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Compatibility of QCD sum-rules and hadron field theory in a dense medium

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Abstract

The compatibility of the QCD sum rules and effective hadronic models predictions are examined. For this purpose we have considered the results for the nucleon self-energy in a dense hadronic environment provided by two independent QCD sum-rules calculations. They are immersed in a theory of hadronic fields giving rise to non-linear interactions, whose vertices are parameterized in different ways. Although all of them reproduce the self-energy used as input, very different descriptions of nuclear observables are obtained. Only under very definite circumstances we have found an acceptable agreement with the nuclear matter properties. To achieve this, phenomenological parameters are not required at all.

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Currently, there is a noticeable interest in interpreting and formalizing the low energy manifestations of the fundamental theory of the strong interactions. However, the mathematical complexity that quantum chromodynamics (QCD) exhibits in this regime makes impossible to reach this aim. Several approaches were proposed to circumvent this difficulty, such as lattice simulations, QCD sum-rules, and effective models, for instance Nambu–Jona-Lasinio, bag-like models, and chiral perturbation theory. Each of these treatments emphasizes some aspects of QCD, considered as the most relevant in the hadronic phase. Contact with low energy physics is ensured by fixing some model parameters, such as hadronic masses and decay constants to its experimental values. It is generally believed that for high density and/or temperatures, the symmetries of the fundamental theory would be recovered, therefore effective models should reproduce this feature to some degree.

The low to medium density states of nuclear matter have been extensively studied by using nuclear potentials. Most of the nuclear structures, reactions,

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and dispersion phenomenology have been successfully described in this way. However, these formulations lack of Lorentz covariance and they violate causality when extrapolated to higher densities. The requirements of covariance and causality can be fulfilled properly within the hadronic field theory (HFT), whose prototype the quantum hadrodynamics [1] usually takes dense nuclear matter as its reference state. This practice contrasts with certain nuclear potential treatments that refer to in-vacuum scattering lengths, ascribing this feature to a more fundamental instance of nuclear potentials as compared with HFT. Inspired in this viewpoint, several investigations have been made in order to make compatible both schemes, due to the simplicity and accuracy of the HFT treatment. The in-medium self-energy of the nucleon plays a key role in these attempts, as it is evaluated in both approaches and then equated to extract medium dependent vertices [2–5].

The idea behind this procedure is that when a piece of information provided by another field of research is coherently inserted into the framework of the HFT, a simpler and more intuitive description is obtained instead of stating first principles interactions and performing involved calculations. This procedure is specially suited for high density systems since the details of the interactions are faded out in favor of a statistical average. A significative exemplification is given by the Brown–Rho scaling of hadronic masses. Taking into account the chiral and scale symmetries of QCD solely, an approximate scaling law for the in-medium hadronic masses was derived in [6]. This hypothesis was applied to describe heavy ion collision, reaching an excellent agreement with the experimental results for the low mass dilepton production rate [7].

On the contrary, going from low to higher energies, Refs. [2–5] take nuclear potentials as the starting point and results are extrapolated to the medium-high dense nuclear matter and atomic nuclei. In Ref. [4] it was stressed that a coherent model requires that the medium dependence of the above mentioned vertices must be introduced in terms of hadronic fields. Otherwise, the *rearrangement* self-energies are missed and thermodynamical consistency is not satisfied.

In this Letter, we try to match QCD inspired results with the HFT formalism, by introducing field dependent strength couplings as proposed in [4]. For this purpose, we have chosen as inputs the nucleon self-energies evaluated within the QCD sum-rules approach [8–12]. We have compared different field parameterizations of the vertices, and examined the ability of our results to fit the nuclear matter phenomenology.

QCD sum-rules is a powerful procedure to reveal the QCD foundations of certain hadronic properties. This method relies on the evaluation of correlation functions in terms of quarks and gluons degrees, then applying the operator product expansion it is possible to express them as combinations of perturbative contributions and condensates (non-perturbative). In the last step, results are connected with the hadronic counterpart, from which information on the spectral function can be inferred. The method was developed to study meson [8] as well as baryon [9] properties in vacuum, it was subsequently generalized to study finite density systems [10–12]. We have used the in-medium nucleon self-energies provided by references [11,12], more precisely the simplified expressions given there as functions of the baryonic density. Both investigations include non-perturbative contributions representing one meson exchange, the structure of the nucleon, and multiple meson exchange. Nevertheless, they differ in the criteria used to simplify the final formulae. The results of Ref. [12] keep all the contributions averaged over the Borel mass parameter; whereas, in [11] only the leading term in the operator product expansion is retained, and the Borel mass is fixed in order that the effective nucleon mass goes to its experimental value in vacuum. In the latter case, a linear dependence on the density is obtained for both the scalar and vector nucleon self-energy.

As it was above mentioned, the density dependent hadron field theory (DDHFT) [4,5] attempts to insert the nucleon self-energy supplied by Dirac–Brueckner calculations with one boson exchange potentials, into a hadronic field description of the nuclear matter phenomenology. In general terms, we have adopted the procedure described in Ref. [4] to merge dynamically the external input into a field model, and we will indicate where we depart from it.

We start with a Lagrangian for nucleons (ψ) and scalar and vector mesons (σ and ω respectively), resembling the QHD-I model of Walecka [1] for isospin symmetric nuclear matter,