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On the Temperature-Dependence of Quarkonia Correlators

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On the Temperature-Dependence of Quarkonia Correlators

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Abstract. Here I review the temperature-dependence of heavy quarkonia correlators in potential models with three different screened potentials, and compare these to the results from lattice QCD. None of the potentials investigated yield results consistent with the lattice data, indicating that screening is likely not the mechanism for heavy quarkonia suppression. I also discuss a simple toy model, not based on temperature-dependent screening, that can reproduce the lattice results.

Keywords: quarkonium suppression, potential models
PACS: specifications see, e.g. `http://www.aip.org/pacs/`

1. Introduction

The idea that the melting of heavy quark bound states at the deconfinement temperature could be considered an unambiguous signal for deconfinement has led to an intense line of studies. Originally it was predicted in [1] that color screening in the deconfined medium would cause the dissolution of the J/ψ. Understanding the modification of the properties of the different quarkonium states in a hot medium is therefore crucial for understanding deconfinement. Experiments have been looking for J/ψ suppression at CERN-SPS and RHIC-BNL [2]. Theoretical studies were mostly phenomenological, and use potential models as a basic tool. In recent years, first principle calculations of QCD carried out on the lattice provided new and unexpected information about quarkonia at high temperatures [3, 4].

Correlation functions of hadronic currents $G(\tau,T)$ have been reliably calculated on the lattice. Any deviation from one of the ratio

$$\frac{G(\tau,T)}{G_{recon}(\tau,T)}=\frac{\int d\omega\sigma(\omega,T)K(\tau,\omega,T)}{\int d\omega\sigma(\omega,T=0)K(\tau,\omega,T)} \tag{1}$$

indicates modification of the spectral function $\sigma(\omega,T)$ with temperature. The integration kernel is $K(\tau,\omega,T)=\cosh(\omega(\tau-1/2T))/\sinh(\omega/2T)$. Fig. 1 shows the ratio of correlators (1) for the scalar (left panel) and pseudo-scalar (right panel) charmonium [4]. In contradiction with what has been theoretically expected from potential model calculations (see for instance [5]), these lattice results indicate that the 1S charmonium survives up to 1.5 T_c and the 1P charmonium dissolves by 1.16 T_c. The spectral functions, extracted from the correlators using the Maximum Entropy Method, not only reinforce these findings, but also indicate that the properties of the 1S states do not change up to these temperatures [4].

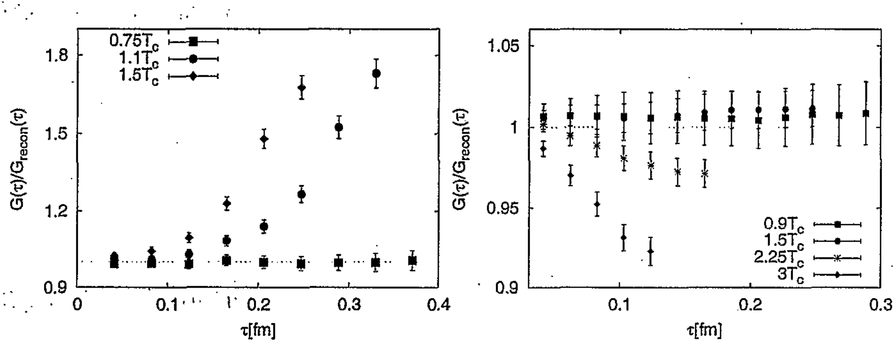

Fig. 1. Temperature dependence of scalar (left panel) and pseudo-scalar (right panel) correlators obtained on the lattice (from [4]).

After the appearance of the lattice data, potential models have been reconsidered using different temperature dependent potentials [6, 7, 8, 9]. With these models quarkonium dissociation temperatures in accordance with the above quoted numbers from the lattice were identified. In [10, 11] however, it has been shown, that even though potential models with certain screened potentials can reproduce qualitative features of the lattice spectral function, such as the survival of the 1S state and the melting of the 1P state, the temperature dependence of the meson correlators is not reproduced. Furthermore, the properties of the states determined with these screened potentials do not seem to reproduce the results indicated by the lattice spectral functions.

The question is thus whether medium modifications of quarkonia correlators can be understood via a temperature-dependent quark-antiquark potential? If yes, what is the potential? And if not, then what is the relevant mechanism responsible for the dissociation of quarkonia at high temperatures?

Here I review some of the main results of [10, 11], and then present a simple toy model with no explicit screened potential which provides results that are consistent with the lattice correlator data. Further developments are discussed in the Outlook.

