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The continuum threshold and the Polyakov loop: A comparison between two deconfinement order parameters

J.P. Carlomagno[a,b], M. Loewe[c,d,e,1]

[a] IFLP, CONICET – Dpto. de Física, Universidad Nacional de La Plata, C.C. 67, 1900 La Plata, Argentina
[b] CONICET, Rivadavia 1917, 1033 Buenos Aires, Argentina
[c] Instituto de Física, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile
[d] Centre for Theoretical and Mathematical Physics and Department of Physics, University of Cape Town, Rondebosch 7700, South Africa
[e] Centro Científico-Tecnológico de Valparaíso - CCTVAL, Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile

Abstract

We compare two order parameters for the deconfinement transition, induced by thermal and density effects, commonly used in the literature, namely the thermal and density evolution of the continuum threshold s_0, within the frame of the QCD sum rules, and the trace of the Polyakov loop Φ in the framework of a nonlocal $SU(2)$ chiral quark model. We include in our discussion the evolution of the chiral quark condensate, the parameter that characterizes the chiral symmetry restoration. We found that essentially both order parameters, s_0 and Φ, provide the same information for the deconfinement transition, both for the zero and finite chemical potential cases. At zero density, the critical temperatures in both cases coincide exactly and, in the case of finite baryonic chemical potential μ, we find evidence for the appearance of a quarkyonic phase.

Keywords: deconfinement order parameters, QCD sum rules, chiral quark models

1. Introduction

In QCD, when quarks are placed in a medium, the color charge is screened due to density and temperature effects [1]. If the density and/or the temperature increases beyond a certain critical value, one expects that the interactions between quarks will not be able to confine them inside a hadron, so that they are free to travel longer distances and deconfine. This transition from a confined to a deconfined phase is usually referred to as the deconfinement phase transition.

A separate phase transition is the realization of chiral symmetry, moving from a Nambu-Goldstone phase into a Wigner-Weyl phase. Based, on lattice QCD evidence [2] one expects these two phase transitions to take place at approximately the same temperature at zero chemical potential. At finite density these two transitions can arise at different critical temperatures. The result will be a quarkyonic phase, where the chiral symmetry is restored but the quarks and gluons remain confined.

It has been customary to study the behavior of the trace of the Polyakov loop (PL) $\Phi(T,\mu)$ (order parameter for deconfinement phase transition) and quark antiquark chiral condensate $\langle\bar{\psi}\psi\rangle(T,\mu)$ (chiral symmetry restoration), as function of temperature and chemical potential.

The goal of our discussion is to compare the Polyakov loop order parameter with a QCD deconfinement parameter [3], that corresponds to the squared energy threshold, $s_0(T,\mu)$, for the onset of perturbative QCD (PQCD) in hadronic spectral functions. For an actual general review see Ref. [4]. Around this energy, and at zero temperature, the resonance peaks in the spec-

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Email addresses: carlomagno@fisica.unlp.edu.ar (J.P. Carlomagno), mloewe@fis.puc.cl (M. Loewe)

[1] Speaker, Corresponding author.

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trum dissapear or become very broad, approaching then the PQCD regime. With increasing temperature approaching the critical temperature for deconfinement, the spectral function should then be described entirely by PQCD.

When both T and μ are nonzero, lattice QCD simulations cannot be used, because of the sign problem in the fermionic determinant. Therefore, one need to resort either to mathematical constructions to overcome the above limitation, or to model calculations.

The two deconfinement order parameters mentioned before: $\Phi(T,\mu)$ and $s_0(T,\mu)$ can be used to realize a phenomenological description of the deconfinement transition at finite temperature and density.

The natural framework to determine s_0 has been that of QCD sum rules. This framework is based on the operator product expansion (OPE) of current correlators at short distances, extended beyond perturbation theory, and on Cauchy's theorem in the complex s-plane. The latter is usually referred to as quark-hadron duality. Vacuum expectation values of quark and gluon field operators effectively parametrize the effects of confinement. An extension of this method to finite temperature was first outlined in [3].

