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Deconfinement phase transition in neutron star matter

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Abstract The transition from hadron phase to strange quark phase in dense matter is investigated. Instead of using the conventional bag model in quark sect, we achieve the confinement by a density-dependent quark mass derived from in-medium chiral condensates, with a thermodynamic problem improved. In nuclear slot, we adopt the equation of state from Brueckner-Bethe-Goldstone approach with three-body force. It is found that the mixed phase can occur, for reasonable confinement parameter, near the normal saturation density, and transit to pure quark matter at 4—5 times the saturation, which is quite different from the previous results from other quark models that pure quark phase can not appear at neutron-star densities.

Key words phase transition, the density-dependent quark model, three-body force

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1 Introduction

The lack of strong observational constraints demands for sophisticated models for the phases of dense stellar matter and for interaction mechanisms. Several recent studies[1—6] on the possible hadron-quark phase transition suggest that the neutron star (NS) can contain a core constituted by a mixed phase, but it is not dense enough to possess a pure quark core. The authors use either MIT bag model[1—3] or the Nambu-Jona-Lasinio (NJL)[4—6] model to describe the quark phase, including also the possibly more realistic color-flavor locked (CFL) phase in Ref. [3].

Presently, however, the CFL phases suffers from the so-called chromomagnetic instability problem for both the two- and three-flavor cases. On the other hand, experiments show that quarks become asymptotically free rather slowly[7]. Therefore, here we are dealing with the ordinary strange quark matter (SQM).

Since when studying the ordinary quark matter one must treat quark confinement in a proper way, we address particularly in the following this point. The conventional standard approach is to add an extra constant term, the famous bag constant B, to the energy density of the system, which provides a negative pressure to confine quarks within a finite volume, usually called a bag. The quark mass is infinitely large outside the bag, and a finite constant within the bag. As is well known, however, particle masses vary with environment[8]. Taking advantage of the density dependence, one can describe quark confinement without using the bag constant. Instead, the quark confinement is achieved by the density dependence of the quark masses derived from in-medium chiral condensates[9].

In the present contribution, the transition from hadron phase to strange quark phase in the dense stellar matter is investigated with the fully consistent density-dependent mass model (CDDM)[9, 10]. In the hadron sector we adopt the equation of state from Brueckner-Bethe-Goldstone approach with three-body forces[11]. This theory, being a completely microscopic approach, can easily incorporate degrees of freedom such as nucleon resonances [Δ(1232) or N∗(1440)], which are expected to appear at higher hadron densities. It is found that the mixed hadron-

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quark phase can occur, for reasonable values of the confinement parameter[9, 10], around the normal saturation density, and can undergo the transition to pure quark matter at 4 ∼ 5 times the saturation, which is quite different from the previous results based on MIT model and also NJL model[1—6].

2 Phase diagram structure

Let us study the nuclear matter, consisting of nucleons and electrons, in equilibrium with a gas of u, d, s quarks and electrons. According to Glendenning[12], we assume the total charge conservation, in addition to total baryon and energy conservation.

The conservation laws can be imposed by introducing the quark fraction χ defined as

$$\chi \equiv V_{\rm q}/V \ , \tag{1}$$

where V is the total volume, $V_{\rm q}$ is the volume occupied by quarks. Then the total baryon density is

$$\rho_{\rm t} = (1-\chi)\rho_{\rm N} + \chi\rho_{\rm q} \ , \tag{2}$$

the total electric charge is

$$Q_{\rm t} = (1-\chi)Q_{\rm N} + \chi Q_{\rm q} \ , \tag{3}$$

and the total energy density is

$$E_{\rm t} = (1-\chi)E_{\rm N} + \chi E_{\rm q} \ , \tag{4}$$

where ρ, $Q_{\rm N}$, and $E_{\rm N}$ are, respectively, the baryon number density, electric charge density, and energy density of nuclear matter, while n, $Q_{\rm q}$, and $E_{\rm q}$ are the corresponding quantities of quark matter.

