Chiral Mirror-Baryon-Meson Model and Nuclear Matter beyond Mean-Field

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Introduction

We consider a chiral baryon-meson model for nucleons (p/n) and their parity partners $N(1535)$ in mirror assignment interacting with pions, sigma and omega mesons to describe the liquid-gas transition of nuclear matter together with chiral symmetry restoration in the high density phase [1]. The model showed promising results in the mean-field approximation [2]. Here we go beyond the mean-field approximation and include mesonic fluctuations making use of the Functional Renormalization Group (FRG).

1 The Parity-Doublet Model

The parity-doublet (or mirror) model consists of two species of mirror-assigned baryons [3] (N_1, N_2) with opposite parity and chirally invariant mass term $\sim m_0$, which are coupled to the scalar/pseudo-scalar meson sector in an $SO(4)$-invariant way. The corresponding Euclidean Lagrangian (including baryon chemical potential μ_B and a vector coupling to the ω-meson) reads

$$\begin{aligned}\mathscr{L} =&\bar{N}_1\big(\not\partial - \mu_B\gamma_0 + h_1(\sigma + \mathrm{i}\gamma_5\vec{\tau}\vec{\pi}) + \mathrm{i}h_v\gamma^\mu\omega_\mu\big)N_1\\ &+\bar{N}_2\big(\not\partial - \mu_B\gamma_0 + h_2(\sigma - \mathrm{i}\gamma_5\vec{\tau}\vec{\pi}) + \mathrm{i}h_v\gamma^\mu\omega_\mu\big)N_2\\ &+m_0(\bar{N}_1\gamma_5 N_2 - \bar{N}_2\gamma_5 N_1) + \mathscr{L}_{\mathrm{mes}}.\end{aligned} \tag{1}$$

With $\vec{\phi} = (\sigma, \vec{\pi})$ the mesonic part is given by

$$\mathscr{L}_{\mathrm{mes}} = \frac{1}{2}\partial_\mu\vec{\phi}\,\partial^\mu\vec{\phi} + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + U(\phi^2, \omega^2) - c\sigma\,, \tag{2}$$

where $F^{\mu\nu} = \partial^\mu\omega^\nu - \partial^\nu\omega^\mu$. The mesonic potential at tree-level, i.e. in the microscopic bare action at the ultraviolet cutoff scale Λ is of the form

$$U(\phi^2, \omega^2) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + \lambda_6\phi^6 + \frac{m_\omega^2}{2}\omega^2, \tag{3}$$

with $\phi^2 = \sigma^2 + \vec{\pi}^2$ and parameters $\mu^2, \lambda, \lambda_6$. A non-vanishing pion mass is taken into account by an explicit linear breaking term $c\sigma$.

2 The Functional Renormalization Group

Beyond mean-field fluctuations are included by means of the Functional Renormalization Group with effective average action Γ_k whose k-dependence is described by Wetterich's flow equation

$$\partial_k\Gamma_k = \tfrac{1}{2}\,\mathrm{Tr}\left[\frac{1}{\Gamma_k^{(2)} + R_k}\partial_k R_k\right]. \tag{4}$$

The fermionic contributions to the flow of the effective potential are given by

$$\partial_k U_{k,F} = -\frac{N_f k^4}{6\pi^2}\sum_{\pm}\left[\frac{2(k^2 + m_0^2 - \epsilon_k^{\pm 2}) + (h_1^2 + h_2^2)\sigma^2}{(\epsilon_k^{\mp 2} - \epsilon_k^{\pm 2})\epsilon_k^{\pm}}\left(\tanh\left(\frac{\epsilon_k^{\pm} + \tilde{\mu}_B}{2T}\right) + \tanh\left(\frac{\epsilon_k^{\pm} - \tilde{\mu}_B}{2T}\right)\right)\right]. \tag{5}$$

The bosonic contribution to the flow of the effective potential is identical to the expression in quark-meson models and reads, for the $3d$-analogue of the LPA-optimized regulator,

$$\partial_k U_{k,B} = \frac{k^4}{12\pi^2}\left[\frac{1}{\epsilon_k^\sigma}\coth\left(\frac{\epsilon_k^\sigma}{2T}\right) + \frac{3}{\epsilon_k^\pi}\coth\left(\frac{\epsilon_k^\pi}{2T}\right)\right]. \tag{6}$$

The parameters in the UV potential V_M are adjusted to realize the physical pion mass $m_\pi =$ 138 MeV and $\bar{\sigma}_0 = f_\pi = 93$ MeV in the IR. For a given m_0 the masses $m_\pm$ are adjusted by the Yukawa couplings h_1 and h_2.

