Two flavor color superconductivity and compact stars

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Baryonic matter at high density and low temperature is a color superconductor. In real world, this state of matter may naturally appear inside compact stars. A construction of a hybrid compact star with two flavor color superconducting quark matter in its interior is presented.

1 Introduction

At large baryon density, quantum chromodynamics (QCD) becomes a weakly interacting theory of quarks and gluons [1]. Because of an attractive interaction between quarks, the ground state of such quark matter is a color superconductor [2,3,4]. At asymptotic densities, quark matter was studied from first principles in Refs. [5,6,7,8]. Unfortunately, these studies are not very reliable quantitatively at realistic densities that exist in nature (i.e., at densities less than about 10ρ0 where ρ0 ≈ 0.15 fm−3 is the normal nuclear density).

In general, QCD at high baryon density has a very rich phase structure. There are many possible color superconducting phases of quark matter made of one, two and three lightest quark flavors. Each of them is characterised by a unique symmetry breaking pattern and by a specific number of bosonic as well as fermionic gapless modes.

In the rest of this paper, we are going to concentrate almost exclusively on matter with two quark flavors. The corresponding ground state of matter is the so-called two-flavor color superconductor (2SC). In this phase, the color gauge group SU(3)c is broken by the Anderson-Higgs mechanism down to SU(2)c subgroup. With the conventional choice of the condensate pointing in the “blue” direction, one finds that the condensate consists of red up (ur) and green down (dg) as well as green up (ub) and red down (dr) quark Cooper pairs. The other two quarks (u_b and d_b) do not participate in pairing. This is the conventional picture of the 2SC phase [3,4,5].

In passing, we mention that quark matter at high density may also contain strange quarks. This would be the case when the constituent medium modified mass of the strange quark is smaller than the value of the strange chemical potential. The current limited knowledge of QCD properties at finite density does not allow us to resolve the issue regarding the strangeness content in baryonic matter at densities existing inside compact stars unambiguously. As a benchmark test, here we study only non-strange quark matter.

We start our discussion by pointing that matter in the bulk of a compact star should be neutral with respect to electrical as well as color charges. Also, such matter should remain in β-equilibrium. Satisfying these requirements impose nontrivial relations between the chemical potentials of different quarks [9,10]. In turn, such relations influence the pairing dynamics between quarks, for instance, by suppressing conventional 2SC phase and favoring the so-called gapless 2SC (g2SC) phase [11].

The condition of charge neutrality should not necessarily be satisfied locally. It is acceptable, for example, if matter stays in a mixed phase that is neutral globally, or on average [12,13]. Below we use this idea to obtain a model equation of state of non-strange hybrid matter that is made in part of the 2SC phase [14].

2 Quark model

We use the simplest SU(2) Nambu-Jona-Lasinio model of Ref. [15] to describe quark matter,

\[ \mathcal{L} = \bar{q}(i\gamma^\mu \partial_\mu - m_0)q + GS [\bar{q}q]^2 + (\bar{q}i\gamma_5 \tau q)^2 + G_D [(\bar{q}C \varepsilon)^\alpha (\bar{q}C q)^\alpha] \, , \] (1)

where \( \bar{q}C = C q^T \) is the charge-conjugate spinor and \( C = i\gamma^2 \gamma^0 \) is the charge conjugation matrix. The quark field is a 4-component Dirac spinor that carries flavor \( (i = 1, 2) \) and color \( (\alpha = 1, 2, 3) \) indices. \( \tau = (\tau^1, \tau^2, \tau^3) \) are Pauli matrices in the flavor space, and \( (\varepsilon)^{ik} \equiv \varepsilon^{ik} \, , \, (\varepsilon^\dagger)^{\alpha\beta} \equiv \varepsilon^{\alpha\beta} \) are antisymmetric tensors in flavor and color, respectively. We introduce two independent coupling constants in the quark-antiquark and diquark channels, \( G_S \) and \( G_D \). Also we restrict ourselves only to the chiral limit \( (m_0 = 0) \).
The values of the parameters in the NJL model are the same as in Ref. [10]: \( G_S = 5.016 \text{ GeV}^{-2} \) and the cut-off \( \Lambda = 653 \text{ MeV} \). The strength of the diquark coupling \( G_D \) is taken to be proportional to the quark-antiquark coupling constant, i.e., \( G_D = \eta G_S \) with \( \eta = 0.75 \). The choice \( \eta = 0.75 \) corresponds to the regime of intermediate strength of the diquark coupling [11].

