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Quark-hadron mixed phase with hyperons in protoneutron stars

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The quark-hadron mixed phase ("pasta" phase) with hyperons and neutrinos is studied at finite temperature. We take into account the finite-size effects to the mixed phase, imposing the Gibbs conditions. As a result, we find that the mixed phase becomes unstable at finite temperature. The presence of neutrinos makes the pasta structures more unstable. These results suggest that the quark-hadron mixed phase will appear during the evolution of protoneutron stars after supernova explosions.

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1. Introduction

Recently, quark matter has attracted much interest as a new form of matter in compact stars. However, there are left many uncertainties about the quark-hadron phase transition, e.g. the equation of state (EOS) of quark matter or deconfinement mechanism. In particular, it is one of the hot topics whether the phase transition is the first order or not at high-density region. If we assume the transition to be of the first order, the phase equilibrium in the mixed phase must be carefully treated by applying the Gibbs conditions in the multi-component system, instead of the usual Maxwell construction [1]. In this case, the non-uniform structures, so-called “pasta structures", automatically appear due to the balance of the Coulomb interaction and surface tension. The charge screening by the many-body effect is also important for their mechanical instability. All these effects are generally known as “*the finite-size effects*".

Here we study the quark-hadron mixed phase with the finite-size effects at finite temperature by extending the previous works [2, 3, 4] to include the neutrino-trapping effect.

2. Equation of state for each phase

The theoretical framework for the hadronic phase is the Brueckner-Hartree-Fock approach including hyperons such as Σ^- and Λ [5]. There is a controversy about the Σ^--N interaction. The recent experimental results about hypernuclei have suggested that it is repulsive [6, 7], while we use here a weak but attractive interaction. It would be interesting to see how our results change by using different Σ^--N interaction, and we will discuss it in the future work. Moreover, we adopt the frozen-correlation approximation at finite temperature [4, 8]. This approximation is feasible at low temperature ($T < 50$ MeV).

For the quark phase, we adopt the MIT bag model or the density dependent bag model consisting of u, d, s quarks for simplicity [9]. We will adopt more sophisticated models [10, 11] in the future study. Here, we assume massless u and d quarks and massive s quarks with the current mass of $m_s = 150$ MeV. We set the bag constant B to be 100 MeV fm^{-3} in the MIT bag model. In the density dependent bag model, we assume the vacuum energy $B(n_B)$ as

$$B(n_B) = B_\infty + (B_0 - B_\infty)\exp[-\beta\frac{n_B}{n_0}] \tag{2.1}$$

with $B_\infty = 50$ MeV fm^{-3}, $B_0 = 400$ MeV fm^{-3}, and $\beta = 0.17$. For more extensive discussion of this topic, the reader is referred to Nicotra et al. [9] and references cited therein.

For the mixed phase, we assume some non-uniform geometrical structures (“pastas"); droplet, rod, slab, tube, and bubble. We introduce the Wigner-Seitz cell to treat such non-uniform structure using the local-density approximation for particles. Between the hadron and quark phases we put a sharp boundary with a constant surface tension parameter, σ_S. Since the role of the surface tension in the mixed phase has been already studied in the previous papers [2, 3], we use only one value, $\sigma_S = 40$ MeV fm^{-2}, in this paper. We impose the Gibbs conditions, i.e. chemical equilibrium among particles in two phases consistent with the Coulomb interaction, and pressure balance in the presence of the surface tension. Here, we do not take into account the anti-particles or muons because of their minor corrections to the results. Finally, we compare the Helmholtz free energy among different kinds of pasta structures and choose which structure is most favored.

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3. Results

In protoneutron stars, we must consider mainly two effects, namely temperature and neutrino fraction. The range of temperature is roughly $\sim$ 0 - 40 MeV, and the range of neutrino fraction is $\sim$ 0 - 0.2 [12]. In the previous paper, we have studied the effects of temperature on the quark-hadron mixed phase [4]. In this study, we discuss the effects of neutrino fraction and summarize the finite-size effects of the quark-hadron mixed phase in the protoneutron stars.

