Non-perturbative reaction rates of heavy quarkonia in the quark-gluon plasma

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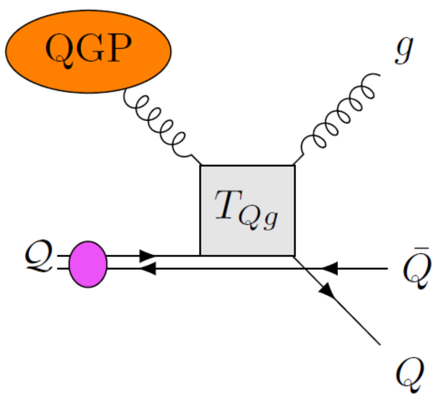
Introduction

Heavy quarks and quarkonia are key probes to study QCD matter as produced in ultra-relativistic heavy-ion collisions (URHICs). These probes facilitate an in-depth examination of the medium produced during these collisions. In particular, the interactions between quarkonia and the constituent partons in the expanding the fireball are typically simulated with transport models [1–3], where the key input are heavy-quarkonium reaction rates. Since the quark-gluon plasma (QGP) created in URHICs is a strongly coupled medium, its microscopic dynamics are inherently nonperturbative, rendering perturbative treatments inadequate. We have therefore carried out a detailed study of quarkonium dissociation rates within a nonperturbative thermodynamic T-matrix framework [4, 5].



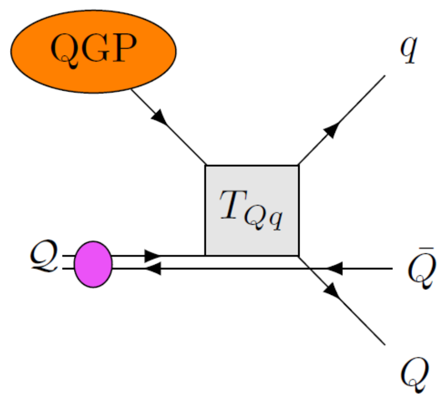


Fig. 1. Diagrammatic representation of heavy-quarkonium dissociation processes in the QGP. A heavy quarkonium, $\boldsymbol{\mathcal{Q}}$, is dissociated into a heavy quark, $\boldsymbol{Q}$, and antiquark, $\bar{\boldsymbol{Q}}$, by a thermal parton, $\boldsymbol{i}$, in the QGP. The thermal parton scattering off one of the heavy quarks in the heavy quarkonium is characterized by a half-off-shell amplitude, T_{Qi}, that incorporates the kinematics of a finite quarkonium binding energy, E_B.

Method

The central ingredient to compute quarkonium dissociation rates are the scattering amplitudes of the heavy quarks inside the bound state on thermal partons in the medium. While gluon-induced dissociation is formally the leading-order process, it turns out that the dissociation of a heavy quarkonium in the QGP through inelastic scattering of thermal partons, $\boldsymbol{i} = \boldsymbol{g}, \boldsymbol{q}, \bar{\boldsymbol{q}}$, off a heavy quark, $\boldsymbol{Q} = \boldsymbol{b}, \boldsymbol{c}$, inside the bound state, $\boldsymbol{\mathcal{Q}} + \boldsymbol{i} \rightarrow \boldsymbol{Q} + \bar{\boldsymbol{Q}} + \boldsymbol{i}$, is the relevant process in practice. It can be described as an inelastic half off-shell two-to-two scattering process, $\boldsymbol{Q} + \boldsymbol{i} \rightarrow \boldsymbol{Q} + \boldsymbol{i}$, where one additionally has to account for the quarkonium binding energy and the spatial correlations of the quark and antiquark in the bound state. The heavy-light amplitude is calculated within the T-matrix formalism which is a quantum many-body approach where the basic ingredient is a non-perturbative driving kernel constrained by lattice-QCD data [6, 7]. Its resummation in a ladder series provides a much enhanced interaction strength compared to previously used perturbative amplitudes coupled to quasiparticle partons in the QGP [1-3]. The in-medium quarkonium properties, i.e., their temperature-dependent binding energies and interference effects from the finite size of the bound state (also referred to as the imaginary part of the heavy-quark potential), are obtained from self-consistent calculations with the same interaction kernel [6], including off-shell parton spectral functions in the loop integrals. We have systematically investigated the interplay of these effects and elaborated on the connections to the dipole approximation widely used in effective field theory.

Results

The dissociation rates of bottomonium states and charmonium states in the QGP at zero 3-momentum are displayed in Fig. 2. Overall, they are much larger than our previous results with a perturbative coupling to a quasiparticle QGP. The rates are rather sensitive to the binding energy, where larger values, such as for $\boldsymbol{\Upsilon(1S)}$, produce much lower rates compared to those with lower binding energies, such as the $\boldsymbol{\Upsilon(2S)}$ or higher excited states. On the other hand, off-shell effects increase the reaction rates as they open additional phase space due to low-energy tails which are absent for zero-width quasiparticles.

Fig. 2. Reaction rates of bottomonia (left) and charmonia (right) as a function of temperature. Also shown is twice the heavy-quark width which constitutes the asymptotic value for free quarks.

However, the interference effects between the heavy quark and antiquark, representing three-body interactions, reduce the reaction rates of quarkonia with large binding energies.

Our findings highlight the crucial role of a nonperturbative treatment and capture the in-medium heavy-light interactions and broad spectral functions characteristic for a strongly coupled QGP, both playing essential roles in quarkonium break-up. The resulting dissociation rates therefore provide a conceptually much improved (and thus more realistic) input to transport simulations of heavy-quarkonium kinetics in URHICS.

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