early concepts of the QGP were guided by the idea of a weakly interacting system of partons which might be described by perturbative QCD (pQCD). However, experimental observations at the Relativistic-Heavy-Ion Collider (RHIC) indicated that the new medium created in ultrarelativistic Au+Au collisions was interacting more strongly than hadronic matter and consequently this concept had to be given up. Moreover, in line with theoretical studies in Refs. [1, 2, 3] the medium showed phenomena of an almost perfect liquid of partons [4] as extracted from the strong radial expansion and elliptic flow of hadrons [4].

The question about the properties of this (nonperturbative) QGP liquid is discussed controversially in the literature and dynamical concepts describing the formation of color neutral hadrons from partons are scarce [5, 6, 7, 8]. A fundamental issue for hadronization models is the conservation of 4-momentum as well as the entropy problem because by fusion/coalescence of massless (or low constituent mass) partons to color neutral bound states of low invariant mass (e.g. pions) the number of degrees of
freedom and thus the total entropy is reduced in the hadronization process [6, 7]. This problem - a violation of the second law of thermodynamics as well as of the conservation of four-momentum and flavor currents - definitely needs a sound dynamical solution.

A consistent dynamical approach - valid also for strongly interacting systems - can be formulated on the basis of Kadanoff-Baym (KB) equations [9, 10] or off-shell transport equations in phase-space representation, respectively [10, 11]. In the KB theory the field quanta are described in terms of propagators with complex selfenergies. Whereas the real part of the selfenergies can be related to mean-field potentials, the imaginary parts provide information about the lifetime and/or reaction rates of time-like 'particles' [3]. Once the proper (complex) selfenergies of the degrees of freedom are known the time evolution of the system is fully governed by off-shell transport equations (as described in Refs. [10, 11]).

The determination/extraction of complex selfenergies for the partonic degrees of freedom has been performed in Refs. [3, 12, 13] by fitting lattice QCD (lQCD) 'data' within the Dynamical QuasiParticle Model (DQPM). In fact, the DQPM allows for a simple and transparent interpretation of lattice QCD results for thermodynamic quantities as well as correlators and leads to effective strongly interacting partonic quasiparticles with broad spectral functions.

2 The PHSD approach

The Parton-Hadron-String-Dynamics (PHSD) approach is a microscopic covariant transport model that incorporates effective partonic as well as hadronic degrees of freedom and involves a dynamical description of the hadronization process from partonic to hadronic matter [14]. Whereas the hadronic part is essentially equivalent to the conventional Hadron-Strings-Dynamics (HSD) approach [15] the partonic dynamics is based on the Dynamical QuasiParticle Model (DQPM) [12, 13] which describes QCD properties in terms of single-particle Green's functions (in the sense of a two-particle irreducible (2PI) approach).

We briefly recall the basic assumptions of the DQPM: Following Ref. [16] the dynamical quasiparticle mass (for gluons and quarks) is assumed to be given by the thermal mass in the asymptotic high-momentum regime, which is proportional to the coupling \( g(T/T_c) \) and the temperature \( T \) with a running coupling (squared),

\[
g^2(T/T_c) = \frac{48\pi^2}{(11N_c - 2N_f) \ln[\lambda^2(T/T_c - T_s/T_c)^2]}.
\]

(1)

Here \( N_c = 3 \) stands for the number of colors while \( N_f \) denotes the number of flavors. The parameters controlling the infrared enhancement of the coupling \( \lambda = 2.42 \) and \( T_s = 0.46T_c \) have been fitted in [16] to lQCD results for the entropy density \( s(T) \). An almost perfect reproduction of the energy density \( \varepsilon(T) \) and the pressure \( P(T) \) from lQCD is achieved as well.

The width for gluons and quarks (for vanishing chemical potential \( \mu_q \)) is adopted in the form

\[
\gamma_g(T) = 3g^2T \frac{2c}{8\pi} \ln\left(\frac{2c}{g^2}\right), \quad \gamma_q(T) = g^2T \frac{2c}{6\pi} \ln\left(\frac{2c}{g^2}\right),
\]

