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Nuclear Physics A 914 (2013) 512–516
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

Modification of hadronic spectral functions under extreme conditions: An approach based on QCD sum rules and the maximum entropy method

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Received 1 December 2012; received in revised form 10 January 2013; accepted 13 March 2013

Abstract

Studies of quarkonium spectral functions at finite temperature, based on an approach combining QCD sum rules and the maximum entropy method are briefly reviewed. QCD sum rules for heavy quarkonia incorporate finite temperature effects in form of changing values of gluonic condensates that appear in the operator product expansion. These changes depend on the energy density and pressure at finite temperature, which we extract from quenched lattice QCD calculations. The maximum entropy method then allows us to obtain the most probable spectral function from the sum rules, without having to introduce any specific assumption about its functional form. Our findings suggest that the charmonium ground states of both S-wave and P-wave channels dissolve into the continuum already at temperatures around or slightly above the critical temperature T_c, while the bottomonium states are less influenced by temperature effects, surviving up to about 2.5 T_c or higher for S-wave and up to about 2.0 T_c for P-wave states.

Keywords: Quarkonium; QCD sum rules; QCD at finite temperature

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0375-9474/$ – see front matter
http://dx.doi.org/10.1016/j.nuclphysa.2013.03.008

1. Introduction

The study of quarkonia in hot matter has, since the early suggestions [1] that were made more than 25 years ago, evolved into a field with diverse activities in both experiment and theory. Especially, through the heavy-ion collision experiments at RHIC and LHC, a huge amount of experimental data on quarkonium production in various reactions is now available, which can be compared with theoretical expectations. This task, however, has turned out to be very complex, as a large number of competing effects have to be taken into account to describe the experimental results (for a review see [2]). The most basic inputs of these calculations are the quarkonia spectral functions, which include all the physically relevant information of the quarkonium states as well as their behavior at finite temperature. It is therefore desirable to obtain these spectral functions from calculations based on QCD. Progress in this direction has been achieved mostly due to the advancement of lattice QCD and the use of the maximum entropy method (MEM) for the extraction of the spectral function from the Euclidean time correlator [3] (see also [4] and the references therein for the latest results).

Another approach for capturing information on quarkonia spectral functions at both zero and finite temperature is provided by QCD sum rules. This method exploits the analytic properties of the two-point function of operators to derive certain integrals over the hadronic spectral functions (the "sum rules"), which, via the operator product expansion (OPE), can be related to a combination of perturbatively calculable quantities and non-perturbative condensates, containing information on the QCD vacuum. In the case of the quarkonia channels considered here, these are gluonic condensates, the most important one being the gluon condensate of mass dimension 4 [5].

Recently, it has become possible to make use of the MEM technique to analyze QCD sum rules [6], which allows to extract the most probable form of the spectral function from the OPE without having to resort to some specific functional form. This approach has since been applied to both charmonium [7] and bottomonium [8] channels and to discuss these results will be the main goal of this article.

The proceedings are organized as follows. After a brief description of our formalism and analysis methods, we recapitulate the results obtained so far in [7,8]. We will also show some novel results on the thermal behavior P-wave charmonia (χ_{c0}, χ_{c1}), which were not included in [7]. Finally, we summarize our results and give an outlook by discussing open issues and possible future directions of further improvements of the sum rule approach presented here.

2. Formalism

QCD sum rules at finite temperature make use of the analyticity of the two-point correlator of some general local operator $j^{\mathrm{J}}(x)$:

$$\Pi^{\mathrm{J}}(q) = i \int d^4x\, e^{iqx} \big\langle T\big[j^{\mathrm{J}}(x) j^{\mathrm{J}}(0)\big]\big\rangle_T. \tag{1}$$

Here, $j^{\mathrm{J}}(x)$ stands for $\bar{h}\gamma_\mu h(x)$, $\bar{h}\gamma_5 h(x)$, $\bar{h}h(x)$ and $(q_\mu q_\nu/q^2 - g_{\mu\nu})\bar{h}\gamma_5\gamma^\nu h(x)$ in the vector, pseudoscalar, scalar and axial-vector channel, respectively, while $h(x)$ represents either a charm- or bottom-quark field. The definition of the expectation value $\langle \mathcal{O}\rangle_T$ is $\langle \mathcal{O}\rangle_T \equiv \mathrm{Tr}(e^{-H/T}\mathcal{O})/\mathrm{Tr}(e^{-H/T})$. Through a dispersion relation, one can relate the correlator calculated in the deep-Euclidean region ($-q^2 \to \infty$) to a specific integral over the hadronic spectral function $\rho^{\mathrm{J}}(s)$. After the application of the Borel transform, one arrives at the following expression: