Dynamics of hot and dense nuclear and partonic matter

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The dynamics of hot and dense nuclear matter is discussed from the microscopic transport point of view. The basic concepts of the hadron-string-dynamical transport model (HSD) – derived from Kadanoff-Baym equations in phase phase – are presented as well as "highlights" of HSD results for different observables in heavy ion collisions from 100 AMeV (SIS) to 21 ATeV (RHIC) energies. Furthermore, a novel extension of the HSD model for the description of the partonic phase – the Parton-Hadron-String-Dynamics (PHSD) approach – is introduced. PHSD includes a nontrivial partonic equation of state – in line with lattice QCD – as well as covariant transition rates from partonic to hadronic degrees of freedom. The sensitivity of hadronic observables to the partonic phase is demonstrated for relativistic heavy ion collisions from the FAIR/NICA up to the RHIC energy regime.

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

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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 AuAu collisions is interacting more strongly than hadronic matter and consequently this concept had to be severely questioned. Moreover, in line with theoretical studies in Refs. [1–3] the medium showed phenomena of an almost perfect liquid of partons [4, 5] as extracted from the strong radial expansion and the scaling of elliptic flow $v_2(p_\mathrm{T})$ of mesons and baryons with the number of constituent quarks and antiquarks [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 colored partons are scarce. 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 [6–8]. This problem – a violation of the second law of thermodynamics as well as the conservation of four-momentum and flavor currents – has been addressed in Ref. [9] on the basis of the DQPM employing covariant transition rates for the fusion of 'massive' quarks and antiquarks to color neutral hadronic resonances or strings. In fact, the dynamical studies for an expanding partonic fireball in Ref. [9] suggest that the latter problems have come to a practical solution.

A consistent dynamical approach – valid also for strongly interacting systems – can be formulated on the basis of Kadanoff-Baym (KB) equations [10] or off-shell transport equations in phase-space representation, respectively [10–12]. In the KB theory the field quanta are described in terms of dressed propagators with complex selfenergies. Whereas the real part of the selfenergies can be related to mean-field potentials (of Lorentz scalar, vector or tensor type), the imaginary parts provide information about the lifetime and/or reaction rates of time-like 'particles' [13]. 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, 13]). The determination/extraction of complex selfenergies for the partonic degrees of freedom has been performed before in Refs. [14, 15] 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. For a review on off-shell transport theory and results from the DQPM in comparison to lQCD we refer the reader to Ref. [13].

Since the actual implementations in the PHSD transport approach have been presented in detail in Ref. [16] we here report again on the actual description of hadronization and present results for PbPb collisions at SPS energies in comparison to experimental data from the NA49 Collaboration.

2. HADRONIZATION IN PHSD

The hadronisation, i.e. the transition from partonic to hadronic degrees of freedom, is described in PHSD by local covariant transition rates as introduced in Ref. [9], e.g. for $q+\bar{q}$ fusion to a meson m of four-momentum $p=(\omega,\mathbf{p})$ at space-time point $x=(t,\mathbf{x})$:

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

In Eq. (1) we have introduced the shorthand notation,

$$Tr_j = \sum_j \int d^4x_j \int \frac{d^4p_j}{(2\pi)^4}\ , \tag{2}$$

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. (1) δ(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, $v_{q\bar{q}}(\rho_p)$ is the effective quark-antiquark interaction from the DQPM (displayed in Fig. 10 of Ref. [15]) as a function of the local parton $(q+\bar{q}+g)$ density ρ_p (or energy density). Furthermore, $W_m(x,p)$ is the dimensionless phase-space distribution of the formed 'pre-hadron', i.e.

$$W_m(\xi,p_\xi) = \exp\left(\frac{\xi^2}{2b^2}\right)\ \exp\left(2b^2(p_\xi^2-(M_q-M_{\bar{q}})^2/4)\right) \tag{3}$$

with $\xi=x_1-x_2=x_q-x_{\bar{q}}$ and $p_\xi=(p_1-p_2)/2=(p_q-p_{\bar{q}})/2$. The width parameter b is fixed by $\sqrt{\langle r^2\rangle}=b=0.66$ fm (in the rest frame) which corresponds to an average rms radius of mesons. We note that the expression (3) corresponds to the limit of independent harmonic oscillator states and that the final hadron-formation rates are approximately independent of the parameter b within reasonable variations. By construction the quantity (3) is Lorentz invariant; in the limit of instantaneous 'hadron formation', i.e. $\xi^0 = 0$, it provides a Gaussian dropping in the relative distance squared $(\mathbf{r}_1 - \mathbf{r}_2)^2$. The four-momentum dependence reads explicitly (except for a factor 1/2)

$$(E_1 - E_2)^2 - (\mathbf{p}_1 - \mathbf{p}_2)^2 - (M_1 - M_2)^2 \leq 0 \tag{4}$$

and leads to a negative argument of the second exponential in (3) favoring the fusion of partons with low relative momenta $p_q - p_{\bar{q}} = p_1 - p_2$.

