Quark-hadron phase transition in protoneutron stars

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(Received 5 January 1995)

We investigate the role of trapped neutrinos on the composition of protoneutron stars with quark-hadron phase transitions. Trapped neutrinos shift the transition to higher baryon densities and also reduce the extent of a mixed phase in comparison to neutrino-free matter. Thus a mixed phase of baryons and quarks is more likely to occur after a neutrino diffusion time scale of several seconds. In contrast with stars containing only nucleons and leptons, stars with quarks have larger maximum masses when neutrinos are trapped than for neutrino-free stars. Hence black hole formation is likely delayed for the neutrino diffusion time scale when quarks are present.

PACS number(s): 97.60.Jd, 12.38.Mh, 21.65.+f, 97.60.Bw

A protoneutron star is formed immediately after the gravitational collapse of the core of a massive star [1]. At birth, the high-density matter in these objects has entropies per baryon of order unity (in units of Boltzmann's constant). In addition, the matter contains neutrinos trapped during collapse. Neutrinos at the star's core have energies $E_\nu \sim$ 200–300 MeV and are primarily of the ν_e type. They escape after diffusing through the star, exchanging energy with the ambient matter in a time of several seconds. The internal constitution of the hot protoneutron star chiefly depends on the nature of strong interactions. Although the composition and the equation of state (EOS) of such matter is not yet certain, QCD-based effective Lagrangians have opened up intriguing possibilities including a transition to strangeness-rich quark matter at high density. Neutrino trapping strongly affects the composition of hot and dense matter [2,3] and offers a means to distinguish between different phases of matter, such as a baryonic phase versus a quark phase. With new-generation neutrino detectors, it is feasible to test different scenarios observationally. Two possible discriminants are the total neutrino energy radiated and the net excess of ν_e emission relative to other neutrino types.

We examine the effects of trapped neutrinos on the composition and structure of protoneutron stars allowing for a hadron to quark phase transition in the stars' interior. These effects have not been considered previously. The presence of quarks and/or strangeness-rich baryonic matter results in a larger ν_e excess relative to the other types compared to the scenario with ordinary matter. Should a mixed phase of baryon and quark matter exist over a wide range of densities, as noted for neutrino-free matter by Glendenning [4], neutrino trapping dramatically alters the quark phase electron content which is otherwise vanishingly small, possibly leading to detectable differences in the neutrino signatures.

In general, changes in the maximum mass due to neutrino trapping are larger than those due to finite temperature [3]. During its early evolution, a protoneutron star attains entropies per baryon of order 1–2 and central temperatures of 30–40 MeV. Such matter is highly degenerate since the chemical potentials of the constituents are typically of order 200–300 MeV. Thermal contributions to the pressure are relatively small and produce only small changes in the gross properties of the star such as the maximum mass. In contrast, the composition changes caused by the trapped neutrinos induce relatively larger changes in the maximum mass. Neglecting finite temperatures will have little effect on our conclusions.

We begin by considering the equilibrium conditions, for bulk baryonic and quark matter coexisting in a uniform background of leptons (e^-, μ^-, and their associated ν's) for neutrino-trapped matter. The influence of complicated finite-size structures due to Coulomb and surface effects [5] will be considered separately. Following Glendenning [4], we require only *global* charge neutrality of bulk matter, considering the separately conserved charges: baryon number and electric charge. An important consequence of this treatment is that baryonic and quark matter can coexist for a finite range of pressures.

