PRODUCTION RATE OF CHARM QUARKS IN THE QUASIPARTICLE APPROACH*

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We study the production rate of charm quarks in hot QCD matter within the effective quasiparticle approach. The quark–gluon plasma is composed of the quasiparticles carrying the dynamical masses which are linked to the lattice QCD equation of state. Describing the evolution of the deconfined medium as a perfect fluid propagating longitudinally, we compute the production rate of charm quarks as a function of temperature and time and show that it significantly depends on the effective masses of the quasiparticles, as well as on the initial conditions of the fireball.

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1. Introduction

Due to their distinctively large mass, the charm quarks are able to survive through the entire evolution of the quark–gluon plasma (QGP) and, therefore, could be considered as good probes of the QGP characteristics [1, 2]. Alongside the analysis of the experimental data on charmed hadrons [3], it is crucial to study the evolution of open charm quarks in the hot QCD medium applying theoretical and phenomenological approaches. In this article, we investigate the production rate of charm quarks within the kinetic quasiparticle model (QPM), whose basics are discussed in Sec. 2. Assuming the QGP obeys the Bjorken flow [4], in Sec. 3 we compute the $c\bar{c}$ production rate and compare it to earlier studies performed in the quasiparticle frameworks with various setups [5, 6]. We give a brief conclusion of our findings in Sec. 4.

2. Quasiparticle framework

In the effective quasiparticle approach, the QGP is composed of weakly interacting quasiparticles with quark and gluon quantum numbers. The equation of state (EoS) of the QGP depends on the contributions coming from gluons (g), as well as light (l) (up + down) and strange (s) (anti)quarks.

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The model assumes that as particles propagate through the medium, they get dressed by the dynamically generated self-energies Π_i, and thus their masses become temperature-dependent in the following way [7]:

$$m_i^2(T) = \left(m_i^0\right)^2 + \Pi_i^2(T)\,, \tag{1}$$

where m_i^0 is the bare particle mass. We use $m_l^0 = 5$ MeV, $m_s^0 = 95$ MeV, and $m_g^0 = 0$ MeV for light, strange quarks, and gluons, respectively. For the self-energy Π_i we utilize the gauge-independent expressions computed in the hard thermal loop approach [8]

$$\Pi_{l,s}(T) \;=\; 2\left(m_{l,s}^0\sqrt{\frac{G(T)^2}{6}T^2} + \frac{G(T)^2}{6}T^2\right)\,, \tag{2}$$

$$\Pi_g(T) \;=\; \left(3 + \frac{3}{2}\right)\frac{G(T)^2}{6}T^2\,. \tag{3}$$

Above, $G(T)$ is the effective running coupling, which is an essential building block of the QPM. We define the temperature dependence of the coupling by postulating that the entropy density in the QPM perfectly matches the result obtained by lattice QCD simulations [9]. Our previous studies show that through the $G(T)$, various quantities computed in the QPM agree with the perturbative QCD expectations at high temperatures while preserving the non-perturbative QCD nature in the vicinity of the crossover [7, 10].

Figure 1 shows numerical results for the masses of dynamical quarks and gluons, as well as the constant charm quark mass. One can notice that the effective masses of the quasiparticles are much larger than their bare masses.

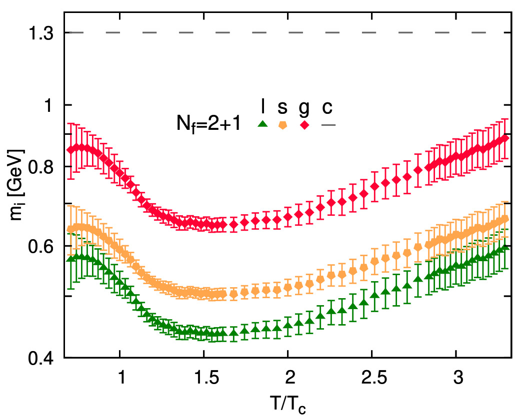

Fig. 1. The effective masses of the QGP constituents, m_i, as functions of temperature T scaled by its pseudocritical value, $T_c = 155$ MeV.

