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WHAT COLLECTIVE FLOW OBSERVABLES TELL US ABOUT THE EXPANSION OF THE PLASMA*

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The dynamics of partons, hadrons and strings in relativistic nucleus–nucleus collisions is analyzed within the novel Parton–Hadron–String Dynamics (PHSD) transport approach, which is based on a dynamical quasiparticle model for partons (DQPM) matched to reproduce recent lattice-QCD results — including the partonic equation of state — in thermodynamic equilibrium. 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), respectively, obeying flavor current-conservation, color neutrality as well as energy-momentum conservation. The PHSD approach is applied to nucleus–nucleus collisions from low SIS to RHIC energies with particular emphasis on strange mesons, baryons and antibaryons as well as azimuthal asymmetries. The traces of partonic interactions are found in particular in the elliptic flow of hadrons with increasing bombarding energy.

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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

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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. However, experimental observations at the Relativistic Heavy Ion Collider (RHIC) indicated that the new medium created in ultrarelativistic Au+Au 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, 2, 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. 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. [6] 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. [6] 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 [7] or off-shell transport equations in phase-space representation, respectively [7]. 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' [8]. 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. [7, 8]). The determination/extraction of complex selfenergies for the partonic degrees of freedom has been performed before in Ref. [9] by fitting lattice QCD '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 the lattice QCD we refer the reader to Ref. [8].

The actual implementations in the PHSD transport approach have been presented in detail in Refs. [10, 11]. Here we present results for transverse mass spectra and elliptic flow for heavy ion collisions at RHIC energies in comparison to data from the experimental collaborations.

2. The PHSD approach

The dynamics of partons, hadrons and strings in relativistic nucleus–nucleus collisions is analyzed here within the Parton–Hadron–String Dynamics approach [12]. In this transport approach the partonic dynamics is based on Kadanoff–Baym equations for Green functions with self-energies from the Dynamical QuasiParticle Model (DQPM) [9] which describes QCD properties in terms of 'resummed' single-particle Green functions. In Ref. [13], the actual three DQPM parameters for the temperature-dependent effective coupling were fitted to the recent lattice QCD results of Ref. [14]. The latter lead to a critical temperature $T_{\rm c} \approx 160\,{\rm MeV}$ which corresponds to a critical energy density of $\epsilon_{\rm c} \approx 0.5\,{\rm GeV/fm}^3$. In PHSD the parton spectral functions ρ_j $(j = q, \bar{q}, g)$ are no longer δ-functions in the invariant mass squared as in conventional cascade or transport models but depend on the parton mass and width parameters which were fixed by fitting the lattice QCD results from Ref. [14]. We recall that the DQPM allows one to extract a potential energy density $V_{\rm p}$ from the space-like part of the energy-momentum tensor as a function of the scalar parton density $\rho_{\rm s}$. Derivatives of $V_{\rm p}$ w.r.t. $\rho_{\rm s}$ then define a scalar mean-field potential $U_{\rm s}(\rho_{\rm s})$ which enters into the equation of motion for the dynamic partonic quasiparticles. Furthermore, a two-body interaction strength can be extracted from the DQPM as well from the quasiparticle width in line with Ref. [3]. The transition from partonic to hadronic d.o.f. (and *vice versa*) is described by covariant transition rates for the fusion of quark–antiquark pairs or three quarks (antiquarks), respectively, obeying flavor current-conservation, color neutrality as well as energy-momentum conservation [12, 13]. Since the dynamical quarks and antiquarks become very massive close to the phase transition, the formed resonant prehadronic color-dipole states ($q\bar{q}$ or qqq) are of high invariant mass, too, and sequentially decay to the groundstate meson and baryon octets increasing the total entropy.

On the hadronic side PHSD includes explicitly the baryon octet and decouplet, the 0^-- and 1^--meson nonets as well, as selected higher resonances as in the Hadron–String–Dynamics (HSD) approach [15, 16]. Hadrons of higher masses ($> 1.5\,{\rm GeV}$ in the case of baryons and $> 1.3\,{\rm GeV}$ for mesons) are treated as 'strings' (color-dipoles) that decay to the known (low-mass) hadrons, according to the JETSET algorithm [17]. Note that PHSD and HSD merge at low energy density, in particular, below the critical energy density $\epsilon_c \approx 0.5\,\mathrm{GeV/fm^3}$.