For the pure phase in which the strongly interacting particles are baryons (hereafter termed phase 1) the composition is determined by the requirements of charge neutrality and equilibrium under the weak processes

$$B_1 \to B_2 + \ell + \overline{\nu}_\ell \,; \qquad B_2 + \ell \to B_1 + \nu_\ell \,, \tag{1}$$

where B_1 and B_2 are baryons, and ℓ is a lepton, either an electron or a muon. Under conditions when the neutrinos have left the system, these two requirements imply that the relations

$$Q_1 = \sum_i q_i n_{B_i} + \sum_{\ell=e,\mu} q_\ell n_\ell = 0 \,, \tag{2}$$

$$\mu_i = b_i \mu_n - q_i \mu_\ell \tag{3}$$

are satisfied. Above, q and n denote the charge and number density, respectively, and the subscript i runs over all the baryons considered. The symbol μ_i refers to the chemical potential of baryon i, b_i is its baryon number, and q_i is its charge. The chemical potential of the

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neutron is denoted by μ_n. Under conditions when the neutrinos are trapped in the system, the β equilibrium condition Eq. (3) is altered to $\mu_i = b_i\mu_n - q_i(\mu_\ell - \mu_{\nu_\ell})$, where μ_{ν_ℓ} is the chemical potential of the neutrino ν_ℓ. Because of trapping, the numbers of leptons per baryon $Y_{L\ell} = Y_\ell + Y_{\nu_\ell}$ of each flavor of neutrino, $\ell = e$ and μ, are conserved on dynamical time scales. Gravitational collapse calculations of massive stars indicate that, at the onset of trapping, $Y_{Le} = Y_e + Y_{\nu_e} \simeq 0.4$, the precise value depending on the efficiency of electron-capture reactions during the initial collapse stage. Also, because no muons are present when neutrinos are trapped, the constraint $Y_{L\mu} = Y_\mu + Y_{\nu_\mu} = 0$ can be imposed. We fix $Y_{L\ell}$ at these values in our calculations for *neutrino-trapped* matter.

In the pure quark phase (hereafter referred to as phase 2), the relevant weak decay processes are similar to Eq. (1) but with B_i replaced by q_f, where f runs over the quark flavors u, d, and s. In neutrino-free matter, charge neutrality and chemical equilibrium under the weak processes imply

$$Q_2 = \sum_f q_f n_f + \sum_{\ell=e,\mu} q_\ell n_\ell = 0 \ , \tag{4}$$

$$\mu_d = \mu_u + \mu_\ell = \mu_s \ . \tag{5}$$

When neutrinos are trapped, the new chemical equilibrium relation is obtained by the replacement $\mu_\ell \to \mu_\ell - \mu_{\nu_\ell}$ in Eq. (5).

To determine the equilibrium concentrations in each phase, we employ a field theoretic model at the mean-field level for hadronic matter and a bag model for quark matter. Specific details of these models are kept close to the work of Glendenning [4], who considered neutrino-free matter. The pressure P_1 of the hadronic phase is obtained from the Lagrangian proposed by Zimanyi and Moszkowski [6], in which the baryons B interact through the exchange of σ, ω, and ρ mesons. All charge states of the baryon octet $B = n, p, \Lambda, \Sigma^+, \Sigma^-, \Sigma^0, \Xi^-, \Xi^0$ as well as the Δ quartet are considered. The contributions of the leptons, $\ell = e^-$, μ^-, and where appropriate their respective ν's, are adequately given by their noninteracting expressions. In our calculations, we assume that all the baryon couplings mediated by a given meson field are the same, which limits the number of unknown constants to three: g_σ/m_σ, g_ω/m_ω, and g_ρ/m_ρ. These may be determined by fitting the empirical properties of nuclear matter at the equilibrium density of $n_0 = 0.16\ \mathrm{fm}^{-3}$ (see Ref. [4] for more details). Specifically, their values are $(g_\sigma/m_\sigma)^2 = 7.487\ \mathrm{fm}^2$, $(g_\omega/m_\omega)^2 = 2.615\ \mathrm{fm}^2$, and $(g_\rho/m_\rho)^2 = 4.774\ \mathrm{fm}^2$. The energy density in phase 1 is $\epsilon_1 = -P_1 + \sum_B n_B\mu_B + \sum_\ell n_\ell\mu_\ell$.

