HADRON-QUARK PHASE TRANSITION AND THE QCD PHASE DIAGRAM

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Different extensions of the Nambu-Jona-Lasinio model, known to satisfy expected QCD chiral symmetry aspects, are used to investigate a possible hadron-quark phase transition at zero temperature and to build the corresponding binodal sections.

Keywords: NJL; QCD; Effective models; Binodals.

1. Introduction

Effective models remain a good source of information about regions of the QCD phase diagram inaccessible by terrestrial experiments or by LQCD methods [1], providing qualitative results and theoretical insights. The present work intends to help in advancing our knowledge towards some of the regions of the QCD phase diagram through this strategy. When this approach is applied to the study of the transition of hadronic matter to the deconfined quark matter, it is sugested that the QCD phase diagram shows a first order phase transition [2] at high chemical potentials and low temperatures, while from the LQCD perspective, the hadron-quark transition is believed to be a crossover at low chemical potentials and high temperatures. This seemingly contradictory picture can be reconciled by the existence of a critical end point in the phase transition curve, linking the LQCD crossover with the effective model first order transition. This idea is reinforced by experimental results [3] signaling to a first order phase transition and pointing out to the possible existence and location of the critical end point.

Considerations on the phase transition at zero temperature have already been done in many works [4–9], but we do believe the formalism we employ in the present work is more adequate, as the effective models employed here exhibit chiral symmetry in both hadronic and quark phases, which is demanded to take seriously the appearance of the quarkyonic phase [10]. The models used here are all included in the Nambu–Jona-Lasinio (NJL) model framework [11], in order to naturally describe the chiral characteristics of QCD matter.

In Refs. 6 and 9, the hadron-quark phase transition was investigated with the help of two different models, namely, the non-linear Walecka model (NLWM) for the hadronic phase and the MIT bag model for the quark phase. A formalism we understand as a more adequate one was used in Refs. 7, 12, 13 at zero temperature and in Ref. 8 for finite temperatures, all considering NJL-type models for the two phases. To describe the hadron phase, the standard NJL model with vector interaction is extended to include a scalar-vector channel in order to render the model capable of saturation at low densities. We revisit the approach of Refs. 7 and 8, but applying an extended NJL model for the hadron phase that includes additional channels to achieve a better description of important nuclear bulk properties [14]. A similar extension of the NJL model for hadronic matter has been developed [15,16] with a different choice of interaction channels. Recently, this version was also applied to investigate the hadron-quark phase transition [17], but the quark phase was still described by the MIT bag model. Hence, we describe the hadronic matter with the extended NJL model from Ref. 14 and the quark matter with the NJL model in its SU(2) version in order to check for which parameters a phase transition is possible, considering both symmetric and asymmetric systems. Whenever possible, the binodal sections are obtained.

2. Binodals

The QCD phase-diagram is characterised by potentially multiple phases, whose phase separation boundaries are referred as *binodals* [18]. Over those boundaries, the phases from the regions of either side of the boundary can coexist. The binodals may be determined using the Gibbs conditions [6]:

$$\mu_B^Q = \mu_B^H, \qquad T^Q = T^H, \qquad P^Q = P^H, \tag{1}$$

where the indexes H and Q refer to the hadronic and quark phases. The chemical potentials μ_B^i are obtained from the chemical potentials of the particles of each phase [6].

At a certain fixed temperature ($T = 0$ in the present context), the phase coexistence condition may be obtained by plotting $P^i \times \mu_B^i$, $i = Q, H$, and looking for the

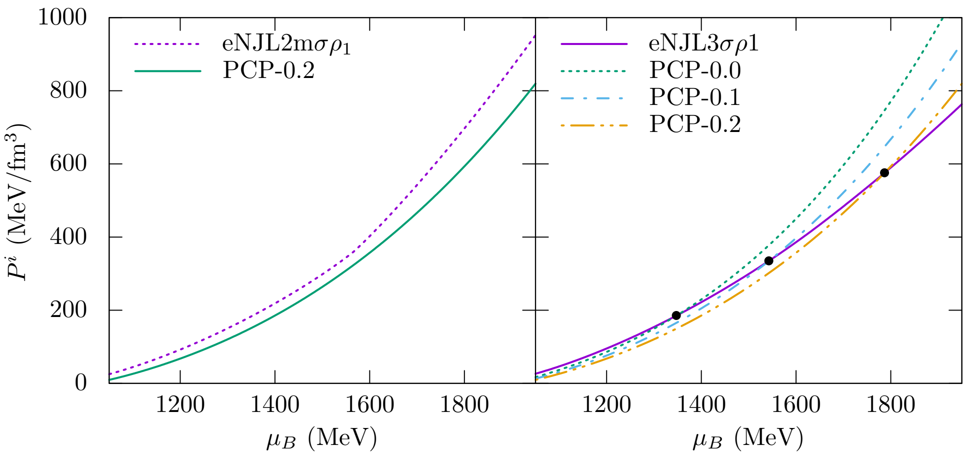

Fig. 1. Combinations of parameter sets for which hadron-quark phase transition is not allowed to happen (left), and combinations for which the transition is allowed to happen (right).

intersection of both curves. In Fig. 1 (left) we display a combination of parameterizations for which there are no intersections, implying that there are no transitions (i.e., the hadron phase is always more stable). In Fig. 1 (right), we compare the results for a hadron parameter set with three quark matter parameter sets, with varying strenght of the vector coupling, obtaining the transitions indicated by the dots.