The β equilibrium conditions are given by

$$\begin{array}{rclcrcl} \mu_{\rm n} &=& \mu_{\rm u}+2\mu_{\rm d}, & & \mu_{\rm u} &=& (2\mu_{\rm p}-\mu_{\rm n})/3, \\ & & & \text{or} & & & \\ \mu_{\rm p} &=& 2\mu_{\rm u}+\mu_{\rm d}. & & \mu_{\rm d} &=& (2\mu_{\rm n}-\mu_{\rm p})/3. \end{array} \tag{5}$$

In general, all other chemical potentials in quark sect can be linked to $\mu_{\rm u}$ and $\mu_{\rm d}$, e.g., $\mu_{\rm s} = \mu_{\rm d}$, $\mu_{\rm e} = \mu_{\rm d} - \mu_{\rm u}$. Similarly, all chemical in nuclear slot can be linked to $\mu_{\rm n}$ and $\mu_{\rm p}$, e.g., $\mu_{\rm e} = \mu_{\rm n} - \mu_{\rm p}$. Therefore, Eq. (5) means that we can choose either ($\mu_{\rm u}$, $\mu_{\rm d}$) or ($\mu_{\rm n}$,$\mu_{\rm p}$) as the two independent chemical potentials. The latter can then be determined by solving the charge neutrality equation and the pressure balance equation for a given total baron number or a given quark fraction[10]. The quark current masses $m_{\rm u0} = m_{\rm d0} = 0$, $m_{\rm s0} = 95$ MeV are taken in this calculation.

In Fig. 1, we display, for the parameter $D = (180 \text{ MeV})^2$ (D is the confinement parameter related to thermodynamic stability[9]), the density dependence of the energy per baryon and pressure in nuclear, mixed, and quark phase. It is seen that the nuclear matter is the most favorite phase at lower densities, and the quark matter is the most stable phase at higher densities, while at modest densities, the mixed phase has the lowest energy. The quark fraction, the nuclear density $\rho_{\rm N}$ and the quark density $\rho_{\rm q}$ are also shown on the right axis. We see that the quark density is always higher than the nuclear density. The transition from hadron phase to mixed phase occurs at the density about 1.6 times the saturation. The transition from mixed phase to pure quark phase occurs at the total density $\rho_{\rm t} = 1.1 \text{ fm}^{-3}$, where the nuclear density is only $\rho_{\rm N} = 0.73 \text{ fm}^{-3}$. The density range of mixed phase is very slightly depending on the temperature[10], at least in temperature range of interest in neutron stars.

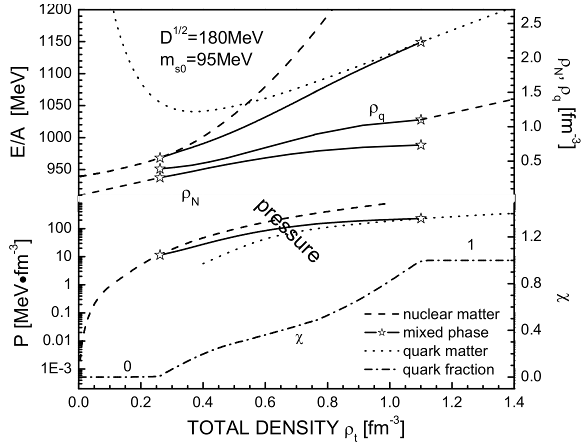

Fig. 1. The energy per baryon and pressure in nuclear (dashed curve), mixed (solid), and quark phase (dotted) vs. density. The quark fraction (dash-dotted lines), the nuclear density $\rho_{\rm N}$ and the quark density $\rho_{\rm q}$ are also shown on the right axis.