2. Model Spectral Function and Potentials

In order to make direct comparison with the lattice data we calculate the ratio of correlators (1). We model the finite temperature spectral function in a given quarkonium channel as the sum of bound state (resonance) contributions and the perturbative continuum above a threshold s_0,

$$\sigma(\omega,T)=\sum_i 2M_i(T)F_i(T)^2\delta\left(\omega^2-M_i(T)^2\right)+\frac{3}{8\pi^2}\omega^2\theta\left(\omega-s_0(T)\right)f\,, \tag{2}$$

with $f=+1$ and -1 in the pseudo-scalar and scalar channels[1]. The mass M_i and the amplitude F_i of the quarkonium states is determined using potential models.

The essence of potential models is to assume that the interaction between a heavy quark and antiquark is mediated by a two-body potential. This assumption is feasible when the quark-antiquark interaction is instantaneous. The properties of a bound state are determined by solving the Schrödinger equation with this potential. At zero temperature the Cornell potential seems to have described quarkonia spectroscopy rather well. At finite temperature, however, the form of the potential is not known. It is even questionable whether a temperature-dependent potential is adequate for the understanding of the properties of quarkonia at finite temperature.

We calculated the correlators for three different potentials that have been popular in the literature: First, the screened Cornell potential [5]

$$V(r,T)=-\frac{\alpha}{r}e^{-\mu(T)r}+\frac{\sigma}{\mu(T)}(1-e^{-\mu(T)r})\,, \tag{3}$$

with parameters described in [10].

Second, the internal energy of a heavy quark-antiquark pair as determined on the lattice [12] and identified as the potential [6]. Our fit of the internal energy is shown on the left panel of Fig. 2, and the details of our parametrization are given in [10]. One should be aware that in leading order perturbation theory, which is valid at high temperatures, the potential is equal to the free energy of the quark-antiquark pair. Beyond leading order there is an entropy contribution to the free energy and therefore it is conceptually difficult to identify this with the potential [13].

Third, we consider a combination of the internal and the free energy from the lattice that has also been suggested by Wong as potential [7]. This potential is shown on the right panel of Fig.2. One common feature of all three potentials is that they incorporate temperature-dependent screening.

3. Results

Figs. 3 and 4 display the ratio of correlators (1) as obtained using the screened Cornell potential (3) and the lattice internal energy. The left and right panels show the results for the scalar χ_c and the pseudo-scalar η_c for different temperatures. One can see that the qualitative behavior for the χ_c correlator agrees with what is seen on the lattice (left panel Fig.1). There is however, no agreement with the

[1] Such a form for the spectral function is justified at $T=0$. We assume that it is an appropriate description also at finite temperature.

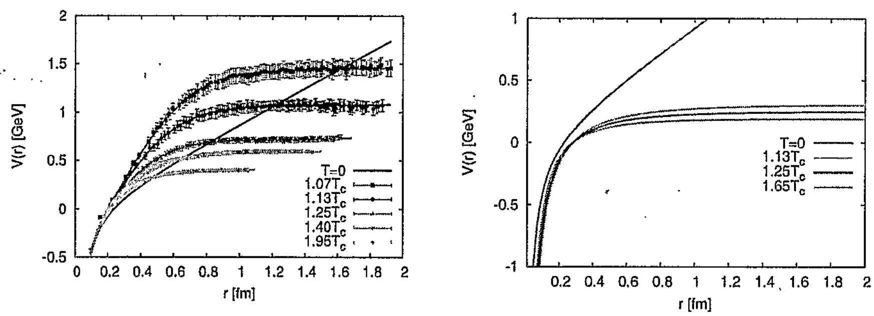

Fig. 2. Lattice internal energy (left panel); Wong-potential (right panel).

lattice (right panel of Fig.1) for the η_c correlator. In the model calculations one can identify a more complex substructure in the η_c correlator: The reduction of the continuum threshold and that the amplitude of the states are distinguishable contributions (see [10] for details). The η_c correlator obtained using the Wong-

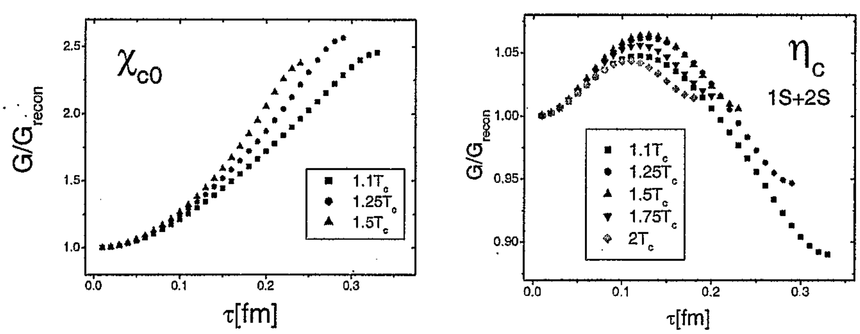

Fig. 3. Temperature dependence of scalar (left panel) and pseudo-scalar (right panel) correlators using the screened Cornell-potential (3).

potential is shown in Fig. 5. This also illustrates a large disagreement with what is seen on the lattice, indicating that the spectral function of the η_c is significantly different than at zero temperature. This further suggests that this state melts near T_c already. The results for the spectral function presented in [14] further confirm this statement.