3 Results at $T = 0$

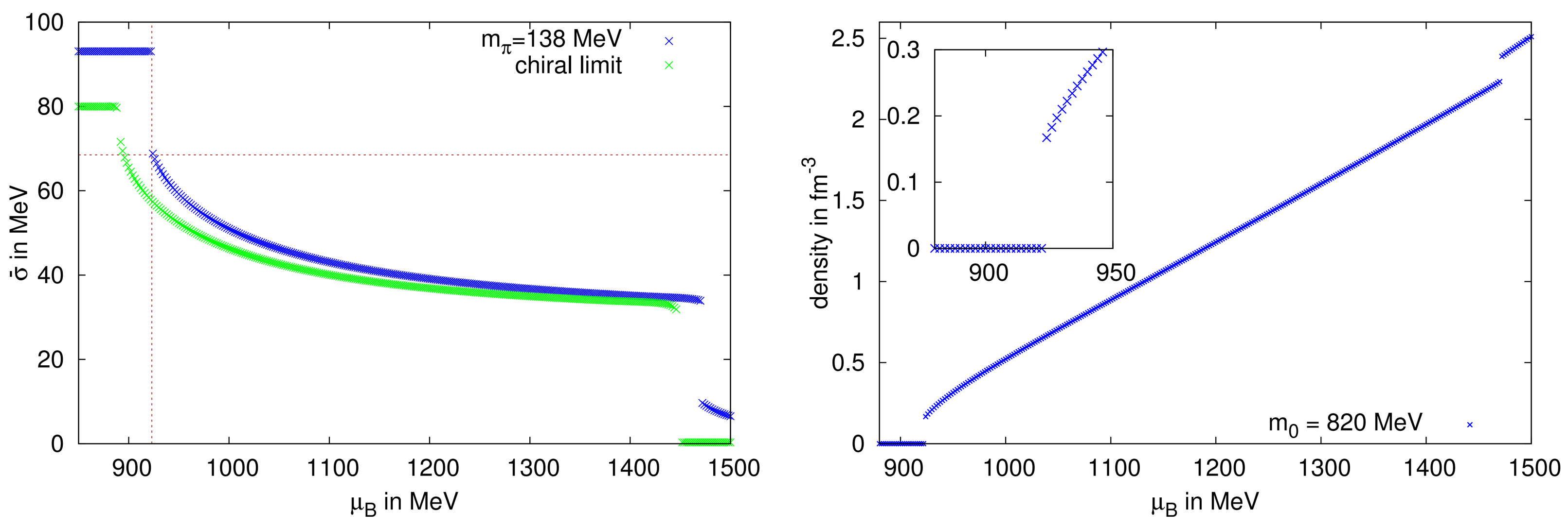
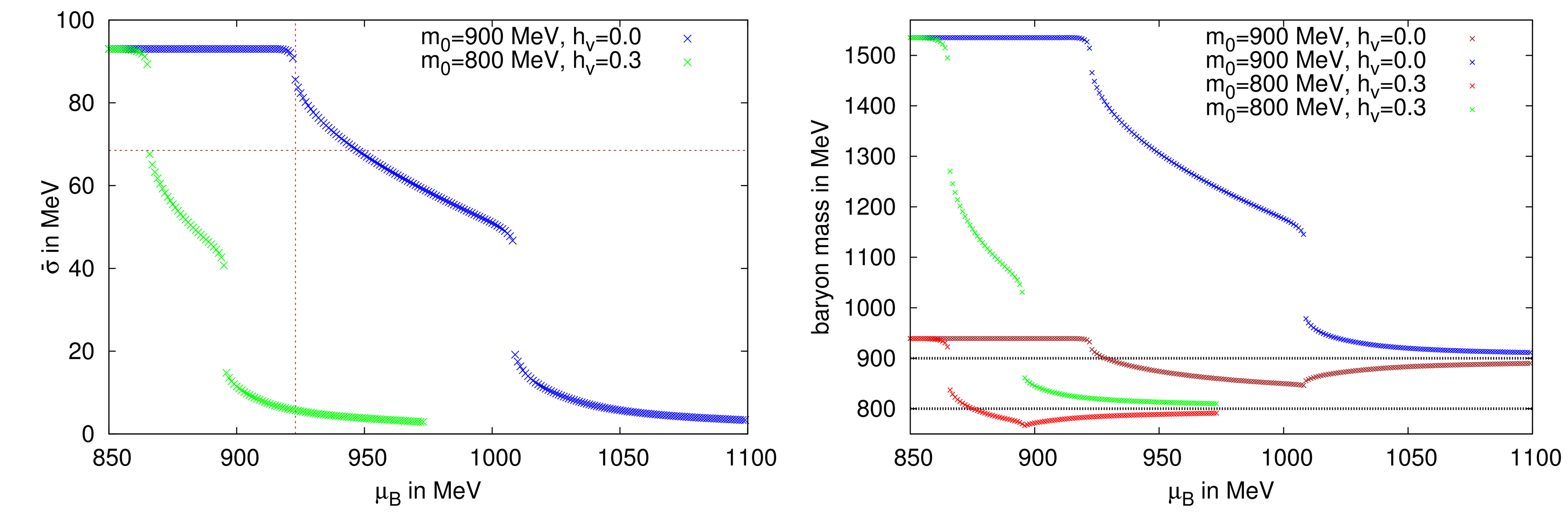