3.1 Thermal effects

In the previous study, we have shown that the thermal effect makes the mixed phase unstable at high temperature [4]. The structure of the mixed phase is mechanically stable below $T \sim 60$ MeV, but the optimal value of the radius R shifts to larger value as T increases. This behavior is a signal of the mechanical instability and it comes from the charge screening effect and the thermal effect. The rearrangement of the charged-particle distribution gives rise to a change of the free energy (correlation energy), and it is enhanced as temperature increases. Consequently the mixed phase is restricted to small density region, and the EOS gets close to the fictitious one given by the Maxwell construction. The details about the effects of temperature, including EOS, are fully discussed in our previous paper [4].

3.2 Effects of neutrinos

The left panel of Fig. 1 shows the free energies per baryon of the droplet structure at several values of neutrino fractions. Here we use the optimal value of $(R/R_W)^3$ at $Y_{\nu_e} = 0.01$ in every curve. In these figures, we adopt the density dependent bag model shown as Eq. (2.1). We normalize them by subtracting the free-energy at infinite radius. The structure of the mixed phase is mechanically stable below $Y_{\nu_e} \sim 0.10$, but the optimal value of the radius R is shifted to the larger value as Y_{ν_e} increases.

To elucidate this point more clearly, we present each contribution to F/A in the right panel of Fig. 1. The baryon-number density and the temperature are set to be $n_B = 2.5\ n_0$ and $T =$ 10 MeV. In this figure, we compare the case for $Y_{\nu_e} = 0.01$ (thin lines) with the one for $Y_{\nu_e} =$ 0.15 (thick lines). We can see the main contributions responsible to the change of free energy are the correlation energy and the Coulomb energy.

Why does the Coulomb energy become important for the neutrino-trapped case? In the presence of neutrinos, the electron fraction becomes large because of the chemical equilibrium. Accordingly the fraction of particles with positive charge is enhanced through the charge neutrality condition. Thus, the net charge density decreases in the whole region of the cell. Consequently the Coulomb energy is largely reduced by the presence of neutrinos. The change of the correlation energy follows that of the Coulomb energy since the rearrangement effect is also reduced. Both the Coulomb and correlation energies give rise to the instability in this case.

Fig. 2 shows the density profiles within the 1D cell (slab) for $n_B = 2.5\ n_0$ at $Y_{\nu_e} = 0.01$ (left panel) and $Y_{\nu_e} = 0.15$ (right panel). The figure clearly shows the change of the Coulomb energy by trapped neutrinos. Each temperature is set to be $T = 10$ MeV. The volume ratio $(R/R_W)^3$ of the quark phase is fixed to be the optimal value at $Y_{\nu_e} = 0.01$. The magnitude of the Coulomb potential is obviously decreased at high neutrino fraction. We can see the enhancement of positive-charge

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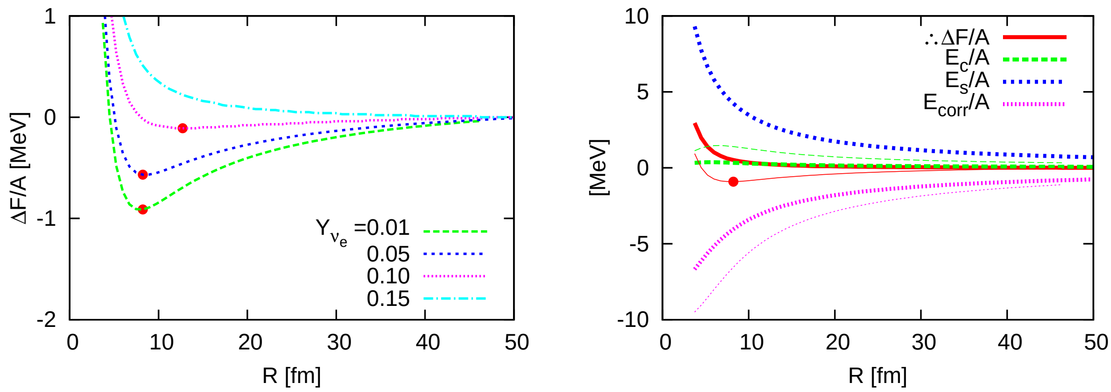