Naturally, the critical densities depend on the parameter D. In Fig. 2, both the nuclear critical density (the solid line, separating the pure nuclear phase and the mixed phase) and the quark critical density (the dashed line, bounding the pure quark phase) are displayed as a function of $D^{1/2}$. If $D^{1/2} < 161.6$ MeV, the two critical densities approach zero, and accordingly SQM is absolutely stable. When $161.6 \text{ MeV} < D^{1/2} < 162.5$ MeV, mixed phase can exist at any lower densities. Only when $D^{1/2} > 162.5$ MeV, nuclear matter is more stable at lower densities.

If we have only two flavor quarks in the quark sect, the critical densities are usually higher. In Fig. 2, we also plot the lower critical density for the two-flavor case. Because we know in our real world the two-flavor quark matter does not exist bellow the saturation density (the dash-dotted line), $D^{1/2}$ should be on the right of the first full dot at $D^{1/2} \approx 168$ MeV (the intersection of the dotted and solid lines) in Fig. 2. On the other hand, to let SQM have a chance to appear bellow the saturation density, $D^{1/2}$ should be on the left of the second full dot where $D^{1/2} = 174$ MeV. However, at that point nuclear matter is so strongly neutron rich that it hard to imagine that it can be observed in terrestrial laboratory experiments. In addition, with the decrease of D, the nuclear critical density may be lowered until below the the nuclear saturation density (when $D^{1/2} < 171.3$ MeV); Similarly, the quark critical density, may drop down to 4—5 times the saturation. Therefore there is a good chance for NS to have a pure quark core[10].

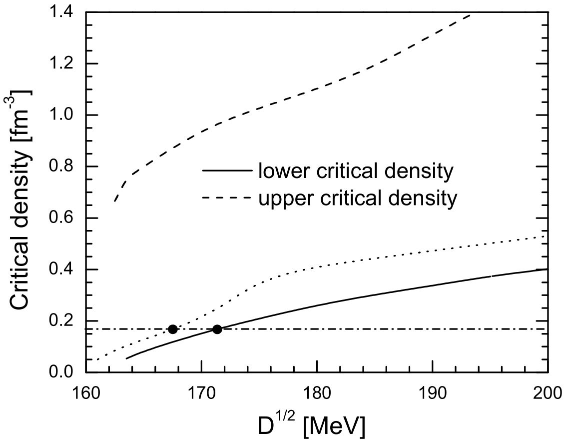

Fig. 2. The critical density of nuclear matter to quark matter as a function of the confinement parameter D. The horizontal line is the nuclear saturation density. The dotted line is the quark critical density in the case of two-flavor quark system.

3 Discussion and conclusions

In this article the possible phase transition to quark phase in NS matter was studied. We included only baryons and quarks in equilibrium with leptons. N$\overline{\text{N}}$ and nucleonic excitations are expected to play a major role. Their effects can be incorporated in a three-body force. The baryon equation of state in weak coupling equilibrium with electrons was derived within the BBG theory suitably extended so to include the three-body force. In the quark sector, we adopted the semiphenomenological CDDM quark model, which exhibits a confinement mechanism alternative to the crude MIT bag model. Furthermore, in contrast with the extension of the MIT model, where the density dependence is introduced artificially[13].

The transition from the low density hadron phase to high density quark phase in beta equilibrium was studied in the Glendenning hypothesis of total charge neutrality. The Gibbs construction enabled to follow the evolution of the mixed hadron-to-quark phase, varying the confinement parameter D. The transition density from hadron to mixed phase is strongly dependent on the confinement parameter and, for D small enough, it becomes lower than the nuclear saturation density. More important, the NS matter may transit to pure quark matter very comfortably at a minimum density of about 4 times the saturation. However, The model developed in this paper misses some important aspects, such as hyperons and their competition with other mechanisms, for example kaon condensation. These aspects may be quite important and deserves additional investigation, as soon as more reliable empirical inputs will be available, especially on the hyperon-nucleon and hyperon-hyperon interaction.

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