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Review

Inhomogeneous chiral condensates☆

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ABSTRACT

The chiral condensate, which is constant in vacuum, may become spatially modulated at moderately high densities where in the traditional picture of the QCD phase diagram a first-order chiral phase transition occurs. We review the current status of this idea, which originally dates back to Migdal's pion condensation, but recently received new momentum through studies on the nature of the chiral critical point and by the conjecture of a quarkyonic-matter phase. We discuss how these nonuniform phases emerge in generalized Ginzburg–Landau analyses as well as in specific calculations, both within effective models and in Dyson–Schwinger or large-N_c approaches to QCD. Questions about the most favored shape of the modulations and its dimension, and about the effects of nonzero isospin chemical potential, strange quarks, color superconductivity, and external magnetic fields on these inhomogeneous phases will be addressed as well.

Contents

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1. Introduction

Quantum Chromodynamics (QCD) is nowadays the widely accepted fundamental theory of strong interactions. Unlike the other theories composing the standard model, QCD exhibits some peculiar nonperturbative features at low energies which render its theoretical treatment extremely challenging. The two most prominent features in this context are confinement, which binds quarks inside hadrons and makes it impossible to observe them as asymptotic isolated particles, and spontaneous chiral symmetry breaking, which leads to the generation of a chiral condensate $\langle\bar{\psi}\psi\rangle \neq 0$ through which particles acquire a dynamical mass. These features which characterize the QCD vacuum are naturally expected to be lost if the energy of the system increases, for example through the introduction of external factors like a finite temperature or density. As such, strong-interaction matter is expected to experience some sort of phase transition from a confined and chirally broken to a deconfined and symmetric phase as these external parameters increase beyond given thresholds.

Thanks to its weak-coupling behavior in the high-energy regime [1,2] the behavior of QCD for very high temperatures and chemical potentials is nowadays well understood: the high T phase is a weakly-coupled quark–gluon plasma [3], while cold and dense matter is expected to form a color-superconductor [4–6], for a review, see Ref. [7].

The intermediate region between vacuum and these asymptotic phases is however still the subject of an intense debate and no definite agreement has yet been found. In particular, while great progress has been made in the past few years in characterizing strong-interaction matter at finite temperature thanks to the development of ab-initio lattice calculations [8] and to increasingly accurate data from heavy-ion collision experiments (see, e.g., [9]), the nature of QCD at finite densities (or baryon chemical potentials) is still poorly understood (see [10,11] for reviews on recent theoretical developments). On the experimental side, most heavy-ion data focuses on the high-temperature regime [9], and only recently the attention has started shifting to the finite-density region, particularly with the new beam energy scan runs at RHIC in Brookhaven [12] and the upcoming facilities FAIR in Darmstadt [13] and NICA in Dubna [14]. From a theoretical point of view, since lattice simulations at finite chemical potentials are plagued by the sign problem [15], in order to investigate the intermediate-density region it is necessary to employ other approaches.

The most widely employed tools in this context are effective models which, by sharing some relevant symmetries with QCD, are expected to reproduce some of its characteristic properties. Among them we find most notably the Nambu–Jona-Lasinio and the quark–meson model (or linear sigma model with quarks), which are built by integrating out gluonic degrees of freedom and incorporating them in effective low-energy couplings. While being rather crude simplifications compared to full QCD, these models are able to describe the phenomenon of spontaneous chiral symmetry breaking as well as its