(2)

where \( c = 14.4 \) (from Ref. [3]) is related to a magnetic cut-off. We stress that a non-vanishing width \( \gamma \) is the central difference of the DQPM to conventional quasiparticle models [17]. It influence is essentially seen in correlation functions as e.g. in the stationary limit of the correlation function in the off-diagonal elements of the energy-momentum tensor \( T^{kl} \) which defines the shear viscosity \( \eta \) of the medium [3]. Here a sizable width is mandatory to obtain a small ratio in the shear viscosity to entropy density \( \eta/s \).
In line with [16] the parton spectral functions thus are no longer $\delta-$ functions in the invariant mass squared but taken as

$$\rho_j(\omega) = \frac{\gamma_j}{E_j} \left( \frac{1}{(\omega - E_j)^2 + \gamma_j^2} - \frac{1}{(\omega + E_j)^2 + \gamma_j^2} \right)$$  \hspace{1cm} (3)$$

separately for quarks and gluons ($j = q, \bar{q}, g$). With the convention $E^2(p) = p^2 + M_j^2 - \gamma_j^2$, the parameters $M_j^2$ and $\gamma_j$ are directly related to the real and imaginary parts of the retarded self-energy, e.g. $\Pi_j = M_j^2 - 2i\gamma_j^2$. With the spectral functions fixed by Eqs. (1)-(3) the total energy density in the DQPM (at vanishing quark chemical potential) can be evaluated as

$$T^{00} = d_q \int_0^\infty \frac{d\omega}{2\pi} \int \frac{d^3p}{(2\pi)^3} 2\omega^2 \rho_q(\omega, p)n_B(\omega/T) + d_q \int_0^\infty \frac{d\omega}{2\pi} \int \frac{d^3p}{(2\pi)^3} 2\omega^2 \rho_g(\omega, p)n_F(\omega/T),$$  \hspace{1cm} (4)$$

where $n_B$ and $n_F$ denote the Bose and Fermi functions, respectively. The number of transverse gluonic degrees of freedom is $d_g = 16$ while the fermic degrees of freedom amount to $d_q = 4N_cN_f = 36$ in case of three flavors ($N_f=3$). The pressure $P$ then may be obtained by integrating the differential thermodynamic relation

$$P - T \frac{\partial P}{\partial T} = -T^{00}$$  \hspace{1cm} (5)$$

with the entropy density $s$ given by

$$s = \frac{\partial P}{\partial T} = \frac{T^{00} + P}{T}.$$  \hspace{1cm} (6)$$

This approach is thermodynamically consistent and represents a 2PI approximation to hot QCD (once the free parameters in (1) and (2) are fitted to lattice QCD results as in Refs. [3, 12, 13]).

As outlined in detail in Refs. [12, 13] the energy density functional (4) can be separated in space-like and time-like sectors when the spectral functions aquire a finite width. The space-like part of (4) defines a potential energy density $V_p$ since the field quanta involved are virtuell and correspond to partons exchanged in interaction diagrams. The time-like part of (4) corresponds to effective field quanta which can be propagated within the light-cone. Related separations can be made for virtuell and time-like parton densities [12, 13]. Without repeating the details we mention that mean-field potentials for partons can be defined by the derivative of the potential energy density $V_p$ with respect to the time-like parton densities and effective interactions by second derivatives of $V_p$ (cf. Section 3 in Ref. [13]).

Based on the DQPM we have developed an off-shell transport approach [14] denoted as PHSD where the degrees-of-freedom are dynamical quarks, antiquarks and gluons ($q, \bar{q}, g$) with rather large masses and broad spectral functions in line with (1) - (3) as well as the conventional HSD approach [15]. On the partonic side the following elastic and inelastic interactions are included $qq \leftrightarrow qq, \bar{q}q \leftrightarrow \bar{q}q, gg \leftrightarrow gg, gg \leftrightarrow g, q\bar{q} \leftrightarrow g$ exploiting 'detailed-balance' with interaction rates from the DQPM. The hadronisation, i.e. transition from partonic to hadronic degrees of freedom, is described by local covariant transition rates e.g. for $q + \bar{q}$ fusion to a meson $m$ of four-momentum $p = (\omega, \mathbf{p})$ at space time point $x = (t, \mathbf{x})$:

$$\frac{dN_m(x,p)}{d^4x d^4p} = Tr_q Tr_{\bar{q}} \delta^4(p - p_q - p_{\bar{q}}) \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right) \times \omega_{\bar{q}} \rho_{\bar{q}}(p_{\bar{q}}) \omega_q \rho_q(p_q) |v_{q\bar{q}}|^2 W_m(x_q - x_{\bar{q}}, p_q - p_{\bar{q}}) \times N_q(x_q, p_q) N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \delta(\text{flavor, color}).$$  \hspace{1cm} (7)$$