The pressure of quarks in phase 2 is given by $P_2 = -B + \sum_{f=u,d,s} P_f + P_\ell$, where the first term accounts for the cavity pressure and the second and third terms are the Fermi degeneracy pressures of quarks and leptons, respectively. The constant B has the simple interpretation as the thermodynamic potential of the vacuum, and will be regarded as a phenomenological parameter in the range (100–250) $\mathrm{MeV\,fm}^{-3}$. The chemical potential of free quarks in the cavity is $\mu_f = \sqrt{k_{F_f}^2 + m_f^2}$, where k_{F_f} is the Fermi momentum of quarks of flavor f. For numerical calculations, we take the u and d quarks as massless and $m_s = 150$ MeV. The baryon density is $n_{b_2} = (n_u + n_d + n_s)/3$ and the energy density is $\epsilon_2 = -P_2 + \sum_q n_q\mu_q + \sum_\ell n_\ell\mu_\ell$.

The description of the mixed phase of hadrons and quarks is achieved by satisfying Gibbs' phase rules: $P_1 = P_2$ and $\mu_n = \mu_u + 2\mu_d$. Further, the conditions of global charge neutrality and baryon number conservation are imposed through the relations $Q = fQ_1 + (1-f)Q_2 = 0$ and $n_b = fn_{b_1} + (1-f)n_{b_2}$, where f represents the fractional volume occupied by phase 1. Notice that unlike in the pure phases [Eqs. (2) and (4)], Q_1 and Q_2 do not separately vanish in the mixed phase. Neutrinos are straightforward to include since all leptons are assumed to be uniformly distributed in the background. The total energy density is $\epsilon = f\epsilon_1 + (1-f)\epsilon_2$.

Figure 1 shows a comparison of the compositions of neutrino-free matter (top panel) and neutrino-trapped matter (bottom panel). In neutrino-free matter, one expects that Λ, with a mass of 1116 MeV, and the Σ^-, with a mass of 1193 MeV, first appear roughly at the same density, because the somewhat higher mass of the Σ^- is compensated by the presence of μ_e in the equilibrium condition of the Σ^-. More massive and more positively charged particles than these appear at higher densities. Notice that with the appearance of the negatively

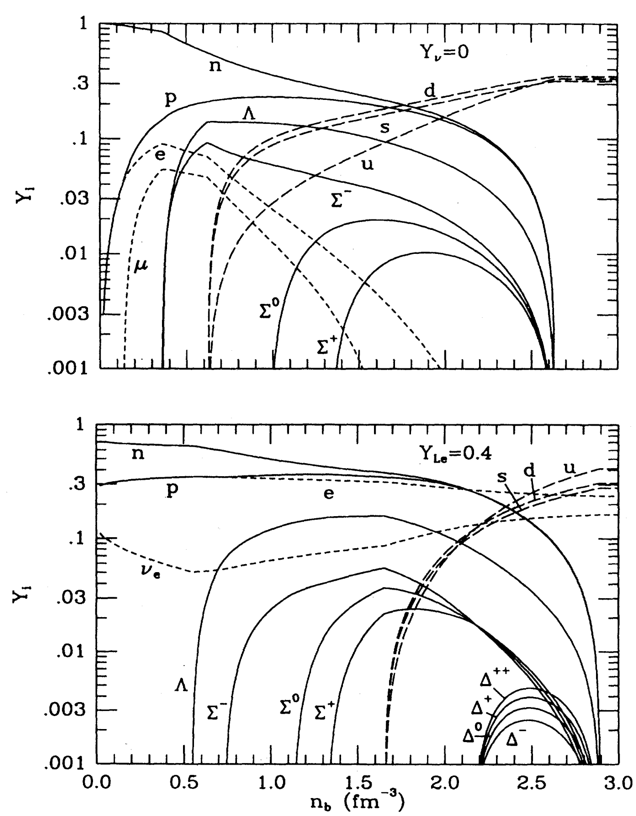

FIG. 1. Compositions of neutrino-free (top) and neutrino-trapped (bottom) matter. The quark phase cavity pressure $B = 200\ \mathrm{MeV\,fm}^{-3}$.

