Is ρ-meson melting compatible with chiral restoration?

P. M. Hohler and R. Rapp

The QCD vacuum spontaneously breaks chiral symmetry at low temperatures and chemical potentials through the formation of the quark condensate. At higher temperatures, this condensate melts across a region around a pseudo-critical temperature, T_{pc}~160MeV, thus restoring the symmetry [1, 2]. How this restoration is imprinted on the observable hadronic states has been a long standing question. One way to study this is through the in-medium spectral functions of chiral partners, e.g. the ρ and a_1 (vector and axial-vector) mesons. The vector channel can be experimentally accessed through dilepton spectra in ultra-relativistic heavy ion collisions [3-5]. Theoretical calculations from a microscopic hadronic effective field theory [6] turn out to agree with experimental data, implying that the in-medium ρ spectral function melts through spectral peak broadening without a significant mass shift [7]. To relate this melting to chiral symmetry restoration requires knowledge about the axial-vector channel. However, to date, the latter remains experimentally elusive. Therefore, progress can only be made through theoretical techniques which inherently connect the vector and axial-vector channels. A rigorous method are sum rules, in particular QCD [8] and Weinberg-type sum rules [9-11] which relate the vector and axial-vector spectral function to each other and to ground-state condensates. Here, our strategy is to provide inputs to the sum rules in terms of the in-medium vector spectral function (as tested in experiment) and condensates from lattice QCD, to search for possible solutions for the axial-vector spectral function to satisfy the sum rules.

In the current work [12], we build on our earlier sum rule investigation [13] of the vacuum vector and axial-vector spectral functions and extend it to finite temperature. In medium, the sum rules translate the temperature dependence of the QCD condensates to medium modifications of the spectral functions. For our analysis, there are four important inputs. The first is the in-medium ρ spectral function for which we use the results of Ref. [6]; thus a direct connection to the dilepton data and the melting scenario is made. The second is the temperature dependence of the condensates. For this we use a hadron resonance gas approach with guidance from lattice QCD calculations. The resulting temperature dependencies of the quark and 4-quark condensates are depicted in Fig. 1. Third, we specify the temperature dependence of the excited vector and axial-vector meson states through chiral mixing with a mixing parameter derived from both thermal pions as well as the pion cloud of other hadrons [14, 15]. In this way, the effect of the hadron resonance gas is incorporated into this mixing. This constraint facilitates to focus our study on the contribution from the axial-vector ground state. Lastly, we stipulate that the chirally invariant vacuum continuum in both vector and axial-vector spectral functions is temperature independent. The medium modifications of the a_1 spectral function are represented by four parameters: one for the mass, two for the width, and one for the coupling strength to the current. These parameters are determined at each temperature by requiring that both the axial-vector QCD sum rule and the Weinberg sum rules are satisfied. It is the combination of *both* sets of sum rules which is critical in constraining possible spectral functions. With these ansaetze, we were able to show that 1) the vector QCD sum rule can be satisfied better than the 0.67% level with a small (order 5%) modification of the vector dominance coupling, and

2) an axial-vector spectral function can be determined which satisfies the axial-vector QCD sum rule better than 0.59% and the first two Weinberg sum rules better than 0.004%.

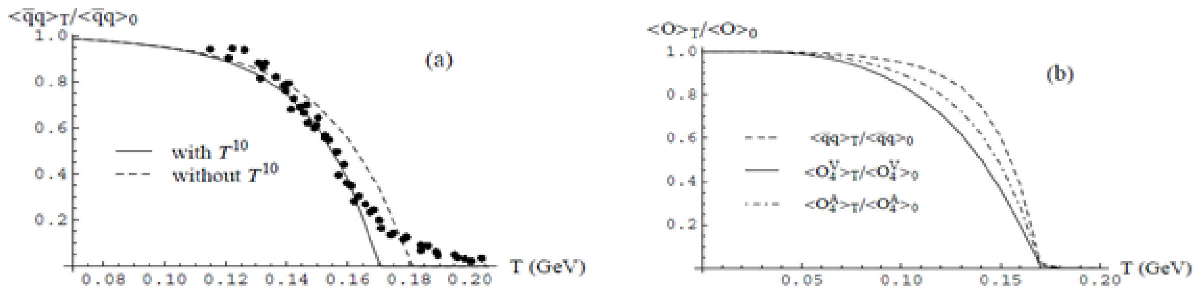

FIG. 1. Temperature dependence of: (a) the quark condensate relative to its vacuum value, compared to thermal lattice-QCD data [1]; (b) axial-/vector 4-quark condensates relative to their vacuum values, compared to the quark condensate.

The resulting spectral functions are shown in Fig. 2. By being able to satisfy the sum rules at each temperature, the manner in which restoration is achieved can be studied through the temperature progression of the spectral functions. One notices that with increasing temperature, the a_1 spectral peak broadens and shifts its mass to lower energies, ultimately merging with the vector channel at the highest temperature. The mass shift in the axial-vector channel can be thought of as the burning off the chirally breaking ρ-a_1 mass difference. This study thus demonstrates that the ρ-melting scenario is consistent with chiral restoration.

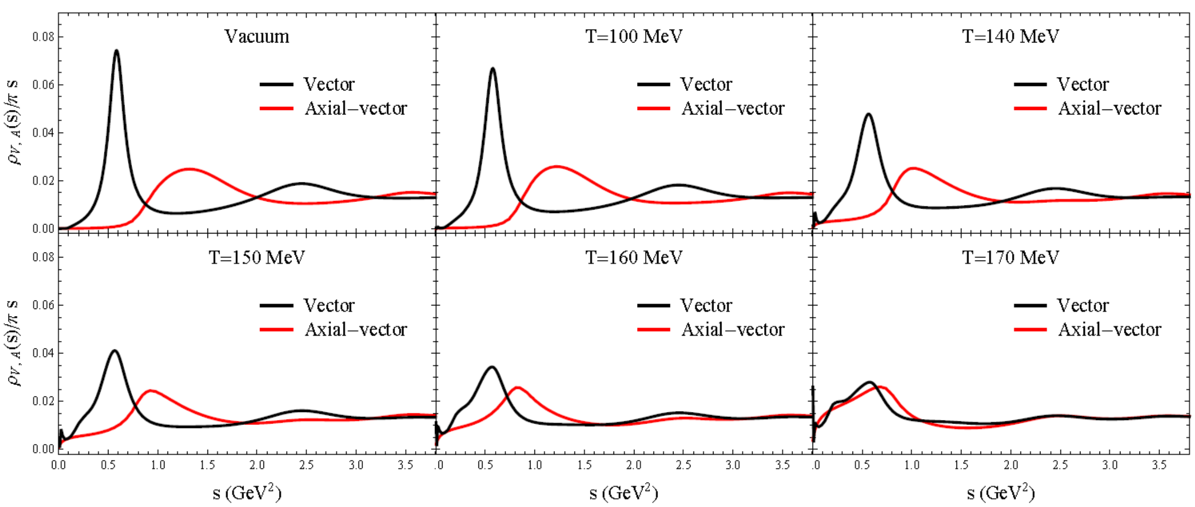

FIG. 2. Finite- temperature vector (black/darker curve) and axial-vector (red/lighter curve) spectral functions.

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