Related transition rates (to Eq. (1)) 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 using Jacobi coordinates (cf. Ref. [16]).

On the hadronic side the PHSD transport approach includes explicitly the baryon octet and decouplet, the 0^-- and 1^--meson nonets as well as selected higher resonances as in HSD [17]. Hadrons of higher masses ($>$ 1.5 GeV in case of baryons and $>$ 1.3 GeV in case of mesons) are treated as 'strings' (color-dipoles) that decay to the known (low-mass) hadrons according to the JETSET algorithm [18]. We discard an explicit recapitulation of the string decay and refer the reader to the original work [18] or Ref. [19].

3. APPLICATION TO NUCLEUS-NUCLEUS COLLISIONS

In this Section we employ the PHSD approach to nucleus-nucleus collisions at moderate relativistic energies. It is of interest, how the PHSD approach compares to the HSD [17] model (without explicit partonic degrees-of-freedom) as well as to experimental data. In Fig. 1 we show the transverse mass spectra of π^-, K^+, and K^- mesons for 7% central PbPb collisions at 40 and 80 AGeV and 5% central collisions at 158 AGeV in comparison to the data of the NA49 Collaboration [20]. Here the slope of the π^- spectra is only slightly enhanced in PHSD relative to HSD which demonstrates that the pion transverse motion shows no sizeable sensitivity to the partonic phase. However, the $K^\pm$ transverse mass spectra are substantially hardened with respect to the HSD calculations at all bombarding energies, i.e.

PHSD is more in line with the data, and thus suggest that partonic effects are better visible in the strangeness-degrees of freedom. The hardening of the kaon spectra can be traced back to parton-parton scattering as well as a larger collective acceleration of the partons in the transverse direction due to the presence of repulsive vector fields for the partons. The enhancement of the spectral slope for kaons and antikaons in PHSD due to collective partonic flow shows up much clearer for the kaons due to their significantly larger mass (relative to pions). We recall that in Ref. [21] the underestimation of the $K^{\pm}$ slope by HSD (and also UrQMD) had been suggested to be a signature for missing partonic degrees of freedom; the present PHSD calculations support this early suggestion. Moreover, the PHSD calculations for RHIC energies show a very similar trend - the inverse slope increases by including the partonic phase.

The strange antibaryon sector is of further interest since here the HSD calculations have always underestimated the yield [22]. Our detailed studies in Ref. [16] show that the HSD and PHSD calculations both give a reasonable description of the $\Lambda + \Sigma^0$ yield of the NA49 Collaboration [23]; both models underestimate the NA57 data [24] by about 30%. An even larger discrepancy in the data from the NA49 and NA57 Collaborations is seen for $(\bar{\Lambda} + \bar{\Sigma}^0)/N_{\rm wound}$; here the PHSD calculations give results which are in between the NA49 data and the NA57 data whereas HSD underestimates the $(\bar{\Lambda} + \bar{\Sigma}^0)$ midrapidity yield at all centralities.

The latter result suggests that the partonic phase does not show up explicitly in an enhanced production of strangeness (or in particular strange mesons and baryons) but leads to a different redistribution of antistrange quarks between mesons and antibaryons. In fact, as demonstrated in Ref. [16], we find no sizeable differences in the double strange baryons from HSD and PHSD – in a good agreement with the NA49 data – but observe a large enhancement in the double strange antibaryons for PHSD relative to HSD.

4. SUMMARY

In this contribution we have addressed relativistic collisions of PbPb at SPS energies in the PHSD approach which includes explicit partonic degrees of freedom as well as dynamical local transition rates from partons to hadrons (1). 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. Since this dynamical hadronization process increases the total entropy the second law of thermodynamics is not violated (as is the case for simple coalescence models incorporating massless partons).