In (7) we have introduced the shorthand notation $Tr_j = \sum_j \int d^4x d^4p/(2\pi)^4$ where $\sum_j$ denotes a summation over discrete quantum numbers (spin, flavor, color); $N_j(x,p)$ is the phase-space density of parton $j$ at space-time position $x$ and four-momentum $p$. In Eq. (7) $\delta(\text{flavor, color})$ stands symbolically
for the conservation of flavor quantum numbers as well as color neutrality of the formed hadron $m$ which can be viewed as a color-dipole or 'pre-hadron'. Furthermore, $v_{qq}(\rho_p)$ is the effective quark-antiquark interaction from the DQPM defined by Eq. (31) of Ref. [13] as a function of the local parton ($q + \bar{q} + g$) density $\rho_p$ (or energy density). Furthermore, $W_m(x, p)$ is the phase-space distribution of the formed 'pre-hadron'. It is taken as a Gaussian in coordinate and momentum space with width $\sqrt{<r^2>} = 0.66$ fm (in the rest frame) which corresponds to an average rms radius of mesons. The width in momentum space is fixed by the uncertainty principle, i.e. $\Delta x \Delta p = 1$ (in natural units). Related transition rates (to Eq. (7)) are defined for the fusion of three off-shell quarks $(q_1 + q_2 + q_3 \leftrightarrow B)$ to color neutral baryonic ($B$ or $\bar{B}$) resonances of finite width (or strings) fulfilling energy and momentum conservation as well as flavor current conservation [14].

3 Hadronization of an expanding partonic fireball

We now turn to actual results from PHSD for the model case of an expanding partonic fireball at initial temperature $T = 1.7 T_c$ ($T_c = 0.185$ GeV) with quasiparticle properties and four-momentum distributions determined by the DQPM at temperature $T = 1.7 T_c$. The initial distribution for quarks, antiquarks and gluons in coordinate space is taken as a Gaussian ellipsoid with a spatial eccentricity $\epsilon = (y^2 - x^2)/(y^2 + x^2)$ (8) and $<z^2> = <y^2>$ in order to allow for the buildup of elliptic flow (as in semi-central nucleus-nucleus collisions at relativistic energies). In order to match the initial off-equilibrium strange quark content in relativistic $pp$ collisions the number of $s$ (and $\bar{s}$ quarks) is assumed to be suppressed by a factor of 3 relative to the abundance of $u$ and $d$ quarks and antiquarks. In this way we will be able to investigate additionally the question of strangeness equilibration. For more details of the numerical treatment we refer the reader to Ref. [14].

In Fig. 1 (l.h.s.) we show the energy balance for the expanding system at initial temperature $T = 1.7 T_c$ and eccentricity $\epsilon = 0$. The total energy $E_{tot}$ (upper line) - which at $t = 0$ is given by (4) integrated over space - is conserved within 3% throughout the partonic expansion and hadronization phase such that for $t > 8$ fm/c it is given essentially by the energy contribution from mesons and baryons (+antibaryons). The initial energy splits into the partonic interaction energy $V_p$ (cf. Eq. (19) in Ref. [13]) and the energy of the time-like (propagating) partons

$$T_p = \sum_i \sqrt{\vec{p}_i^2 + M_i^2(\rho_p)}$$

(9)

with fractions determined by the DQPM [13]. In Eq. (9) the summation over $i$ runs over all testparticles in an individual run. The hadronization mainly proceeds during the time interval $1$ fm/c $< t < 7$ fm/c (cf. r.h.s of Fig. 1 where the time evolution of the $q, \bar{q}, g$, meson and baryon (+antibaryon) number is displayed). As one observes from Fig. 1 on average the number of hadrons from the resonance or 'string' decays is larger than the initial number of fusing partons.

In order to shed some light on the hadronization process in PHSD we display in Fig. 2 the invariant mass distribution of $q\bar{q}$ pairs (solid line) as well as $qqq$ (and $q\bar{q}\bar{q}$) triples (dashed line) that lead to the formation of final hadronic states. In fact, the distribution for the formation of baryon (antibaryon) states starts above the nucleon mass and extends to high invariant mass covering the nucleon resonance mass region as well as the high mass continuum (which is treated by the decay of strings within the JETSET model [18]). On the 'pre-mesonic side the invariant-mass distribution starts roughly above the two-pion mass and extends up to continuum states of high invariant mass (described again in terms of string excitations). The low mass sector is dominated by $\rho, a_1, \omega$ or $K^*, \bar{K}^*$ transitions etc. The excited 'pre-hadronic' states decay to two or more 'pseudoscalar octet' mesons such that the number of final
Figure 1: (Color online) L.h.s.: Time evolution of the total energy $E_{\text{tot}}$ (upper solid line), the partonic contributions from the interaction energy $V_p$ and the energy of time-like partons $T_p$ in comparison to the energy contribution from formed mesons $E_m$ and baryons (+ antibaryons) $E_{B+\bar{B}}$. R.h.s: Time evolution in the parton, meson and baryon number for an expanding partonic fireball at initial temperature $T = 1.7 T_c$ with initial eccentricity $\epsilon = 0$.