The PHSD approach was applied to nucleus–nucleus collisions from $s_{NN}^{1/2} \sim 5$ to $200\,\mathrm{GeV}$ in Refs. [12, 13] in order to explore the space-time regions of partonic matter. It was found that even central collisions at the top-SPS energy of $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$ show a large fraction of nonpartonic, *i.e.* hadronic or string-like matter, which can be viewed as a hadronic corona. This finding implies that neither hadronic nor only partonic models can be employed to extract physical conclusions in comparing model results with data.

3. Calculational results and comparison to data

The anisotropy in the azimuthal angle ψ is usually characterized by the even order Fourier coefficients $v_n = \langle \exp(\imath\, n(\psi - \Psi_{\mathrm{RP}}))\rangle$, $n = 2, 4, \ldots$, since for a smooth angular profile the odd harmonics become equal to zero. As noted above, Ψ_{RP} is the azimuth of the reaction plane and the brackets denote averaging over particles and events. In particular, for the widely used second order coefficient, denoted as an elliptic flow, we have

$$v_2 = \langle \cos(2\psi - 2\Psi_{\mathrm{RP}})\rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle , \tag{1}$$

where p_x and p_y are the x and y components of the particle momenta. This coefficient can be considered as a function of centrality, pseudo-rapidity η and/or transverse momentum p_{T}. We note that the reaction plane in PHSD is given by the $(x$–$z)$ plane with the z-axis in the beam direction.

In Fig. 1 the experimental v_2 excitation function in the transient energy range is compared to the results from the PHSD calculations; HSD model results are given as well for reference. We note that the centrality selection and acceptance are the same for the data and models.

We recall that the HSD model has been very successful in describing heavy-ion spectra and rapidity distributions from SIS to SPS energies. A detailed comparison of HSD results with respect to a large experimental data set was reported in Ref. [20] for central Au+Au (Pb+Pb) collisions from AGS to top SPS energies. Indeed, as shown in Fig. 1 (dashed lines), HSD is in good agreement with experiment for both data sets at the lower edge ($\sqrt{s_{NN}} \sim 10\,\mathrm{GeV}$) but predicts an approximately energy-independent flow v_2 at larger energies and, therefore, does not match the experimental

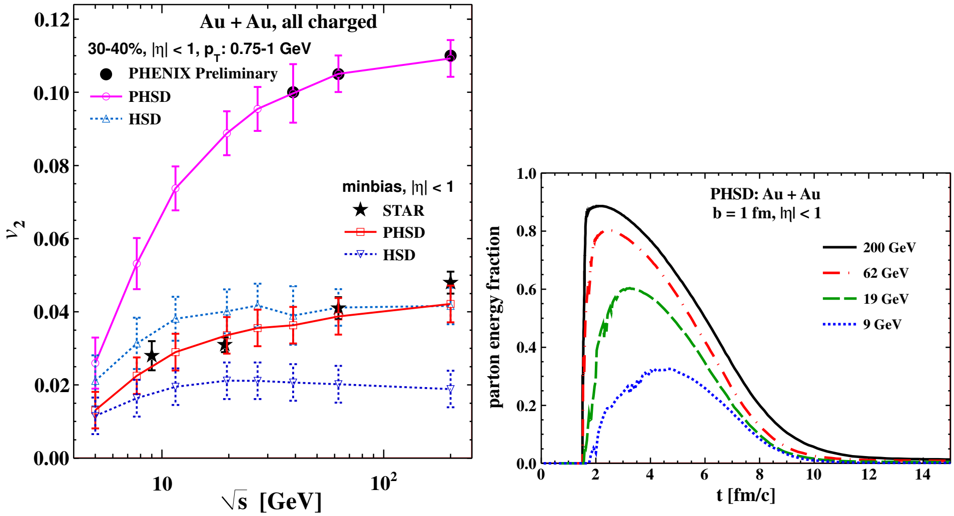

Fig. 1. Left: Average elliptic flow v_2 of charged particles at midrapidity for two centrality selections calculated within the PHSD (solid curves) and HSD (dashed curves). The v_2 STAR data compilation for minimal bias collisions are taken from [18] (stars) and the preliminary PHENIX data [19] are plotted by filled circles. Right: The evolution of the parton fraction of the total energy density at the mid-pseudorapidity for different collision energies with PHSD.

observations. This behavior is in quite close agreement with another independent hadronic model, the UrQMD (Ultra-relativistic Quantum Molecular Dynamics) [21] (*cf.* with [18]).

