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Theory of Heavy Flavor in the Quark-Gluon Plasma

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Abstract

Heavy-quark interactions in the Quark-Gluon Plasma are analyzed in terms of a selfconsistent Brueckner scheme using a thermodynamic T-matrix based on a potential model. The interrelations between quarkonium correlators, spectral functions and zero-modes, and open heavy-flavor transport and susceptibilities are elaborated. Independent constraints from thermal lattice QCD can be used to improve predictions for heavy-quark phenomenology in heavy-ion collisions.

Keywords: Quark-gluon plasma, heavy quarks, Brueckner theory

1. Introduction

A basic challenge in many-body physics is the understanding of matter properties in terms of the forces between the constituents. Medium modifications of the force (or potential) render its determination an additional challenge. It is therefore important to have a good control over the force at least in the vacuum. In Quantum Chromodynamics (QCD), the fundamental force between static charges, i.e., a heavy quark (Q) and antiquark ($\bar{Q}$), is well established, both theoretically and phenomenologically. The heavy-quark (HQ) potential has been extracted with high accuracy from lattice-QCD (lQCD) computations [1] and can be well represented by the so-called Cornell potential,

$$V_{Q\bar{Q}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r \,, \qquad (1)$$

characterized by a perturbative color-Coulomb interaction at small distances and a “string” term dominant at large r, cf. left panel of Fig. 1. This potential successfully describes charmonium and bottomonium spectroscopy in vacuum, which can be understood as an effective field theory (EFT) of QCD in a $1/m_Q$ expansion (m_Q: HQ mass). The string tension, $\sigma \simeq 1$ GeV/fm, is of nonperturbative origin and most likely associated with the gluon-condensate structure of the QCD vacuum. The string term plays an important role already at rather small distances; e.g., for $V(r_0)$=0, i.e., at $r_0 \simeq \frac{1}{4}$ fm, it is equal in magnitude (but opposite in sign) to the Coulomb term. Consequently, the charmonium spectrum is largely governed by the nonperturbative force (e.g., the ground-state binding, $E_B^{J/\psi} \simeq 0.6$ GeV, collapses to ∼0.05 GeV if the string term is switched off). With a “calibrated” strong force in vacuum at hand one can study its medium modifications and infer from these information about the phase structure and transport properties of QCD matter. The analysis of quarkonium production and heavy-flavor spectra in ultrarelativistic heavy-ion collisions (URHICs) is aimed at precisely at these objectives, i.e., to identify signals of deconfinement and to extract heavy-quark diffusion coefficients from the produced medium (see, e.g., Refs. [3, 4, 5, 6] for recent reviews).

The HQ free energy has also been computed at finite temperature, cf. right panel of Fig. 1. One observes a gradual penetration of medium effects to smaller distances, naturally interpreted as a decrease of the “Debye” screening

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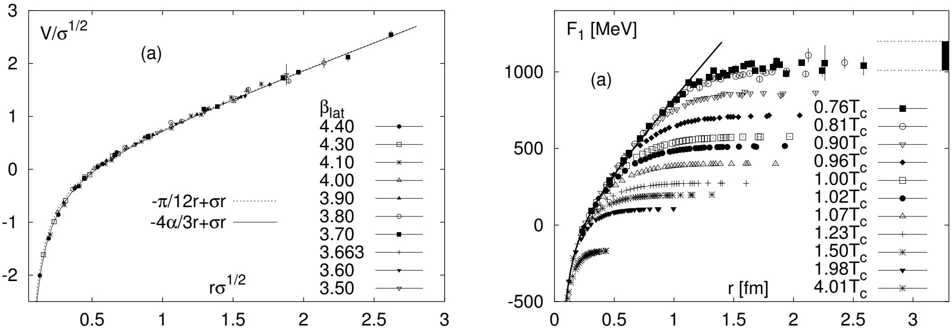


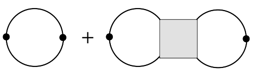
Figure 1: The static heavy-quark potential in vacuum (left)[1] and the color-singlet free energy in medium (right; reprinted with permission from [2]) as "measured" in lattice QCD as a function of Q-$\bar{Q}$ separation.

length, $r_D \sim 1/m_D$ (m_D: Debye mass). However, even at temperatures as high as $2T_c \approx 350$ MeV, the free energy still levels off at a positive value indicative for nonperturbative effects (string term). The applicability of the potential approach requires the 4-momentum transfer to be dominantly spacelike, i.e., $q_0 \simeq \vec{q}^{\,2}/2m_Q \ll |\vec{q}|$. In the vacuum this is satisfied by the smallness of the quarkonium binding energy. In the medium the latter is expected to decrease further. The thermal momentum scale of a single heavy quark also remains parametrically large not too far above T_c, $p_{\rm th}^2 \simeq 2m_Q T \gg T^2$ (T^2: momentum transfer from the medium). Thus, thermal Q-$\bar{Q}$ and Q-medium interactions are essentially static and elastic but involve nonperturbative interactions. This suggests the possibility of a unified description of heavy quarkonia and heavy-flavor transport, with a simultaneous treatment of bound and scattering states including resummations. The thermodynamic T-matrix approach, which is based on potential interactions, is such a framework, and has been successfully applied to electromagnetic plasmas [7]. The in-medium QCD interaction is, of course, much more involved than in QED, but the idea of using input from lQCD has revived the potential approach in recent years [8, 3]. In this paper we will elaborate on the T-matrix approach for open and hidden heavy flavor in the QGP (Sec. 2), and how numerical results for spectral and correlation functions, as well as transport coefficients, can be tested by thermal lQCD (Sec. 3). We conclude in Sec. 4.

2. One- and Two-Body Correlations in the QGP

The commonly studied quantity in thermal lattice QCD characterizing the propagation of a hadronic current with quantum numbers α is the imaginary-time (τ) correlation function which is given by a thermal expectation value as

$$G_\alpha(\tau,\vec{r}) = \langle\langle j_\alpha(\tau,\vec{r}) j_\alpha^\dagger(0,\vec{0})\rangle\rangle \ = \qquad (2)$$



The second equality is a diagrammatic representation for a meson state in terms of its free quark-antiquark loop and a 2-body interaction term. The physical information on the excitation spectrum in that channel is given by the spectral function in momentum space, $\rho_\alpha(E,p) = -2\,{\rm Im}\,G_\alpha^R(E,p)$. It is related to the euclidean correlator, Eq. (2), via

$$G_\alpha(\tau,p;T) = \int\limits_0^\infty \frac{dE}{2\pi}\rho_\alpha(E,p;T)\frac{\cosh[E(\tau-1/2T)]}{\sinh[E/2T]} \ , \qquad (3)$$

which illustrates the difficulty in extracting spectral functions from lQCD "data" of the euclidean correlator, since the latter is only obtained for a finite number of τ-points on a finite interval, $0<\tau<\frac{1}{2T}$. However, using model calculations for the spectral function a straightforward comparison to lQCD data can be performed and constraints evaluated. Note