charged Σ^- hyperon, which competes with the leptons in maintaining charge neutrality, the lepton concentrations begin to fall. With the appearance of quarks, which occurs around $4n_0$ for $B = 200$ MeV fm^{-3}, the neutral and negative particle abundances begin to fall, since quarks furnish both negative charge and baryon number. The bottom panel of Fig. 1 shows the influence of trapped neutrinos, with $Y_{Le} = 0.4$, on the relative fractions. The primary role of trapped neutrinos is to increase the proton and electron abundances, which strongly influences the threshold for the appearance of hyperons. The Λ and the Σ's now appear at densities higher than those found in the absence of neutrinos. In addition, the transition to a mixed phase with quarks is delayed to about $10n_0$. Qualitatively similar trends are observed for other values of the bag constant B.

In Fig. 2, we show the phase boundaries as a function of the bag pressure B. The onset of the transition is at density $n_1 = u_1 n_0$ and a pure quark phase begins at density $n_2 = u_2 n_0$. Also shown are the central densities $n_c = u_c n_0$ of the maximum mass stars. Trapping shifts the onset of the phase transition to higher baryon densities and also reduces the extent of the mixed phase in comparison to the case of neutrino-free matter. The existence of a mixed phase inside the star depends on whether or not hyperons are present. In the absence of hyperons (top panel), a mixed phase is present for a range of quark pressures. When hyperons are present (bottom panel), the mixed phase is present only when the pressure due to quarks is sufficiently high ($B \leq 165$ MeV fm^{-3}) and occurs over a smaller range in density than that found in the absence of hyperons. The abrupt change in the onset of the transition around $B = 140$ MeV fm^{-3} is related to the appearance of hyperons prior to that of quarks. The dashed lines correspond to the case in which neutrinos have left the star. Whether or not hyperons are present, the mixed phase is present over a wide range of density inside the star. Note also that, since the central density of the star $u_c < u_2$ for all cases considered, the presence of a pure quark phase is precluded. It is clear that a mixed phase of hadrons and quarks is more likely to occur when the neutrinos have left the star.

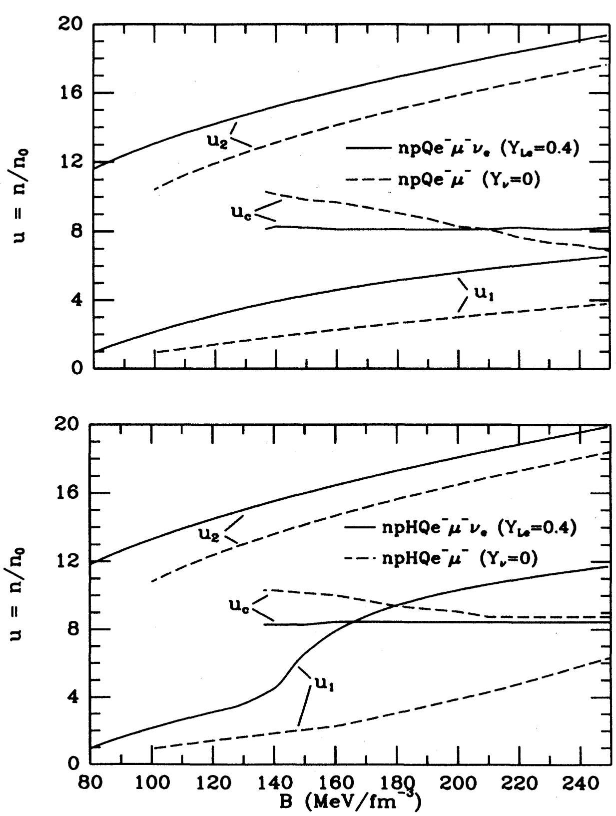

FIG. 2. Quark-hadron phase-transition boundaries in matter with nucleons and leptons (top) and nucleons, hyperons, and leptons (bottom). The equilibrium nuclear density $n_0 = 0.16$ fm^{-3}.

