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Nuclear Physics A 795 (2007) 70–97

NUCLEAR PHYSICS A

Dynamical quasiparticles properties and effective interactions in the sQGP

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Received 13 June 2007; received in revised form 30 July 2007; accepted 17 August 2007

Available online 4 September 2007

Abstract

Dynamical quasiparticle properties are determined from lattice QCD along the line of the Peshier model for the running strong coupling constant in case of three light flavors. By separating time-like and space-like quantities in the number density and energy density the effective degrees of freedom in the gluon and quark sector may be specified from the time-like densities. The space-like parts of the energy densities are identified with interaction energy (or potential energy) densities. By using the time-like parton densities (or scalar densities) as independent degrees of freedom—instead of the temperature T and chemical potential μ_q as Lagrange parameters—variations of the potential energy densities with respect to the time-like gluon and/or fermion densities lead to effective mean-fields for time-like gluons and quarks as well as to effective gluon–gluon, quark–gluon and quark–quark (quark–antiquark) interactions. The latter dynamical quantities are found to be approximately independent on the quark chemical potential μ_q and thus well suited for an implementation in off-shell parton transport approaches. Results from the dynamical quasiparticle model (DQPM) in case of two dynamical light quark flavors are compared to lattice QCD calculations for the net quark density $\rho_q(T, \mu_q)$ as well as for the 'back-to-back' differential dilepton production rate by q–$\bar{q}$ annihilation. The DQPM is found to pass the independent tests.

PACS: 12.38.Mh; 12.38.Aw; 25.75.-q

Keywords: Quark–gluon plasma; General properties of QCD; Relativistic heavy-ion collisions

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0375-9474/$ – see front matter
doi:10.1016/j.nuclphysa.2007.08.010

1. Introduction

The 'Big Bang' scenario implies that in the first micro-seconds of the universe the entire system 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 (cf. [1–3] and references therein). Early concepts of the QGP were guided by the idea of a weakly interacting system of partons since the entropy density s and energy density ϵ were found in lattice QCD to be close to the Stefan Boltzmann (SB) limit for a relativistic noninteracting system [4]. 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 notion had to be given up. Moreover, in line with earlier theoretical studies in Refs. [5–7] the medium showed phenomena of an almost perfect liquid of partons [8,9] as extracted from the strong radial expansion and elliptic flow of hadrons as well the scaling of the elliptic flow with parton number, etc. All the latter collective observables have been severely underestimated in conventional string/hadron transport models [10–12] whereas hydrodynamical approaches did quite well in describing (at midrapidity) the collective properties of the medium generated during the early times for low and moderate transverse momenta [13,14]. The question about the constituents and properties of this QGP liquid is discussed controversely in the literature (cf. Refs. [15–17]) and practically no dynamical concepts are available to describe the dynamical freezeout of partons to color neutral hadrons that are finally observed experimentally. Since the partonic system appears to interact more strongly than even hadronic systems the notation strong QGP (sQGP) has been introduced in order to distinguish from the dynamics known from perturbative QCD (pQCD).

Lattice QCD (lQCD) calculations provide some guidance to the thermodynamic properties of the partonic medium close to the transition at a critical temperature T_c up to a few times T_c, but lQCD calculations for transport coefficients presently are not accurate enough [18] to allow for firm conclusions. Furthermore, it is not clear whether the partonic system really reaches thermal and chemical equilibrium in ultrarelativistic nucleus–nucleus collisions [19] such that nonequilibrium models are needed to trace the entire collision history. The available string/hadron transport models [20–22] partly fail—as pointed out above—nor do partonic cascade simulations [23–26] (propagating massless partons) sufficiently describe the reaction dynamics when employing cross sections from perturbative QCD. Some models, e.g., the Multiphase Transport Model AMPT [27], employ strong enhancement factors for the cross sections, however, use only on-shell massless partons in the partonic phase as in Ref. [24]. The same problem comes about in the parton cascade model of Ref. [28] where additional $2 \leftrightarrow 3$ processes like $gg \leftrightarrow ggg$ are incorporated but massless partons are considered.

On the other hand, it is well known that strongly interacting quantum systems require descriptions in terms of propagators D with sizeable selfenergies Π for the relevant degrees of freedom. Whereas the real part of the selfenergies can be related to mean-field potentials, the imaginary parts of Π provide information about the lifetime and/or reaction rate of time-like 'particles' [6]. In principle, off-shell transport equations are available in the literature [29–31], but have been applied only to dynamical problems where the width of the quasiparticles stays moderate with respect to the pole mass [32]. On the other hand, the studies of Peshier [33,34] indicate that the effective degrees of freedom in a partonic phase should have a width γ in the order of the pole mass M already slightly above T_c. This opens up the problem how to interpret/deal