The PHSD approach has been also applied to nucleus-nucleus collisions from 40 to 160 AGeV as well as for RHIC energies in order to explore the space-time regions of 'partonic matter' [16]. We have found that even central collisions at the top SPS energy of ~158 AGeV show a large fraction of non-partonic, i.e. hadronic or string-like matter, which can be viewed as a 'hadronic corona' [25]. This finding implies that neither purely hadronic nor purely partonic 'models' can be employed to extract physical conclusions in comparing model results with data. On the other hand - studying in detail PbPb reactions at SPS energies in comparison to the data [16] - it is found that the partonic phase has only a very low impact on the longitudinal rapidity distributions of hadrons but a sizeable influence on the transverse-mass distribution of final kaons due to the partonic interactions. The most pronounced effect is seen on the production of multi-strange antibaryons due to a slightly enhanced $s\bar{s}$ pair production in the partonic phase from massive time-like gluon decay and a more abundant formation of strange antibaryons in the hadronization process. This enhanced formation of strange antibaryons in central PbPb collisions at SPS energies by hadronization supports the early suggestion by Braun-Munzinger and Stachel [26, 27] in the statistical hadronization model - which describes well particle ratios from AGS to RHIC energies.

At RHIC energies our PHSD calculations show also a good reproduction of the hadron transverse mass and rapidity spectra. Furthermore, the elliptic flow v_2 is well described for AuAu reactions at $\sqrt{s} = 200$ GeV as a function of centrality as well as of transverse momenta up to $p_{\mathrm{T}} \simeq 1.5$ GeV/c.

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FIGURES

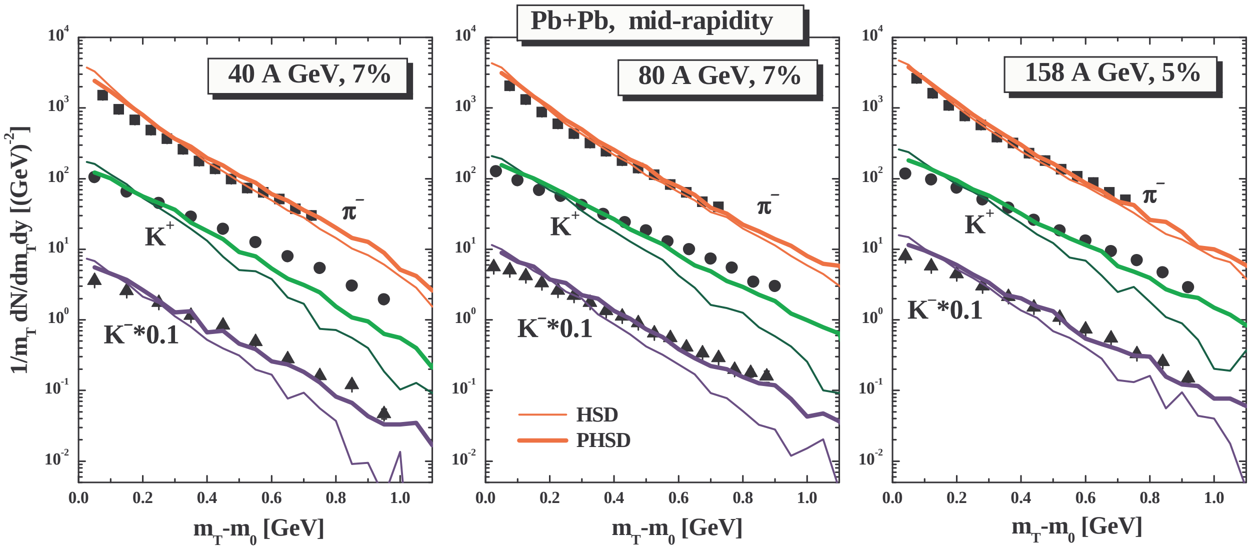

Figure 1. The π^-, K^+, and K^- transverse mass spectra for central PbPb collisions at 40, 80 and 158 AGeV from PHSD (thick solid lines) in comparison to the distributions from HSD (thin solid lines) and the experimental data from the NA49 Collaboration [20].

FIGURE CAPTIONS

Fig. 1: The π^-, K^+, and K^- transverse mass spectra for central PbPb collisions at 40, 80 and 158 AGeV from PHSD (thick solid lines) in comparison to the distributions from HSD (thin solid lines) and the experimental data from the NA49 Collaboration [20].