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Massive Yang–Mills for vector and axial-vector spectral functions at finite temperature

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ABSTRACT

The hadronic mechanism which leads to chiral symmetry restoration is explored in the context of the $\rho\pi a_1$ system using Massive Yang–Mills, a hadronic effective theory which governs their microscopic interactions. In this approach, vector and axial-vector mesons are implemented as gauge bosons of a local chiral gauge group. We have previously shown that this model can describe the experimentally measured vector and axial-vector spectral functions in vacuum. Here, we carry the analysis to finite temperatures by evaluating medium effects in a pion gas and calculating thermal spectral functions. We find that the spectral peaks in both channels broaden along with a noticeable downward mass shift in the a_1 spectral peak and negligible movement of the ρ peak. The approach toward spectral function degeneracy is accompanied by a reduction of chiral order parameters, *i.e.*, the pion decay constant and scalar condensate. Our findings suggest a mechanism where the chiral mass splitting induced in vacuum is burned off. We explore this mechanism and identify future investigations which can further test it.

1. Introduction

Chiral symmetry is a basic symmetry of quantum chromodynamics (QCD), the theory of the strong nuclear force. This symmetry is spontaneously broken in the vacuum via the formation of quark

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condensates. At higher temperatures, the symmetry is restored as the condensates melt passing through a pseudo-critical region [1,2] around $T_{pc} \simeq 160$ MeV. This behavior is imprinted on the hadronic spectra when heating up the vacuum. Despite these well-established properties of QCD, the hadronic mechanism leading to chiral restoration is not fully understood to date.

The only in-medium hadronic spectral function which is experimentally accessible is that of the light vector mesons, dominated by the ρ, which can be probed via low-mass dilepton spectra in heavy-ion collisions [3–7]. Theory calculations reveal that the experimental data are compatible with a ρ melting scenario whereby the spectral peak broadens without a significant shift in its mass, see, *e.g.*, Refs. [8,9]. It has been conjectured that this broadening is an indication of chiral symmetry restoration based on QCD and chiral sum rules [10]. However, for a definitive assertion of restoration, the in-medium spectral function of the chiral partner of the ρ, namely the light axial-vector meson a_1, needs to be calculated to test spectral degeneracy. This spectral function is difficult to measure experimentally. Thus one is led to study the $\rho\pi a_1$ system theoretically to establish chiral restoration.

Recent sum rule analyses indicate that the experimental dilepton measurements are consistent with an approach toward restoration and spectral degeneracy between the vector (V) and axial-vector (AV) channels [10]. This degeneracy is imprinted on the a_1 spectral function by a mass shift toward the ρ mass, accompanied by spectral broadening. This analysis suggests a possible mechanism for restoration in the hadronic spectrum. However, other analyses suggest that the sum rules can be satisfied in medium without a mass shift or a need to approach spectral degeneracy [11]. Therefore, it is in order to explore the mechanism from a microscopic perspective.

A theoretically appealing construction is to implement the ρ and a_1 as the gauge bosons of a local chiral gauge group [12]. This combines chiral effective theories, which have had considerable success in describing pion driven low-energy properties of QCD [13], with the general field theoretical concept of gauge symmetries. This has been realized in two formalisms, Massive Yang–Mills (MYM) [14] and Hidden Local Symmetry (HLS) [15,16], which have been shown to be on-shell equivalent.

Early applications of MYM successfully describe the tree level masses and decays of the ρ and a_1 mesons [14,17,18]. These studies were extended to finite temperatures [19–21] revealing a reduction of the a_1 mass along with an increase in the ρ mass. However, these calculations do not survive the scrutiny of a loop calculation needed to determine the vacuum spectral functions which have been experimentally measured with high precision through τ leptons decaying into multi-pion states [22,23]. An in-medium mass reduction in the a_1 spectral function is also compatible with the HLS framework [24], though a satisfactory description of vacuum spectral functions has not yet been demonstrated either.

The complications in describing the vacuum spectral functions with MYM and HLS triggered investigations which abandon the local implementation of the gauge group in favor of a global one [25–27]. These models have also been extended to include temperature effects; using a loop expansion, a broadening of the ρ spectral peak without a mass shift was found in Ref. [28], whereas Ref. [29], using a 2-particle irreducible truncation scheme for the in-medium masses, found a slightly increasing ρ-mass to degenerate with a dropping a_1-mass above the critical temperature.

In a recent work, we have re-evaluated MYM as an effective theory to describe the light-meson chiral properties, and were able to overcome the initial difficulties associated with the vacuum spectral functions [30]. This was made possible by two critical ingredients: a fully dressed ρ propagator in the calculation of the a_1 self-energy, and the inclusion of a chirally invariant continuum. In the present paper, motivated by this development and the theoretical appeal of MYM, we implement this approach in a finite-temperature pion gas, examining the medium modifications of the spectral functions to deduce information on the hadronic mechanism of chiral restoration. We also extend our studies to the linear realization of the chiral pion Lagrangian by introducing an explicit σ field in the vacuum and carrying it to finite temperature. On the one hand, this allows us to assess systematic uncertainties of our results. On the other hand, the linear realization has the well-known benefit of a more natural approach to degeneracy in the scalar–pseudoscalar channel which could be beneficial for future extensions of our in-medium studies.

Our paper is organized as follows. In Section 2, we briefly introduce MYM. In Section 3, we recall our strategy of implementing a broad ρ spectral function into the vacuum MYM framework, and extend our earlier work to the linear σ model and with further applications to vacuum observables.