Therefore, we expect the scatterings between such massive quasiparticles to generate a significant production rate of charm quarks. The detailed discussion on m_i can be found in [7].

3. Production rate of charm quarks

Assuming that the QGP with $N_f = 2 + 1$ is in thermal and chemical equilibrium, we insert charm quarks into the medium as obstacles with constant mass $m_c = 1.3$ GeV, which appear out of chemical equilibrium and do not contribute to the EoS. The production rate of charm quarks enters the rate equation [5, 11, 12], reading

$$\partial_\mu \left(n_c\, u^\mu\right) = R_c^{\text{gain}} - R_c^{\text{loss}} \,, \tag{4}$$

$$R_c^{\text{gain}} = \frac{1}{2}\,\bar{\sigma}_{gg\to c\bar{c}}\, \left(n_g^0\right)^2 + \bar{\sigma}_{l\bar{l}\to c\bar{c}}\, \left(n_l^0\right)^2 + \bar{\sigma}_{s\bar{s}\to c\bar{c}}\, \left(n_s^0\right)^2 \,, \tag{5}$$

$$R_c^{\text{loss}} = \left[\frac{1}{2}\,\bar{\sigma}_{c\bar{c}\to gg} + \bar{\sigma}_{c\bar{c}\to l\bar{l}} + \bar{\sigma}_{c\bar{c}\to s\bar{s}}\right] n_c^2 \,. \tag{6}$$

Above, the pre-factor 1/2 is included to avoid the double counting of the gluon pairs; $\bar{\sigma}_{i\bar{i}\to j\bar{j}}$ represents the total energy-averaged cross section between the (quasi)particles [7], whose number densities are defined as

$$n_i^{(0)} = d_i \int \frac{\mathrm{d}^3p}{(2\pi)^3}\, f_i \,. \tag{7}$$

Here, the superscript 0 denotes the chemical equilibrium of the (quasi)particle species i with the corresponding degeneracy factor d_i specified explicitly as $d_l = 12,\ d_{s,c} = 6,\ d_g = 16$ [7]. The momentum-distribution function,

$$f_i = \lambda_i \left(\mathrm{e}^{E_i(T)/T} \pm \lambda_i\right)^{-1} \,, \tag{8}$$

describes the statistics of bosons (+) or fermions (−) obeying the dispersion relation $E_i^2(T) = p^2 + m_i^2(T)$, with $m_i^2(T)$ defined in Eq. (1). The fugacity parameter λ_i indicates how far the considered partons appear from chemical equilibrium. Since we assume the quasiparticles to be chemically equilibrated, $\lambda_{l,s,g} = 1$, and therefore Eq. (8) corresponds to the standard Fermi–Dirac or Bose–Einstein statistics at vanishing chemical potential. The charm quark statistics however depend on $\lambda_c(\tau)$ which should be determined from the rate equation. We have previously studied the temperature and time dependence of charm quark fugacity in [12].

Since the creation and annihilation rates of the $c\bar{c}$ pairs become equal once the charm quarks reach chemical equilibrium, *i.e.*, $\lambda_c = 1$, Eq. (4) can be rewritten as [5, 11, 13]

$$\partial_\mu(n_c\, u^\mu) = R_c^{\text{gain}} \left[1 - \left(\frac{n_c}{n_c^0}\right)^2\right], \tag{9}$$

where $n_c^0 \equiv n_c(\lambda_c = 1)$. In this study, the QGP obeys the longitudinal boost-invariant propagation known as the Bjorken flow [4]. The time evolution of the system is then specified by the scaling solution defined as

$$T(\tau) = T_0(\tau_0)\left(\frac{\tau_0}{\tau}\right)^{1/3}, \tag{10}$$

where τ denotes the time, while $T_0(\tau_0)$ represents the initial conditions, $T_0 = 624$ MeV, $\tau_0 = 0.2$ fm, at which the fireball is created and hydrodynamics become applicable. The pseudocritical temperature $T_\text{c} = 155$ MeV is reached at $\tau \simeq 13$ fm.