Figure 1: Chiral condensate (left) and baryon-density (right) for $m_0 = 820$ MeV in the extended mean-field (eMF) approximation (purely fermionic RG flow).



(a) **(b)**

Figure 2: Chiral condensate (left) and masses (right) of the nucleons and their parity partners at $m_0 = 800$ MeV and 900 MeV with physical pion masses for the full FRG flow.

Fig.(2b) shows how chiral symmetry restoration is realized in the parity-doublet model, rather than having vanishing baryon masses in the chiral limit, the parity partners' masses become degenerate with mass m_0.

4 Results at finite temperature

Since the flow equation for the effective potential is already formulated for finite temperatures it is in principle straightforward to obtain the phase diagram of the model in the (T, μ_B)-plane.

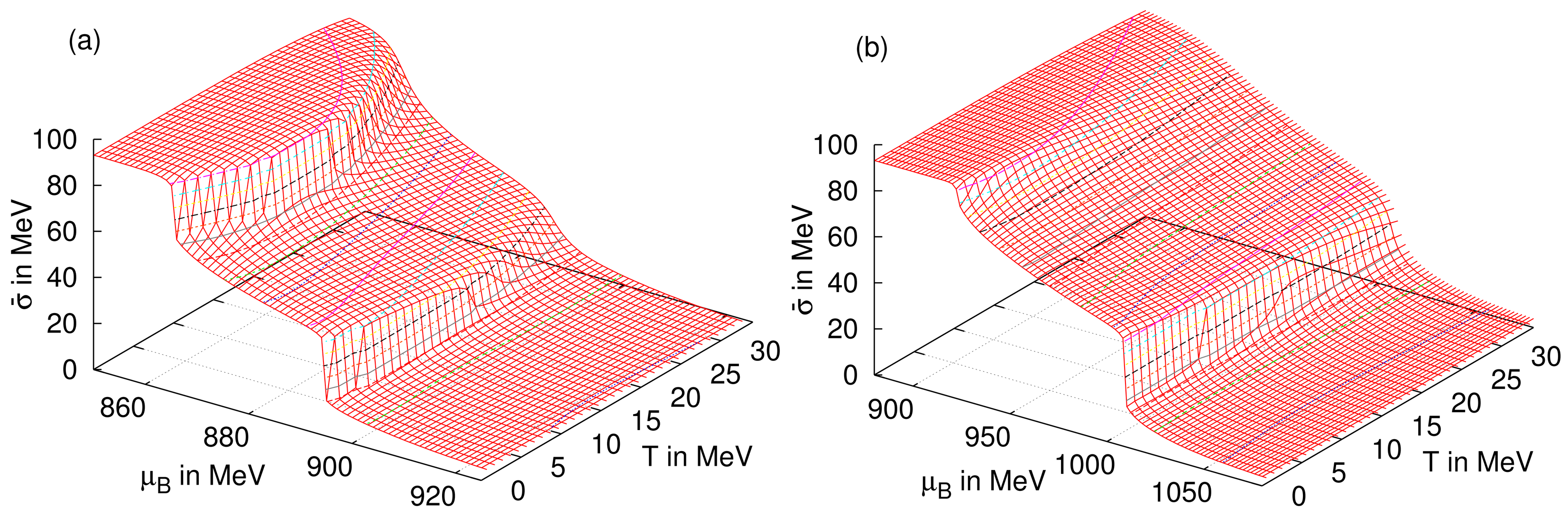


Figure 3: Chiral condensate over chemical potential μ_B and temperature T from the full FRG flow for $m_0 = 800$ MeV (left) and $m_0 = 900$ MeV (right).