Table I shows the maximum masses of stars as a function of the composition of matter. With only nucleons and leptons (last row), neutrino trapping generally *reduces* the maximum mass from the case of neutrino-free matter. This is caused by the smaller pressure support of lepton-rich matter in which the gain in symmetry pressure exceeds the increase in leptonic pressure. However, the introduction of quarks, which softens the EOS, causes the maximum mass for the trapped case to be *larger* than that for neutrino-free matter. This reversal in behavior is due to the appearance of quarks at a higher density in the neutrino-trapped star. The fact that quark matter is negatively charged leads to a higher threshold density for its appearance. The overall EOS is thus stiffer in this case. This result is not altered for matter that also contains hyperons. In fact, our result for quark matter is just another example of the behavior first noted by Thorsson, Prakash, and Lattimer [2] in the study of stars with kaon condensates and subsequently by Keil and Janka [7] for stars with hyperons. These other two cases also involve a nonleptonic negatively charged softening component in the EOS. We therefore arrive at the general result that *when matter contains nonleptonic negative charges, the maximum mass of the neutrino-trapped star is larger than that of the neutrino-free star.*

The differences in the maximum masses of neutrino-

TABLE I. Maximum masses of stars with baryonic matter that undergo a phase transition to quark matter without ($Y_\nu = 0$) and with ($Y_{Le} = 0.4$) trapped neutrinos. Results are for a mean-field model of baryons and a bag model of quarks. B denotes the bag pressure in the quark EOS.

	$M_{\max}/M_\odot$			
	Without hyperons		With hyperons	
B (MeV fm^{-3})	$Y_\nu = 0$	$Y_{Le} = 0.4$	$Y_\nu = 0$	$Y_{Le} = 0.4$
136.6	1.440	1.610	1.434	1.595
150	1.444	1.616	1.436	1.597
200	1.493	1.632	1.471	1.597
250	1.562	1.640	1.506	1.597
No quarks	1.711	1.645	1.516	1.597

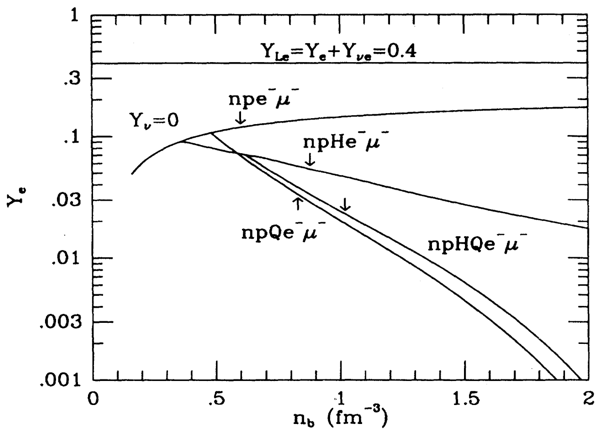

FIG. 3. Electron concentrations for neutrino-free matter for different compositional cases. The quark phase cavity pressure $B = 200$ MeV fm^{-3}. Arrows indicate central densities of $1.44 M_\odot$ stars. Differences of each curve from $Y_{Le} = 0.4$ show the net Y_{ν_e} lost at each density during cooling.

trapped and neutrino-free stars has bearing on other issues as well, such as the time when black holes might form [8]. Most scenarios for gravitational collapse supernovas suggest that accretion onto a protoneutron star lasts for only a brief interval, at most a few seconds following core bounce. For nucleons-only stars, a black hole could only form promptly after core bounce because neutrino-trapped matter cannot support more mass than neutrino-free matter. However, this is not the case for matter with nonleptonic negatively charged softening components. For matter containing either hyperons or hyperons and quarks, the maximum mass of the neutrino-trapped star is larger than that of the neutrino-free star. In the event that the maximum baryon mass of the cold neutrino-free star is close to $1.5 M_\odot$, black hole formation is possible only after the neutrinos diffuse out of the protoneutron star, i.e., on the order of 10 s following bounce. Burrows [9] has demonstrated that black hole formation should be accompanied by a dramatic cessation of neutrino signal, since the event horizon invariably forms outside the neutrinosphere. Such behavior would be relatively easy to observe from a galactic supernova.