Figure 1: The left panel shows that the droplet radius R dependence of the free-energy per baryon for $n_B = 2.5\, n_0$ and different neutrino fractions Y_{ν_e} at constant temperature, $T = 10$ MeV. In this case, we set the quark volume fraction $(R/R_W)^3$ is fixed to be the optimal value at $Y_{\nu_e} = 0.01$ for each curve. The filled circles on each curve shows the energy minimum. The right panel shows each contribution to the R dependence of the free energy, the Coulomb energy, the surface energy, or the correlation energy per baryon (E_C/A, E_S/A, $E_{\rm corr}/A$) at $Y_{\nu_e} = 0.15$ MeV (thick lines) and $Y_{\nu_e} = 0.01$ MeV (thin lines).

particles following the enhancement of negative-charge electrons. Accordingly the negative charge of the quark slab is suppressed. Consequently the net charge becomes small in the cell.

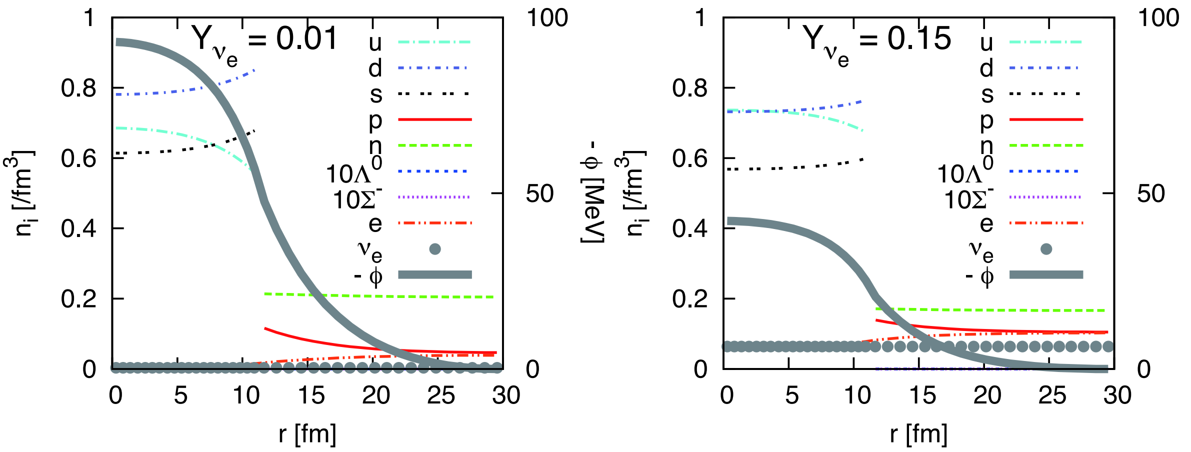

Figure 2: Density profiles and Coulomb potential ϕ within 1D (slab) for $n_B = 2.5\, n_0$ at $T = 10$ MeV. Here, the neutrino fractions are set to be $Y_{\nu_e} = 0.01$ (left panel) and $Y_{\nu_e} = 0.15$ (right panel). The cell sizes are set as $R_W = 30$ fm in these figures. The slab size is $R = 10.9$ fm. $(R/R_W)^3$ is fixed to be the optimal value at $Y_{\nu_e} = 0.01$.

4. Summary and Discussion

Considering the quark-hadron phase transition, we have studied the properties of the mixed phase in protoneutron stars, taking into account the thermal effects in the presence of neutrinos. We have considered the finite-size effects by imposing the Gibbs conditions on the phase equilibrium, and calculating the density profiles in a self-consistent manner.

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Our calculation suggests that the quark-hadron mixed phase becomes unstable at high temperature and/or high lepton fraction. The instability by the neutrino trap comes from both the correlation energy and the Coulomb energy, while the latter one is not important in the absence of neutrinos [4].

Hence, we conclude that the EOS during the quark-hadron phase transition is close to that obtained with the Maxwell construction at the very first stage of protoneutron stars, because the temperature is high, $T \sim 40$ MeV, and the neutrino fraction is also high, $Y_{\nu_e} \sim 0.2$. However, in the middle stage of evolution of protoneutron stars, the pasta structure will appear, where initial cooling and deleptonization proceed. We can see the similar discussions in the recent papers by Schaffner's Group, though they have not fully studied the mixed phase [13, 14].

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