Figure 2: (Color online) The invariant mass distribution for fusing $q\bar{q}$ pairs (solid line) as well as $qq$ (and $q\bar{q}q$) triples (dashed line) that lead to the formation of final hadronic states for an expanding partonic fireball at initial temperature $T = 1.7 T_c$ with initial eccentricity $\epsilon = 0$.

hadrons is larger than the initial number of fusing partons. Accordingly, the hadronization process in PHSD leads to an increase of the total entropy and not to a decrease as in case of coalescence models [6, 7]. This is a direct consequence of the finite (and rather large) dynamical quark and antiquark masses as well as mean-field potentials which - by energy conservation - lead to ‘pre-hadron’ masses well above those for the pseudo-scalar meson octett or the baryon octett, respectively. This solves the entropy problem in hadronization in a natural way and is in accordance with the second law of thermodynamics!

The parton dynamics itself is governed by their propagation in the time-dependent mean-field $U_p(\rho_p)^1$ which is adopted in the parametrized form (as a function of the parton density $\rho_p$) given by Eq. (29) in Ref. [13]. Since the mean-field $U_p$ is repulsive the partons are accelerated during the expansion phase on expense of the potential energy density $V_p$ which is given by the integral of $U_p$ over $\rho_p$ (cf. Sec. 3 in Ref. [13]). The interaction rates of the partons are determined by effective cross sections which for $gg$ scattering have been determined in Ref. [3] as a function of $T/T_c$. The latter are re-parametrized in the actual calculation as a function of the parton density using the available dependence of $\rho_p(T)$ on

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1Analogous mean-field phenomena are well known from studies on $K^\pm$, $\rho$-meson and nucleon flow at SIS energies [19, 20, 21].
the temperature $T$ from the DQPM. The channels $q\bar{q}\rightarrow g$ are described by a relativistic Breit-Wigner cross section which is determined by the actual masses of the fermions, the invariant energy $\sqrt{s}$ and the resonance parameters of the gluon (from the DQPM). In this case a further constraint on flavor neutrality and open color is employed. The gluon decay to a $u\bar{u}$, $d\bar{d}$ or $s\bar{s}$ pair is fixed by detailed balance. Further channels are $gg\leftrightarrow g$ which are given by Breit-Wigner cross sections (with the gluon resonance parameters) and detailed balance, respectively.

It is also interesting to have a look at the final hadronic particle ratios $K^+/\pi^+$, $p/\pi^+$, $\Lambda/K^+$ etc. (after hadronic decays) which are shown in Table 1. The latter ratios are compared to the grand-canonical statistical hadronization model (SM) [22, 23] at baryon chemical potential $\mu_B = 0$. For $\mu_B = 0$ the particle ratios depend only on temperature $T$ and one may fix a freeze-out temperature, e.g., by the proton to $\pi^+$ ratio. A respective comparison is given also in Table 1 for $T = 160$ MeV and $170$ MeV for the SM which demonstrates that the results from PHSD are close to those from the SM for $T \approx 170$ MeV. This also holds roughly for the $\Lambda/K^+$ ratio. On the other hand the $K^+/\pi^+$ ratio only smoothly depends on the temperature $T$ and measures the amount of strangeness equilibration. Recall that we initialized the system with a relative strangeness suppression factor of $1/3$. The deviation from the SM ratio by about 13\% indicates that strangeness equilibration is not fully achieved in the calculations. This is expected since the partons in the surface of the fireball hadronize before chemical equilibration may occur.

|         | $p/\pi^+$ | $\Lambda/K^+$ | $K^+/\pi^+$ |
|---------|-----------|---------------|-------------|
| PHSD    | 0.086     | 0.28          | 0.157       |
| SM $T = 160$ MeV | 0.073     | 0.22          | 0.179       |
| SM $T = 170$ MeV | 0.086     | 0.26          | 0.180       |

Table 1: Comparison of particle ratios from PHSD with the statistical model (SM) for $T = 160$ MeV and 170 MeV.