We also analyzed the bottomonium states, and found that in this case too, the correlators calculated in the potential models cannot reproduce the lattice results. We refer the interested reader to [10, 14] .

Clearly, none of these potentials lead to correlators that agree with the lattice. It is thus a reasonable question to ask whether such temperature-dependent screened potentials are the right way to describe modification of quarkonia properties with

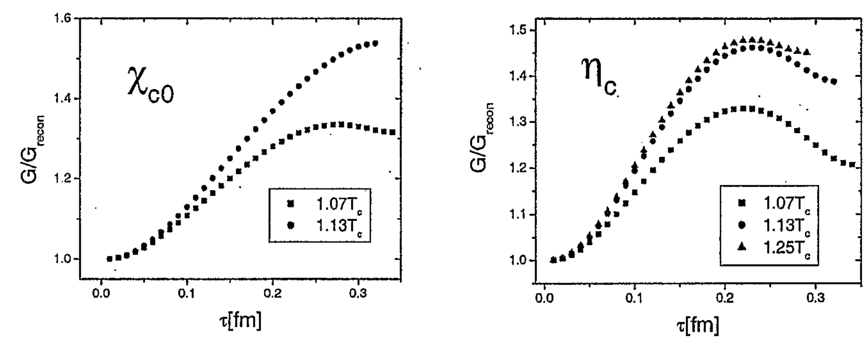

Fig. 4. Temperature dependence of scalar (left panel) and pseudo-scalar (right panel) correlators obtained using the lattice internal energy as potential.

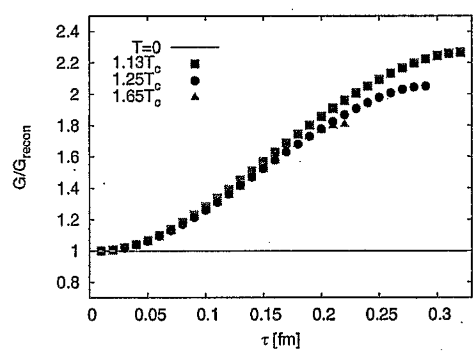

Fig. 5. Temperature-dependence of the pseudo-scalar correlator obtained using the Wong-potential.

temperature. As a first attempt to answer this question consider the following simple model:

4. Toy Model

Keeping the lattice results in mind, namely that no modification in the properties of the 1S charmonium compared to the zero temperature values has been observed up to well above T_c, we use for the mass and decay rate of this state the Particle Data Group values. Also, since lattice data suggest that higher excited states disappear near the transition temperature, we "melt" the 2S and 3S states, and also the 1P state at T_c.

This model does not include temperature dependent screening. The only parameter is the continuum threshold s_0. The main idea is to compensate for the melting of the higher excited states above T_c with the decrease of the threshold. On Fig. 6 the charmonium correlators for the scalar (upper branch) and pseudo-scalar (lower branch) channels are shown for different values of s_0. This figure illustrates that we can recover the qualitative behavior of the lattice correlators of Fig.1: the flatness of the η_c and the increase in the χ_c correlator.

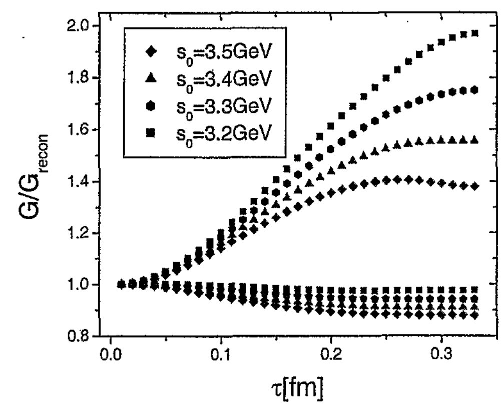

Fig. 6. The scalar (upper branch) and pseudo-scalar (lower branch) charmonium correlators in the toy model for different values of the continuum threshold.

5. Outlook

We illustrated that potential models utilizing temperature-dependent screened potentials are not successful in reproducing qualitatively the lattice results for quarkonium correlators. We further showed that a simple toy model with no screening is consistent with the lattice. This model shows that the decrease of the threshold with increasing temperature can compensate for the melting of the higher excited states.

To overcome possible errors that could be introduced by our spectral function Ansatz, we performed a full non-relativistic calculation of the Green's function [11, 14], whose imaginary part provides the quarkonium spectral function. Our results produced for the different screened potentials again do not show qualitative agreement with what is seen on the lattice [11, 14].

We then conclude that screening is likely not responsible for quarkonia suppression. This can happen when the time-scale of screening is not short compared to the time-scale of the heavy quark motion. Then gluon dissociation becomes the mechanism behind the dissolution of heavy quarkonia states. This is the topic of our ongoing investigations.

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