The conditions of phase coexistence are also important in asymmetric matter and to obtain the binodal sections as a function of the system asymmetry, we use the prescription given in [4]. The isospin chemical potentials are defined as

$$\mu_3^H = \mu_p - \mu_n, \qquad \mu_3^Q = \mu_u - \mu_d, \tag{2}$$

and enforced to be identical according to the Gibbs conditions. The asymmetry parameters of the hadron and quark phases are respectively

$$\alpha^H = (\rho_n - \rho_p)/(\rho_n + \rho_p), \qquad \alpha^Q = 3(\rho_d - \rho_u)(\rho_d + \rho_u), \tag{3}$$

in such a way that $0 \leq \alpha^H \leq 1$ (just nucleons) and $0 \leq \alpha^Q \leq 3$ (just quarks).

The *binodals* are obtained through the determination of hadron and quarks phase pressures for each value of μ_B and μ_3 (the μ_3 parameter directly controls the proton fraction of both phases): whenever the pressure difference is below 0.1 MeV, we assume that both phases coexist. This procedure leads to the results shown in Fig. 2. The pressures shown for $\alpha = 0$ in the right panel correspond to the intersections marked in Figure 1. Also from this figure, we can clearly see that the increase in strength of the vector coupling causes a substantial modification on the transition point, which reflects in the values of the pressure in the binodal sections.

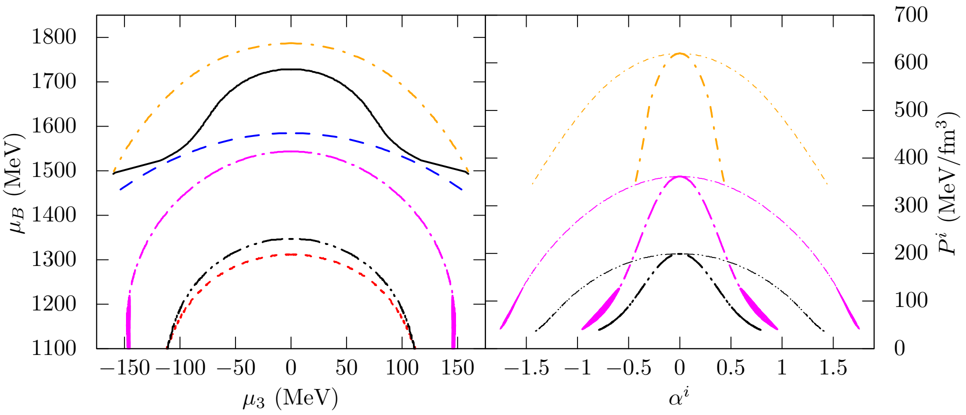

Fig. 2. Baryonic chemical potentials as a function of μ_3 (left) and pressure as a function of asymmetry (right) at the coexistence point for: BuballaR-2 and eNJL2m$\sigma\rho$1 (black line), BuballaR-2 and eNJL3$\sigma\rho$1 (blue long-dashed line), PCP-0.0 and eNJL2m$\sigma\rho$1 (red short-dashed line), PCP-0.0 and eNJL3$\sigma\rho$1 (black double-dot dashed line), PCP-0.1 and eNJL3$\sigma\rho$1 (magenta long-dash dotted line), and PCP-0.2 and eNJL3$\sigma\rho$1 (orange short-dash dotted line).

3. Conclusions

We have revisited the study of hadron-quark phase transition at zero temperature with different extensions of the NJL model, which are more appropriate to describe systems where chiral symmetry is an important ingredient. We analysed possible phase transitions from a hadron phase described by an extended NJL model to a quark phase described by the SU(2) NJL with the inclusion of a vector interaction of arbitrary strenght. We have first considered symmetric matter and checked that not all parameterization combinations produce a system in which a phase-transition is favored. Another manifestation of the dependence of the results on the choice of parameters is the range of barionic chemical potentials for which the transition takes place, spanning from around 1300 MeV to around 1800 MeV, indicating a strong parameter dependence. We have next analysed assymetric systems and whenever possible, binodal sections were obtained. Both pressures and chemical potential increase drastically with the increase of the vector interaction strenght in the quark sector. As a next step on this analysis, we plan to expand our results to include finite temperature in the system and obtain the complete binodal sections.

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