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Transverse gluon contributions to the thermal static potential of heavy quarkonium

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Abstract

The transverse gluon contributions to the thermal static potentials of heavy quarkonia in isotropic medium are studied. Using the resummation of the damping rates method developed by Hou and Li, the infrared divergence that appeared in the effective potential calculations of transverse gluon is avoided. The comparisons between the transverse and the longitudinal contributions for heavy quarkonia are discussed. The results show that the dissociation scales of quarkonia in thermal medium are decreased by the transverse gluon contributions.

Keywords: Heavy quarkonium; Transverse gluon; In-medium static potential; Finite temperature QCD

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1. Introduction

Heavy quarkonium moving in thermal medium is a major field of the research for the quark gluon plasma. Since the Debye screening of the Coulomb-like potential between a heavy quark and its antiquark was proposed as a dissociation mechanism [1,2], the derivation for the in-medium quarkonium potential from Quantum Chromodynamics (QCD) has received a lot of attention (see Refs. [3–5] for reviews). Using the hard-thermal loop (HTL) resummed perturbation theory, Laine et al. [6,7] calculated the static Wilson loop to leading non-trivial order and gave the first form of the static potential at temperature T. This static potential includes a real

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part, which is the screened Coulomb-like potential, and an imaginary part which provides a thermal width Γ. It has been shown that, instead of the Debye screening, Γ gives the most important contribution to the quarkonium dissociation at high temperature [8–15].

Further studies show that the static potential at temperature T can also be obtained by the Fourier transform from the HTL resumed gluon propagator in the static limit [8,10]. Obviously, Laine et al. just considered the longitudinal thermal gluon, since at the HTL level, the transverse thermal gluon self-energy $\Pi_T = 0$, static magnetic fields are not screened, the infrared divergences will appear in the integration, which is similar to the calculation of the next to leading order Debye screening mass. The traditional method used to treat the infrared singularities is to introduce a nonperturbatively magnetic mass [16–18], whose nature has not yet been well understood. In order to solve this problem, Hou and Li [19] (see also Refs. [20,21]) considered the resummation of the damping rates for transverse gluons, and reasonably obtained the same result by using the magnetic mass. In this paper, we use their method to deal with the infrared problem in the Fourier transform for the transverse thermal gluon, and get some meaningful results.

Our paper is organized as follows. In Section 2, we briefly review the form of thermal field theory and the HTL result of thermal gluon self-energy. The method of Hou and Li is used to derive the transverse effective potential in isotropic medium. In Section 3, we firstly consider the coupling constant g as a function of temperature. The real part of the transverse and longitudinal thermal single-gluon exchange potential for three heavy quarkonia in 1s states are calculated and compared with the free energy models (and corresponding internal energy models). The thermal widths are also calculated and compared with one internal energy model. Secondly, because the premise of HTL approximation has a contradiction with the $g = g(T)$ case, we set $g = 0.5$ to calculate the binding energies and widths. Finally, in Section 4 we summarize our results.

2. Formulation

As a consequence of the background temperature, the ground state energy of a system must be modified. This means there are two kinds of particles: the "positive energy" particles which include the temperature effects, and the "negative energy" particles which obey the dynamics of the zero-temperature theory. Therefore, in order to include the effects of the "negative energy", the vacuum state and the field operators must be modified. For this purpose, the original Hilbert space need to be expanded. This leads to the thermal field theory developed by Takahashi and Umezawa [22–24].

For boson, we define a new field operator to incorporate the "negative energy" effects,

$$\mathrm{A} = \begin{pmatrix} A \\ \tilde{A} \end{pmatrix}, \tag{1}$$

where A is the "positive energy" field, and the Tilde operator $\tilde{A}$ denotes the "negative energy" field. The thermal vacuum $|0(\beta)\rangle$ can be similarly constructed from the original vacuum and its Tilde companion. Therefore, the thermal boson propagator can be presented as

$$\begin{aligned} \mathrm{D}(x) &= \langle 0(\beta)|\, T\left(\mathrm{A}(x)\mathrm{A}^{\dagger}(0)\right) |0(\beta)\rangle \\ &= \langle 0(\beta)| \begin{pmatrix} T(A(x)A(0)) & T(A(x)\tilde{A}(0)) \\ T(\tilde{A}(x)A(0)) & T(\tilde{A}(x)\tilde{A}(0)) \end{pmatrix} |0(\beta)\rangle . \end{aligned} \tag{2}$$

For convenience, $\mathrm{D}(x)$ can be transformed to the formula only containing the "positive energy" parts. By using the Feynman–Stüchelberg interpretation of negative energy particle, we have