Neutron star matter in a chiral quark theory†

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[MATTER AT HIGH DENSITY, Neutron matter]

Many ideas in the area of finite density phase transitions have been developed in the context of neutron star calculations, in particular the phase transitions from nuclear matter (NM) to quark matter (QM)1. In this work we calculate both the NM and QM phases in β-equilibrium using the flavor SU(2) flavor Nambu–Jona-Lasinio (NJL) model. Recently, the problem of NM saturation has been addressed with a method to simulate confinement in the description of the nucleon as a quark-diquark bound state2. In the QM phase, we allow for the possibility of scalar diquark condensation (color superconductivity)3, and the mixed phases are calculated using the method of Glendenning1.

The effective potential for NM is

\[ V^{NM} = V_{vac} + V_{N} - V_{o} - V_{p} - V_{e}, \]

where the vacuum term \( V_{vac} \) accounts for the polarization of the quark Dirac sea due to the valence nucleons2, \( V_{N} \) represents the Fermi motion of the nucleons which are described as quark-diquark bound states, \( V_{o} \) and \( V_{p} \) are contributions from the isoscalar and isovector mean vector fields respectively, and \( V_{e} \) is the electron contribution which is necessary for chemical equilibrium.

The effective potential for QM is

\[ V^{QM} = V_{vac} + V_{Q} - V_{e} + V_{\Delta}, \]

where the vacuum and electron terms are as above and the term for the Fermi motion of the quarks \( V_{Q} \) is analogous to \( V_{N} \), but referring to up and down quarks instead of protons and neutrons. Color superconducting quark matter (SQM) includes a contribution from the quark pairing arising at the Fermi surface. This is expressed by the term \( V_{\Delta} \), which involves the pairing gap \( \Delta \) and a coupling constant \( G_{s} \) for the pairing interaction in the scalar diquark channel.

In the calculations we set the constituent quark mass to zero, as it is known to decrease rapidly with density3. The strength of the pairing interaction is set to \( G_{s} = 0.25 G_{\pi} \), where the coupling constant in the pionic channel \( G_{\pi} \) is fixed by reproducing the pion mass. To construct the phase diagram we compare the NM and QM effective potentials for each baryon and isospin chemical potential \( \mu_{B} \) and \( \mu_{I} \), respectively.

Fig. 1 shows the phases in the plane of the chemical potentials. The charge neutral equation of state trace the lines between the positively and negatively charged regions. It begins in the NM region, proceeds along the boundary between negatively charged NM and positively charged SQM, and ends in the SQM phase. The boundary between the NM(−) phase and the SQM(+) phase, which is rather short in this case, corresponds to the NM/SQM mixed phase. The volume fractions of NM and SQM in the mixed phase are obtained by the requirement of charge neutrality. It is important to observe that the coupling constant \( G_{s} = 0.25 G_{\pi} \) is sufficiently strong to support a superconducting gap which is stable for isospin asymmetric matter. Fig. 2 shows the phases in the plane of the charge density \( \rho_{C} \) and the baryon density \( \rho_{B} \). We see that charge neutral matter will have a pure NM phase in the lower density region and a pure SQM phase at high densities. Between there is a mixed phase at intermediate densities.

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References