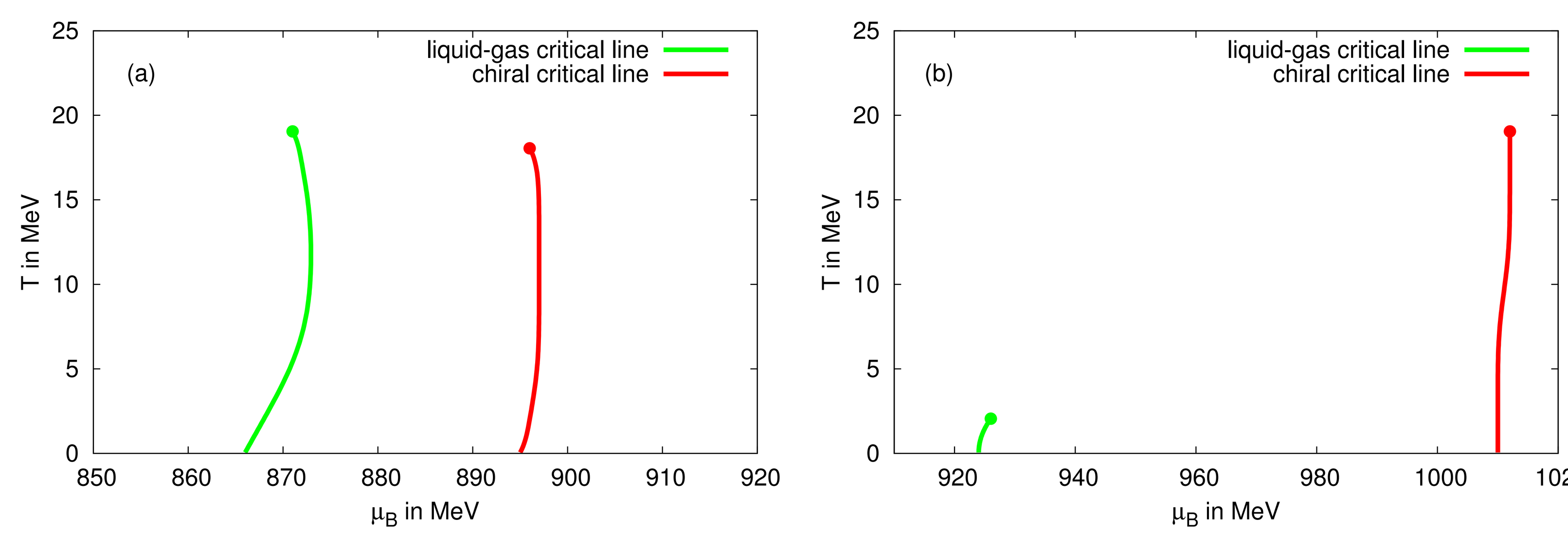


Figure 4: First-order lines with the corresponding critical endpoints in the (T, μ_B)-plane for the liquid-gas (green) and chiral (red) phase transitions for m_0 = 800 MeV (left) and $m_0 = 900$ MeV (right).

5 Conclusions and Outlook

The inclusion of a heavy parity partner in a chiral baryon-meson model such as the parity-doublet model within an FRG framework allows for a realization of quantitative properties of symmetric nuclear matter in the extended mean-field approximation without collective mesonic fluctuations (see Fig.(1)).

Including mesonic fluctuations does not change the qualitative behaviour but one is no longer free to adjust the parameters so as to reproduce the binding energy $E_b \simeq 16$ MeV , the nuclear saturation density $n_0 = 0.16$ fm^{-3} and the correct in medium condensate $\bar{\sigma}(n_0) \simeq 69$ MeV at the same time (see Fig.(2a)).

However, a simultaneous description of the liquid-gas transition of nuclear matter together with a chiral first order transition inside the high baryon-density phase stays robust.

Calculations at finite temperature (and chemical potential) provide the general features of the phase diagram of the model with the two first-order lines ending in two distinct critical endpoints.

References

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