In \( \beta \)-equilibrium, the diagonal matrix of quark chemical potentials is given in terms of baryon (\( \mu_B \equiv 3\mu \)), electrical and color chemical potentials as follows:

\[
\mu_{ij,\alpha\beta} = (\delta_{ij} - \mu_e Q_{ij})\delta_{\alpha\beta} + \frac{2}{\sqrt{3}} \mu_S \delta_{ij} (T_8)_{\alpha\beta},
\]

where \( Q \) and \( T_8 \) are the generators of \( \text{U}(1)_{\text{em}} \) of electromagnetism and \( \text{U}(1)_8 \) subgroup of \( \text{SU}(3)_c \) group.

In the mean field approximation, the effective potential for zero temperature quark matter in \( \beta \)-equilibrium with electrons takes the form [11]

\[
\Omega = \Omega_0 - \frac{\mu_e^4}{12\pi^2} + \frac{m^2}{4G_S} + \frac{\Delta^2}{2G_D} - \sum_a \int \frac{d^3p}{(2\pi)^3}|E_a|,
\]

where \( \Omega_0 \) is a constant added to make the pressure of the vacuum vanishing. The sum in the last term runs over all (6 quark and 6 antiquark) quasiparticles. The dispersion relations and the degeneracy factors of the quasiparticles read

\[
E_{\pm ab}^\pm = E(p) \pm \mu_{ab}, \quad [\times 1] \quad (4)
\]
\[
E_{+ db}^\pm = E(p) \pm \mu_{db}, \quad [\times 1] \quad (5)
\]
\[
E_{\Delta z}^\pm = \sqrt{[E(p) \pm \mu]^2 + \Delta^2 \pm \delta \mu}. \quad [\times 2] \quad (6)
\]

Here we used the following shorthand notation:

\[
E(p) = \sqrt{p^2 + m^2},
\]
\[
\bar{\mu} = \frac{\mu_{ur} + \mu_{dg}}{2} = \frac{\mu_{ug} + \mu_{dr}}{2} = \mu - \frac{\mu_e}{6} + \frac{\mu_S}{3},
\]
\[
\delta \mu = \frac{\mu_{dg} - \mu_{ur}}{2} = \frac{\mu_{dr} - \mu_{ug}}{2} = \frac{\mu_e}{2}.
\]

The solution that satisfies the gap equation and both neutrality conditions was studied in detail in Ref. [11]. It was found that the corresponding phase of matter is the g2SC phase. This phase has the same symmetry of the ground state as the conventional 2SC phase. In the low-energy spectrum, however, it has two additional gapless fermionic quasiparticles.

Our analysis shows that the neutral g2SC phase is more favorable than the neutral normal phase of quark matter [11]. We find, in particular, that the pressure difference of these two phases is of order 1 MeV/fm³.

\section{3 Mixed phases}

In addition to homogeneous phases, one could also study various mixed phases of quark matter. The most promising components for constructing mixed phases are (i) normal phase, (ii) g2SC phase, and (iii) ordinary 2SC phase. Note that the first two of them allow locally neutral phases by themselves, while the last one tends to be positively charged. In principle, other phases could also be taken into consideration.

Inside mixed phases, the charge neutrality is satisfied “on average” rather than locally. This means that different components of a mixed phase may have non-zero densities of conserved charges, but the total charge of all components vanishes. In absence of local neutrality, the pressure of each phase could be considered as a function of baryon chemical potential, as well as a function of chemical potentials related to other conserved charges (e.g., \( \mu_e \) and \( \mu_S \) in the model at hand). This information is used as an input to obtain the most favorable mixed phase construction (see below).

While we intend to relax the local neutrality condition with respect to the electrical charge, in this paper we always enforce the condition of local color neutrality. Here we cannot fully justify this constrain. However, one could speculate that separation of color charges is less likely in mixed phases.

