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Chiral density wave in nuclear matter

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Abstract

Inspired by recent work on inhomogeneous chiral condensation in cold, dense quark matter within models featuring quark degrees of freedom, we investigate the chiral density-wave solution in nuclear matter at zero temperature and nonvanishing baryon number density in the framework of the so-called extended linear sigma model (eLSM). The eLSM is an effective model for the strong interaction based on the global chiral symmetry of quantum chromodynamics (QCD). It contains scalar, pseudoscalar, vector, and axial-vector mesons as well as baryons. In the latter sector, the nucleon and its chiral partner are introduced as parity doublets in the mirror assignment. The eLSM simultaneously provides a good description of hadrons in vacuum as well as nuclear matter ground-state properties. We find that an inhomogeneous phase in the form of a chiral density wave is realized, but only for densities larger than $2.4\rho_0$, where ρ_0 is the nuclear matter ground-state density.

Keywords: Chiral density wave; Nonzero density; Chiral restoration

1. Introduction

The spontaneous breaking of chiral symmetry in the QCD vacuum is a nonperturbative phenomenon which has to be reflected in low-energy hadronic theories, see e.g. Refs. [1–3]. The order parameter of chiral symmetry breaking is the chiral condensate, denoted as $\langle \bar{q}q \rangle \sim \langle \sigma \rangle$, which contributes to hadronic masses and is responsible for the mass splitting of so-called chiral partners, i.e., hadrons with the same quantum numbers except for parity and G-parity.

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At sufficiently large temperature and density, it is expected that the spontaneously broken chiral symmetry is (at least partially) restored. Lattice-QCD calculations [4,5] show that, for values of the quark masses realized in nature, this so-called chiral transition is cross-over along the temperature axis of the QCD phase diagram. Along the density axis, lattice-QCD calculations are not yet available (for realistic quark masses), but phenomenological models [6,7] indicate that chiral symmetry restoration may occur through a first-order phase transition.

An interesting possibility is that the effective potential is minimized by an order parameter which varies as a function of spatial coordinate. Such inhomogeneous phases were already suggested in the pioneering works of Refs. [8–19]. In particular, the chiral condensate may assume the form of the so-called chiral density wave where not only the chiral condensate $\langle\sigma\rangle$ but also the expectation value of the neutral pion field is non-vanishing, $\langle\pi^3\rangle \neq 0$. However, the problem of the aforementioned approaches was that, without nucleon–nucleon tensor forces, inhomogeneous chiral condensation took place already in the nuclear matter ground state, in contradiction to experimental findings.

More recently, inhomogeneous phases were studied in the framework of the $(1+1)$-dimensional Gross–Niveau model [21,22], where it was indeed found that a spatially varying order parameter minimizes the effective potential at high density. In Refs. [23,24], the authors coined the phrase "quarkyonic matter" for an inhomogeneous phase at high density, where the chiral density-wave solution is realized within QCD in the large-N_c limit. Inhomogeneous phases were also investigated in Refs. [25–30] in the framework of the Nambu–Jona-Lasinio as well as the quark–meson model.

In this work, we re-investigate the question whether inhomogeneous condensation at nonzero density occurs in a model solely based on the degrees of freedom of the QCD vacuum, i.e., hadrons. We employ dilatation invariance and chiral symmetry of QCD, and include scalar, pseudoscalar, vector, and axial-vector mesons, as well as baryons and their chiral partners. This approach, developed in Refs. [31–33] and denoted as extended linear sigma model (eLSM), successfully describes hadron vacuum phenomenology both in the meson [31,32] and baryon [33] sectors. In the latter, the nucleon and its chiral partner are treated in the mirror assignment [34,35], in which a chirally invariant mass term exists [see also Refs. [36–40] and references therein].

The chiral condensate $\langle\sigma\rangle$ is the expectation value of the σ field which is the chiral partner of the pion $\vec{\pi}$. In the framework of the eLSM the resonance corresponding to the σ field is not the lightest scalar resonance $f_0(500)$ (as proposed in older versions of the σ model), but the heavier state $f_0(1370)$. This result is in agreement with a variety of studies of low-energy QCD, e.g. Refs. [41,42] and references therein. In Ref. [43], the $f_0(500)$ state is interpreted as a resonance in the pion–pion scattering continuum. Other works [44–46] favor an interpretation of $f_0(500)$ as a tetraquark state. This fact has an important consequence for studies at nonzero density; namely, when using a chiral linear sigma model, both resonances $f_0(500)$ and $f_0(1370)$ should be taken into account, the former being the lightest scalar state and the latter being an excitation of the chiral condensate. This was, for instance, done in Ref. [39] where, in the framework of the eLSM, the resonance $f_0(500)$ was coupled in a chirally invariant manner to nucleons and their chiral partners. An important result of this study was that the nuclear matter ground-state properties (i.e., density, binding energy, and compressibility) could be successfully described. In the mean-field approximation, and assuming homogeneous condensates, Ref. [39] reports the onset of a first-order phase transition at a density of about $2.5\rho_0$. The important role of both aforementioned scalar resonances has been also investigated at nonzero temperature in the framework of a simplified version of the eLSM in Ref. [47]. Interestingly, the necessity to include