Figure 2 shows the production rate of charm quarks, R_c^{gain}, as a function of temperature (left) and time (right) computed in various quasiparticle frameworks [5, 6]. In all the approaches, charm quarks with constant mass are inserted into the hot QCD medium in thermal and chemical equilibrium.

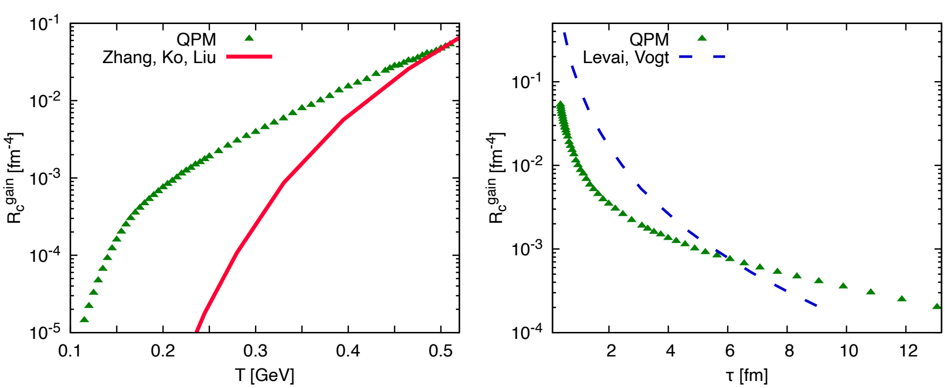

Fig. 2. The production rate of charm quarks, R_c^{gain}, as a function of temperature T (left) and time τ (right). We additionally present the available results obtained by Zhang, Ko, and Liu [5] (left), and Lévai and Vogt [6] (right) in various quasiparticle approaches.

At high T, we observe a numerical agreement with the $R_c^{\text{gain}}(T)$ investigated previously in [5] by employing the cross sections at leading order, see the left panel of Fig. 2. Although the features of our QPM differ from the setup used in [5], our results overlap at high T, since the role of the effective quasiparticle masses is reduced there compared to its significant impact at lower T.

In contrast to our QPM, the investigation performed by [5] considers the light and strange quarks to be degenerate, as well as neglects the quasiparticle masses $m_i(T)$ in the evaluation of the total cross sections. We assume that these could lead to the crucial underestimation of the charm quark production rate obtained at lower T, since the cross sections $\sigma_{i\bar{i}\to c\bar{c}}$ depend on the dynamical masses of scattered quasipartiles.

As a function of time (see the right panel of Fig. 2), the slope of the $R_c^{\rm gain}(\tau)$ qualitatively agrees with the results acquired by [6]. The overall quantitative disagreements observed in both panels of Fig. 2 arise due to the distinct features of the considered quasiparticle frameworks, *e.g.* temperature profile of the running coupling $G(T)$ and the quasiparticle masses m_i(T); initial conditions $T_0(\tau_0)$ influencing the $T(\tau)$ evolution; different expressions for thermal-averaged cross sections $\bar{\sigma}_{i\bar{i}\to c\bar{c}}$ [5, 6].

4. Conclusions

We studied the production rate $R_c^{\rm gain}$ of charm quarks in the equilibrated hot QCD matter employing the phenomenological quasiparticle model (QPM). Assuming that the QGP is composed of massive quasi-quarks and -gluons which interact by the effective running coupling $G(T)$ linked to the lattice QCD thermodynamics, we compute the production rate of charm quarks with constant mass. We observe that the thermal production is directly influenced by a set of the taken assumptions, *e.g.*, the initial conditions of the fireball or the quasiparticle effective masses, which play an important role in the charm quark production, especially at lower temperatures. The $R_c^{\rm gain}$ presented in this work can be straightforwardly applied to compute the total number of the created $c\bar{c}$ pairs. This will be reported elsewhere.

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