Without going into much detail, let us give a brief introduction into the general method of constructing mixed phases by imposing the Gibbs conditions of equilibrium [12] which are the conditions of mechanical and chemical equilibrium between different components. In regard to a mixed phase of the normal and 2SC components of quark matter, for example, these conditions read

\[
P^{(NQ)}(\mu, \mu_e) = P^{(2SC)}(\mu, \mu_e),
\]
\[
\mu = \mu^{(NQ)} = \mu^{(2SC)},
\]
\[
\mu_e = \mu_e^{(NQ)} = \mu_e^{(2SC)}.
\]

These conditions are easy to visualize by plotting the pressure as a function of chemical potentials (\( \mu \) and |open-quote|}
for the hadronic phase (at the bottom), for the 2SC phase (on the right in front) and the normal phase of quark matter (on the left). The dark solid line follows the neutrality line in hadronic matter, and two mixed phases: (i) a mixture of the hadronic and normal quark phases; and (ii) a mixture of the normal and 2SC quark phases.

\[ \mu_e \equiv \frac{\mu_B}{3} \] for each component, see Fig. 1. As is clear, the Gibbs conditions are satisfied automatically along the intersection lines of different pressure surfaces.

In a mixed phase, different components occupy different volumes of space. To describe this quantitatively, we introduce the volume fraction of the normal phase of quark matter: \( \chi_{2SC}^{NQ} \equiv V_{NQ}/V \) (notation \( \chi_A^B \) means “volume fraction of phase A in a mixture with phase B”). Then, the volume fraction of the 2SC phase is given by \( \chi_{2SC}^{2SC} = 1 - \chi_{2SC}^{NQ} \). From the definition, it is clear that \( 0 \leq \chi_{2SC}^{NQ} \leq 1 \).

The average electric charge density of the mixed phase is determined by the charge densities of its components taken in the proportion of the corresponding volume fractions. Thus,

\[ n_e^{(MP)} = \chi_{2SC}^{NQ} n_e^{(NQ)} + (1 - \chi_{2SC}^{NQ}) n_e^{(2SC)}. \] (14)

If the charge densities of the two components have opposite signs, the global charge neutrality condition, \( n_e^{(MP)} = 0 \), can be imposed. Otherwise, a neutral mixed phase could not exist. In the case of quark matter, the charge density of the normal quark phase is negative, while the charge density of the 2SC phase is positive along the line of the Gibbs construction (dark solid line in Fig. 1). So, a neutral mixed phase exists, and the volume fractions of its components are

\[ \chi_{2SC}^{NQ} = \frac{n_e^{(2SC)}}{n_e^{(2SC)} - n_e^{(NQ)}}, \] (15)
\[ \chi_{2SC}^{2SC} = 1 - \frac{n_e^{(NQ)}}{n_e^{(NQ)} - n_e^{(2SC)}}. \] (16)

By making use of these expressions, we can calculate the energy density of the corresponding mixed phase,

\[ \varepsilon^{(MP)} = \chi_{2SC}^{NQ} \varepsilon^{(NQ)} + (1 - \chi_{2SC}^{NQ}) \varepsilon^{(2SC)}. \] (17)

This is essentially all that we need in order to construct the equation of state of the mixed phase.

So far, we neglected the effects of the Coulomb forces and the surface tension between different components of the mixed phase. In a real system, however, these are important. In particular, the balance between the Coulomb forces and the surface tension determines the size and geometry of different components of the mixed phase. In our case, nearly equal volume fractions of the two quark phases are likely to form alternating layers (slabs) \([17]\). The thickness \( a \) of the layers scales as \( \sigma^{1/3} (n_e^{(2SC)} - n_e^{(NQ)})^{-2/3} \), where \( \sigma \) is the surface tension. In the model at hand \( a \approx 10 \text{ fm} \).

The energy cost per unit volume to produce the layers scales as \( \sigma^{2/3} (n_e^{(2SC)} - n_e^{(NQ)})^{2/3} \) \([17]\). Therefore, the mixed phase is favorable only if the surface tension is not too large. Our estimates show that \( \sigma_{\text{max}} \lesssim 20 \text{ MeV/fm}^2 \). For slightly larger values, \( 20 \lesssim \sigma \lesssim 50 \text{ MeV/fm}^2 \), the mixed phase is also possible, but its first appearance occurs at higher densities, \( \rho_B \lesssim \rho_B \lesssim 5 \rho_0 \). Note that the value of the maximum surface tension is of the same order as in Refs. \([17, 18]\). In this study we assume that actual value of the surface tension is not very large.