The agreement between the PHSD and SM results for the baryon to meson ratio in the strangeness $S=0$ and $S=1$ sector may be explained as follows: Since the final hadron formation dominantly proceeds via resonance and string formation and decay - which is approximately a micro-canonical statistical process - the average over many hadronization events with different energy/mass and particle number (in the initial and final state) leads to a grand-canonical ensemble. The latter (for $\mu_B = 0$) is only characterized by the average energy or an associated Lagrange parameter $\beta = 1/T$.

Of additional interest are the collective properties of the partonic system during the early time evolution. In order to demonstrate the buildup of elliptic flow we show in Fig. 3 (l.h.s.) the time evolution of

$$v_2 = \langle (p_x^2 - p_y^2)/(p_x^2 + p_y^2) \rangle$$

(10)

for partons (solid line), mesons (long dashed line) and baryons (dot-dashed line) for an initial eccentricity $\epsilon = 0.33$. As seen from Fig. 3 the partonic flow develops within 2 fm/c and the hadrons essentially pick up the collective flow from the accelerated partons. The hadron $v_2$ is smaller than the maximal parton $v_2$ since by parton fusion the average $v_2$ reduces and a fraction of hadrons is formed early at the surface of the fireball without a strong acceleration before hadronization. It is important to point out that in PHSD the elliptic flow of partons predominantly stems from the gradients of the repulsive parton mean-fields (from the DQPM) at high parton (energy) density. To demonstrate this statement we show in Fig. 3 (r.h.s.) the result of a simulation without elastic partonic rescattering processes by the short dashed line.

We note in passing that the final hadron $v_2$ increases linearly with the initial eccentricity $\epsilon$ and indicates that the ratio $v_2/\epsilon$ is practically constant ($\approx 0.2$)[14] as in ideal hydrodynamics. Accordingly
Figure 3: (Color online) L.h.s.: Time evolution of the elliptic flow $v_2$ for partons and hadrons for the initial spatial eccentricity $\epsilon = 0.33$ for an expanding partonic fireball at initial temperature $T = 1.7T_c$. R.h.s.: The elliptic flow $v_2$ - scaled by the number of constituent quarks $n_q$ - versus the transverse kinetic energy divided by $n_q$ for mesons (dashed line) and baryons (solid line).

The parton dynamics in PHSD are close to ideal hydrodynamics. This result is expected since the ratio of the shear viscosity $\eta$ to the entropy density $s$ in the DQPM is on the level of $\eta/s \approx 0.2$ [3] and thus rather close to the lower bound of $\eta/s = 1/(4\pi)$.

A further test of the PHSD hadronization approach is provided by the 'constituent quark number scaling' of the elliptic flow $v_2$ which has been observed experimentally in central Au+Au collisions at RHIC [4, 24]. In this respect we plot $v_2/n_q$ 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. For mesons we have $n_q = 2$ and for baryons/antibaryons $n_q = 3$. The results for the scaled elliptic flow are shown in Fig. 3 (r.h.s.) for mesons and baryons and suggest an approximate scaling. We note that the scaled hadron elliptic flow $v_2/n_q$ does not reflect the parton $v_2$ at hadronization and is significantly smaller. Due to the limited statistics especially in the baryonic sector with increasing $p_T$ this issue will have to be re-addressed with high statistics in the actual heavy-ion case where the very early parton $p_T$ distribution also shows 'power-law' tails.

4 Summary

In summary, the expansion dynamics of an anisotropic partonic fireball has been studied within the PHSD approach which includes dynamical local transition rates from partons to hadrons (7) (and vice versa). It shows collective features as expected from ideal hydrodynamics in case of strongly interacting systems. The hadronization process conserves four-momentum and all flavor currents and slightly increases the total entropy since the 'fusion' of rather massive partons dominantly leads to the formation of color neutral strings or resonances that decay microcanonically to lower mass hadrons. This solves the entropy problem associated with the simple coalescence model!

We find that the hadron abundancies and baryon to meson ratios are compatible with those from the statistical hadronization model [22, 23] - which describes well particle ratios from AGS to RHIC energies - at a freeze-out temperature of about 170 MeV. Our calculations show that the hadron elliptic flow is essentially produced in the early partonic stage where also the strong repulsive parton mean-fields contribute to a large extent.
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