To lowest order, neutrinos from a cooling protoneutron star are equally populated in all types [1]. Conservation of lepton number will ensure that a slight excess of ν_e's will be emitted. The magnitude of the excess will depend, among other factors, on the net change in Y_{Le} during cooling, which is illustrated in Fig. 3. The initial $Y_{Le} = Y_e + Y_{\nu_e} = 0.4$ is shown by the horizontal line. The different curves show Y_e in neutrino-free matter. The arrows show the corresponding central densities of a $1.44 M_\odot$ star. The difference of each curve from $Y_{Le} = 0.4$ gives the net number of electron neutrinos escaping at a given density. The net excess of ν_e's emitted is obtained by integrating $n_{\nu_e} = n_b Y_{\nu_e}$ over the star's structure. It is evident that matter containing negatively charged nonleptonic matter gives rise to a larger net excess of electron neutrinos than nucleons-only matter. With new-generation neutrino telescopes, it might be possible to discriminate between the different scenarios.

In Fig. 4, we show the gravitational masses as a function of the baryonic masses for matter with three different compositions. To date, all of the observed neutron star gravitational masses [10] lie in the band $1.3 < M/M_\odot < 1.5$. The vertical difference of the two curves in each panel is the binding energy released during the long-term neutrino diffusive-emission stage, and is very nearly the same for the three cases, for a given baryon mass. (Note that this difference is not the total binding energy of the neutron star.) Therefore, the binding energy is not likely to be a good discriminant of the composition.

In conclusion, we have shown that the hadron to quark phase transition in a protoneutron star is shifted to higher baryon densities than those for neutrino-free stars. A mixed phase of hadrons and quarks is more likely to occur after a period of several seconds during which neutrinos diffuse out from the protoneutron star. When matter contains nonleptonic negative charges, such as Σ^- hyperons, or d and s quarks, the maximum masses of neutrino-trapped stars are larger than those of neutrino-free stars, in contrast to nucleons-only matter where the behavior

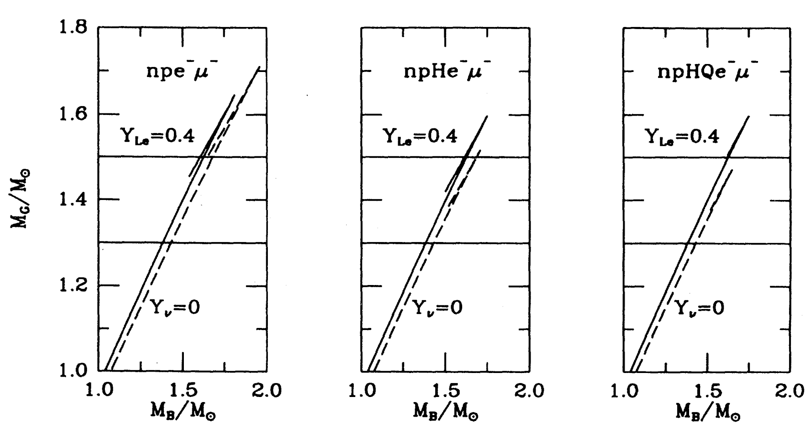

FIG. 4. Enclosed gravitational mass versus baryonic mass for neutrino-rich (solid curves) and neutrino-free (dashed curves) matter. Observed values for M_G lie in the band $1.3 < M_G/M_\odot < 1.5$.

of the maximum masses is reversed. In the presence of negatively charged particles and if the maximum mass of the neutrino-trapped star is near $1.5M_{\odot}$, black hole formation is possible after the neutrino diffusion time scale of several seconds. Further, the net number of electron-type neutrinos, relative to other neutrinos radiated from stars containing nonleptonic negative charges, are larger than those from stars with nucleons-only matter. These effects may be distinguishable with new-generation neutrino detectors.

We thank Roland Knorren for discussions and Norman Glendenning for useful correspondence. This work was supported in part by U.S. Department of Energy Grants No. DE-FG02-88ER40388 and No. DE-FG02-87ER40317.

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