From the above comparison one may conclude that the rise of v_2 with bombarding energy is not due to hadronic interactions and models with partonic d.o.f. have to be addressed. Indeed, the PHSD approach incorporates the parton medium effects in line with a lattice QCD equation-of-state, as discussed above, and also includes a dynamic hadronization scheme based on covariant transition rates. It is seen from Fig. 1 that PHSD performs better: The elliptic flow v_2 from PHSD (solid curve) is fairly in line with the data from the STAR and PHENIX collaborations and clearly shows the growth of v_2 with the bombarding energy [22].

The increase of v_2 is clarified in Fig. 1, where the partonic fraction of the energy density at mid-pseudorapidity with respect to the total energy density in the same pseudorapidity interval is shown. We recall that the repulsive scalar mean-field potential $U_{\rm s}(\rho_{\rm s})$ for partons in the PHSD model leads to an increase of the flow v_2 as compared to that for HSD or PHSD calculations without partonic mean fields. As follows from Fig. 1, the energy fraction of the partons substantially grows with increasing bombarding energy while the duration of the partonic phase is roughly the same. Thus, the collective flow v_2 provides sensitive information on the presence of partonic degrees of freedom in relativistic heavy-ion collisions.

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REFERENCES

[1] E. Shuryak, *Prog. Part. Nucl. Phys.* **53**, 273 (2004).

[2] M.H. Thoma, *J. Phys. G* **31**, L7 (2005); *Nucl. Phys.* **A774**, 307 (2006).

[3] A. Peshier, W. Cassing, *Phys. Rev. Lett.* **94**, 172301 (2005).

[4] I. Arsene *et al.*, *Nucl. Phys.* **A757**, 1 (2005); B.B. Back *et al.*, *Nucl. Phys.* **A757**, 28 (2005); J. Adams *et al.*, *Nucl. Phys.* **A757**, 102 (2005); K. Adcox *et al.*, *Nucl. Phys.* **A757**, 184 (2005).

[5] T. Hirano, M. Gyulassy, *Nucl. Phys.* **A769**, 71 (2006).

[6] W. Cassing, E.L. Bratkovskaya, *Phys. Rev.* **C78**, 034919 (2008).

[7] S. Juchem, W. Cassing, C. Greiner, *Phys. Rev.* **D69**, 025006 (2004); *Nucl. Phys.* **A743**, 92 (2004).

[8] W. Cassing, *Eur Phys. J.* **168**, 3 (2009).

[9] W. Cassing, *Nucl. Phys.* **A795**, 70 (2007).

[10] W. Cassing, E.L. Bratkovskaya, *Nucl. Phys.* **A831**, 215 (2009).

[11] E.L. Bratkovskaya, W. Cassing, V.P. Konchakovski, O. Linnyk, *Nucl. Phys.* **A856**, 162 (2011).

[12] W. Cassing, E.L. Bratkovskaya, *Nucl. Phys.* **A831**, 215 (2009).

[13] E.L. Bratkovskaya *et al.*, *Nucl. Phys.* **A856**, 162 (2011).

[14] Y. Aoki *et al.*, *J. High Energy Phys.* **0906**, 088 (2009).

[15] W. Ehehalt, W. Cassing, *Nucl. Phys.* **A602**, 449 (1996).

[16] W. Cassing, E.L. Bratkovskaya, *Phys. Rep.* **308**, 65 (1999).

[17] H.-U. Bengtsson, T. Sjöstrand, *Comput. Phys. Commun.* **46**, 43 (1987).

[18] M. Nasim, L. Kumar, P.K. Netrakanti, B. Mohanty, *Phys. Rev.* **C82**, 054908 (2010).

[19] X. Gong [PHENIX Collaboration], invited talk at the Quark Matter 2011, Annecy, France.

[20] E.L. Bratkovskaya *et al.*, *Phys. Rev.* **C69**, 054907 (2004); *Phys. Rev. Lett.* **92**, 032302 (2004).

[21] S.A. Bass *et al.*, *Prog. Part. Nucl. Phys.* **41**, 255 (1998); M. Bleicher *et al.*, *J. Phys. G* **25**, 1859 (1999).

[22] V.P. Konchakovski *et al.*, *Phys. Rev.* **C85**, 011902 (2012).