The validity of the quark model is limited when the baryon density decreases. In fact, at sufficiently low densities, quarks are confined inside hadrons, and it is more natural to use a hadronic model. Here we use the chiral SU(3)_L x SU(3)_R model of Ref. \([19]\). It is expected that the hadronic and quark phases are separated by a first order phase transition. Then, the hadronic and quark phases can co-exist in a mixed phase \([12]\) that is constructed by satisfying the Gibbs conditions similar to those discussed earlier. Thus, we plot the hadronic surface of the pressure along with the quark surfaces in Fig. 1. Again, the intersection lines of different surfaces indicate all potentially viable mixed phases. Although the Gibbs conditions are satisfied along all such lines, not all of them can produce neutral phases (e.g., there are no neutral constructions along the lightly shaded solid lines in Fig. 1).
The dark solid line in Fig. 1 gives the full construction that consists of three pieces. The lowest part of the curve (up to the point denoted by □) corresponds to the neutral hadronic phase. Within this region matter is composed mostly of neutrons and a small fraction of protons and electrons.

The mixed phase of hadronic and normal quark matter starts at the baryon density \( \rho_B \approx 1.49 \rho_0 \) (□-point in Fig. 1). At this point the first bubbles of deconfined quark matter appear in the system. At the beginning of this hadron-quark mixed phase, the deconfined bubbles are small but highly negatively charged, whereas the hadronic phase, in which the bubbles are embedded, is slightly positively charged. The charge neutrality condition reads

\[
n_c^{(MP)} = \lambda_H^{NQ} n_e^{(NQ)} + (1 - \lambda_H^{NQ}) n_c^{(H)} = 0. \tag{18}
\]

where \( n_c^{(H)} \) and \( n_e^{(NQ)} \) are the charge densities of hadronic and normal quark phases, respectively. This condition is satisfied at each point along the middle part of the dark solid line (i.e., between □- and △-points). With increasing density (up to \( 2.56 \rho_0 \)), the volume fraction of the hadronic phase decreases (down to 0.59). However, one does not reach a point where the fraction of hadronic phase would vanish completely. Instead, at baryon density about \( 2.56 \rho_0 \) (△-point in Fig. 1), the mixed phase is replaced by another mixed phase which is made of the normal and 2SC quark components. At this point, the positively charged hadronic component will be suddenly converted into a positively charged 2SC quark component. As a result of this rearrangement, the values of the baryon density and the energy density experience small jumps: the baryon density changes from about \( 2.56 \rho_0 \) to \( 2.75 \rho_0 \) and the energy density changes from 378 MeV/fm\(^3\) to 415 MeV/fm\(^3\). After the transition, the fractions of the 2SC and normal quark phases are 0.53 and 0.47, respectively.

At higher densities, the mixture of the normal and 2SC quark phases is the most favorable globally neutral construction in the model at hand. The volume fractions of the components in this mixed phase stay nearly constant with increasing density.

The complete equation of state of hybrid baryon matter is shown in Fig. 2 by solid line. For comparison, the equation of state for globally neutral quark matter is also shown. As before, the points that indicate the beginning of two different mixed phases of hybrid matter are denoted by □ and △ symbols.

4 Star properties

Here we use the equation of state of hybrid matter that is shown in Fig. 2 to construct non-rotating compact stars. This is done by solving the well known Tolman-Oppenheimer-Volkoff (TOV) equations.

The energy density profiles for hybrid stars with different central energy densities are displayed in Fig. 3. The star with the lowest central energy density in Fig. 3, \( \epsilon_c = 210 \text{ MeV/fm}^3 \), is composed of pure confined hadronic matter, mainly neutrons, surrounded by a thin compact star crust consisting of leptons and nuclei. To get the equation of state for the crust, we use the results of Ref. [20] for \( \rho_B < 0.001 \text{ fm}^{-3} \) and the results of Ref. [21] for \( 0.001 < \rho_B < 0.08 \text{ fm}^{-3} \).

The next energy density profile in Fig. 3 corresponds to the central energy density \( \epsilon_c = 370 \text{ MeV/fm}^3 \). We see that the corresponding star already has a rather large core (the radius is about 8 km) consisting of a mixture of hadronic and normal quark matter. The core of the star is surrounded by a layer of hadronic matter and a crust.