To analyze the role of the PL, we will concentrate on nonlocal Polyakov−Nambu−Jona-Lasinio (nlPNJL) models (see [5, 6] and references therein), in which quarks move in a background color field and interact through covariant nonlocal chirally symmetric four point couplings. These approaches, offer a common framework to study both the chiral restoration and deconfinement transitions. In fact, the nonlocal character of the interactions arises naturally in the context of several successful approaches to low-energy quark dynamics, and leads to a momentum dependence in the quark propagator that can be made consistent [7] with lattice results.

The aim of the present work is to study the relation between both order parameters for the deconfinement transition at finite temperature and chemical potential, Φ and s_0, using the thermal finite energy sum rules (FESR) with inputs obtained from nlPNJL models.

2. Finite energy sum rules

We begin by considering the (charged) axial-vector current correlator at $T = 0$

$$\begin{aligned}\Pi_{\mu\nu}(q^2) &= i\int d^4x\, e^{iq\cdot x}\,\langle 0|T(A_\mu(x)A_\nu(0))|0\rangle,\\ &= -g_{\mu\nu}\,\Pi_1(q^2) + q_\mu q_\nu \Pi_0(q^2)\,, \end{aligned} \quad (1)$$

where $A_\mu(x) = \,:\bar{u}(x)\gamma_\mu\gamma_5 d(x):$ is the axial-vector current, $q_\mu = (\omega,\vec{q})$ is the four-momentum transfer, and the functions $\Pi_{0,1}(q^2)$ are free of kinematical singularities. Concentrating on the function $\Pi_0(q^2)$ and writing the OPE beyond perturbation theory in QCD , one of the two pillars of the sum rule method, one has

$$\Pi_0(q^2)|_{\text{QCD}} = C_0\,\hat{I} + \sum_{N=1} C_{2N}(q^2,\mu^2)\langle\hat{O}_{2N}(\mu^2)\rangle\,, \quad (2)$$

where μ^2 is a renormalization scale. The Wilson coefficients C_N depend on the Lorentz indices and quantum numbers of the currents. Finally, the local gauge invariant operators $\hat{O}_N$, are built from the quark and gluon fields in the QCD Lagrangian. The vacuum expectation values of those operators $(\hat{O}_{2N}(\mu^2))$, dubbed as condensates, parametrize nonperturbative effects and have to be extracted from experimental data or model calculations.

The second pillar of the QCD sum rules technique is Cauchy's theorem in the complex squared energy s-plane and this allows us to establish the following FESR. For details, we refer the reader to Ref. [4] and to the original article Ref. [6]

$$\begin{aligned}(-)^{N-1}C_{2N}\langle\hat{O}_{2N}\rangle &= 4\pi^2\int_0^{s_0} ds\, s^{N-1}\,\frac{1}{\pi}\text{Im}\Pi_0(s)|_{\text{HAD}}\\ &\quad -\frac{s_0^N}{N}\,[1+O(\alpha_s)] \quad (N=1,2,\cdots)\,. \end{aligned} \quad (3)$$

For $N = 1$, the dimension $d = 2$ term in the OPE does not involve any condensate, as it is not possible to construct a gauge invariant operator of such a dimension from the quark and gluon fields. There is no evidence for such a term (at $T = 0$) from FESR analyses of experimental data on e^+e^- annihilation and τ decays into hadrons [8, 9]. At high temperatures, though, there seems to be evidence for some $d = 2$ term [10]. However, the analysis to be reported here is performed at lower values of T, so that we can safely ignore this contribution in the sequel.

The dimension $d = 4$ term, a renormalization group invariant quantity, is given by

$$C_4\langle\hat{O}_4\rangle = \frac{\pi}{6}\langle\alpha_s G^2\rangle + 2\pi^2(m_u+m_d)\langle\bar{q}q\rangle\,. \quad (4)$$

The extension of this program to finite temperature is fairly straightforward [3, 11, 12], with the Wilson coefficients in the OPE, Eq. (2), remaining independent of T at leading order in α_s, and the condensates developing a temperature dependence.

In the static limit ($\vec{q} \to 0$), to leading order in PQCD, and for $T \neq 0$ and $\mu \neq 0$ the function $\Pi_0(q^2)|_{\text{QCD}}$ in

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