In the model at hand, there are no stars with central energy densities in the window between 378 MeV/fm\(^3\) and 415 MeV/fm\(^3\). At \( \epsilon_c > 415 \text{ MeV/fm}^3 \), a quark core (made of the mixed phase of the normal and 2SC components) forms at the center of the star. Two examples of the corresponding energy density profiles are also shown in Fig. 3. The star with the central energy density \( \epsilon_c = 500 \text{ MeV/fm}^3 \) contains a quark phase core with radius about 6 km. This core is separated from the layer of the hadron-quark mixed phase by
Figure 3. Energy density profiles for hybrid stars. The locations of the interface between the two types of mixed phases are denoted by $\triangle$, while the locations of the boundary between the pure hadronic phase and the hadron-quark mixed phase are denoted by $\Box$.

A sharp interface (the corresponding point is denoted by $\triangle$ in Fig. 3). The star with the largest possible mass within this model has the central energy density $\epsilon_c = 1392 \text{ MeV}/\text{fm}^3$. This star is composed mainly of the quark core surrounded by a relatively thin layer of the hadron-quark mixed phase, as well as the pure hadronic phase and the crust on the outside.

The results for the mass-radius relation of hybrid and quark stars are shown in Fig. 4. As one would expect, the pure quark stars have much smaller radii and the value of their maximum mass is slightly smaller. The difference between hybrid and pure quark stars is mostly due to the low density part of the equation of state. This is also evident from the qualitative difference in the dependence of the radius as a function of mass for the hybrid and quark stars with low masses. The corresponding hybrid stars are large because of a sizable low density hadronic layer, while the quark stars are small because they have no such layers.

Our results for pure quark stars are comparable to those in Refs. [22, 23, 24, 25]. Also, the maximum masses and the corresponding radii of the hybrid stars obtained here are similar to those of the strange hybrid stars of Ref. [24], provided the strange quark mass is not very small ($m_s \gtrsim 300 \text{ MeV}$) and the superconducting gap is not too large ($\Delta \lesssim 50 \text{ MeV}$). At small values of the strange quark mass and/or large values of the superconducting gap, the strange hybrid stars tend to have smaller maximum masses and smaller radii [23].

5 Summary and outlook

Here we constructed a realistic equation of state of non-strange baryonic matter that is globally neutral and satisfies the condition of $\beta$-equilibrium. This equation of state might be valid up to densities of about $8\rho_0$ in the most optimistic scenario. In our construction, matter at low density ($\rho_B \lesssim 1.49\rho_0$) is mostly made of neutrons with traces of protons and electrons. At intermediate densities ($1.49\rho_0 \lesssim \rho_B \lesssim 2.56\rho_0$), homogeneous hadronic matter is replaced by the mixed phase of positively charged hadronic matter and deconfined bubbles of negatively charged normal quark matter. The volume fraction of normal quark matter gradually grows with increasing density. Before the volume fractions of two phases become equal, the mixed phase undergoes a rearrangement in which the hadronic component of matter turns into the two-flavor color superconductor. At higher densities ($\rho_B \gtrsim 2.75\rho_0$), only the quark mixed phase exists. This latter is composed of about equal fractions of normal and 2SC quark matter.

Previously, it was argued that 2SC quark matter could not appear in compact stars when the charge neutrality condition is imposed locally [9]. The main reason for this is the strong preference of the 2SC phase to remain positively charged. Our study shows, how-
ever, that the positively charged 2SC quark component appears naturally in a quark mixed phase at densities around $3\rho_0$. The other component of the globally neutral mixed phase is negatively charged normal quark matter. The corresponding construction turns out to be rather stable. In particular, we observe that the volume fractions of the two quark components remain approximately the same with changing baryon density in a wide range.

By making use of the equation of state of hybrid matter, we construct non-rotating compact stars. We find that the radius is 10.86 km, the mass $1.81M_\odot$ and the central baryon density $7.58\rho_0$. This star has a large (8 km) quark core, and a relatively thin outer layers of hadronic matter and a crust. One could speculate that the appearance of a large core is connected with the fact that the quark phase starts to develop at relatively low densities, $\rho_B \approx 2.75\rho_0$, in the model used.

In the end, we would like to mention that performing a systematic study of the model dependence of hybrid matter constructions with various color superconducting phases would be an important task for future. Such a study will be crucial for resolving some apparent differences between the results currently existing in the literature regarding non-strange as well as strange quark matter [14, 22, 23, 24, 25].

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