

Quark matter formation in dense stellar objects

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Abstract. It is expected that at very large densities and/or temperatures a quark-hadron phase transition takes place. Lattice QCD calculations at zero baryon density indicate that the transition occurs at $T_c \sim 150\text{--}170$ MeV. The transition is likely to be second order or a cross over phenomenon. Although not much is known about the density at which the phase transition takes place at small temperatures, it is expected to occur around the nuclear densities of few times nuclear matter density. Also, there is a strong reason to believe that the quark matter formed after the phase transition is in colour superconducting phase. The matter densities in the interior of neutron stars being larger than the nuclear matter density, the neutron star cores may possibly consist of quark matter which may be formed during the collapse of supernova. Starting with the assumption that the quark matter, when formed consists of predominantly u and d quarks, we consider the evolution of s quarks by weak interactions in the present work. The reaction rates and time required to reach the chemical equilibrium are computed here. Our calculations show that the chemical equilibrium is reached in about 10^{-7} seconds. Further more during the equilibration process enormous amount of energy is released and copious numbers of neutrinos are produced. Implications of these on the evolution of supernovae will be discussed.

Keywords. Quark matter; neutron star.

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1. Introduction

When the nuclear matter is compressed and/or heated, one expects that it will undergo hadron-quark transition and the phase at higher densities or temperatures will consist of deconfined quarks and gluons. A schematic phase diagram for this transition is shown in figure 1. Although the idea of quark-hadron phase transition is, by now, widely accepted, the details of the transition are not yet well understood. Recent lattice-QCD calculations [1] show that for three flavour matter, the transition temperature at zero baryon chemical potential (or baryon density) is about 170 MeV. These calculations also show that at the transition point, the system consists of deconfined but strongly interacting quarks and gluons and only when the temperature reaches 230 MeV or larger the interactions become weak and the matter can be regarded as (almost) free quarks and gluons. Above this temperature the energy density and pressure start approaching the value for the gas of non-interacting relativistic particles. At the transition temperature the energy density is around $0.6 \text{ GeV}/\text{fm}^3$ and when the temperature reaches 230 MeV or so the energy density is around $3 \text{ GeV}/\text{fm}^3$. Note that earlier estimates [2] of the transition energy density

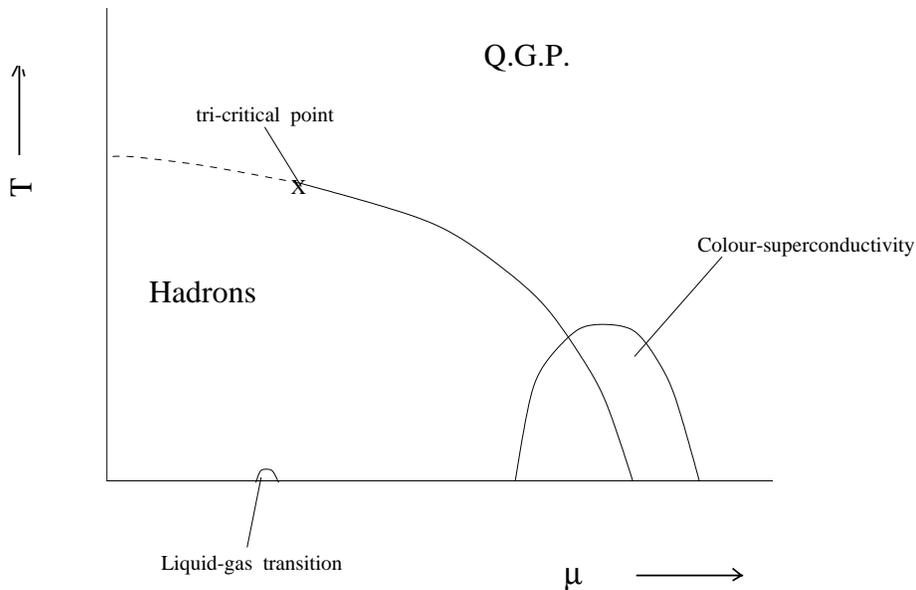


Figure 1. The schematic phase diagram.

had been about $2 \text{ GeV}/\text{fm}^3$, which are 3 to 4 times larger than the current lattice estimate. Depending on the strange quark mass, the phase transition may be second order or cross-over. It is expected that when the baryon chemical potential is increased from zero, at some point a tricritical point is reached and beyond that point the transition is expected to be first order. The lattice QCD calculations cannot tell much about the chemical potential or density at which the transition takes place when the temperature is small. However, it is reasonable to assume that the energy density at which the phase transition occurs does not depend sensitively on the temperature or chemical potential. In that case, at small temperatures the baryon density at the transition is expected to be around 3–5 times nuclear matter density [2a].

Recent theoretical investigations have [3] shown that, because of attractive quark-quark interaction in isospin-singlet and colour- $\bar{3}$ channel, the quark matter, after the phase transition, should be in colour-superconducting phase. The Cooper pairs of the colour-superconducting phase will have diquark structure with the colour being in $\bar{3}$ channel. Although the details of the colour-superconducting phase are not yet known it is expected that the superconducting gap should be tens of MeV and therefore the colour superconductivity should persist at temperatures of tens of MeV. This is likely to have interesting consequences on the cooling of neutron stars. We shall discuss this point later.

The preceding discussion implies that the nuclear matter is likely to undergo hadron-quark phase transition when the nuclear densities increase above $3\text{--}5 \times \rho_{\text{NM}}$ where ρ_{NM} is the equilibrium nuclear matter density (0.17 fm^{-3}). Calculations based on a widely different nuclear equations of state [4] show that the baryon number densities in the cores of neutron stars are quite large (7 times ρ_{NM} or larger) and therefore it is reasonable to expect that the cores of the neutron stars would consist of quark matter. In the present work, we shall be investigating the details of the formation of quark matter in such situations.

In particular, we shall be considering the scenario where the baryonic matter at the phase transition contains few strange particles and therefore after the transition the quark matter will consist of predominantly u and d quarks. This is not a chemically equilibrated configuration of the quark matter. This can be understood as follows. At the transition point, the matter will predominantly consist of d and u quarks and some electrons, with d quark density being roughly two times u quark density and practically no s quarks. Thus d and u quark chemical potentials will be large (much larger than the s quark mass). As a result, it would be energetically favourable for the d quarks at the Fermi surface to decay into s quarks by weak interaction till chemical equilibrium between d and s quarks is reached. At the chemical equilibrium, the chemical potentials of the three quark species will be almost equal. Further more, since the baryon density of the quark matter is larger than $3-5 \times \rho_{\text{NM}}$, the chemical potentials of the quarks will be large in comparison with the quark masses. This implies that the densities of the quarks of three flavours will be almost equal. Therefore, the strangeness fraction (defined as the ratio of strangeness density to baryon number density) would be close to unity in the quark matter. On the other hand, the strangeness fraction is expected to be close to zero in the hadronic phase [4a]. Thus, the chemical equilibration of the quark matter will be associated with the generation of strangeness.

In addition to the production of strangeness the equilibration process will liberate considerable amount of energy which will result in the increase in the temperature of the quark matter. The reason for this is the fact that the weak interaction reactions will be converting the d quarks having large momenta (and therefore energy) to s quarks having small momenta since the initial Fermi momentum of d quarks is much larger than the Fermi momentum of s quarks. The difference in the energies of the d and s quarks will lead to raising of the temperature matter. In addition, the semi-leptonic weak interactions will produce a large number of neutrinos during the chemical equilibration. In the present work, we have computed the different weak reaction rates which are responsible for the chemical equilibration process. Using these reaction rates the chemical equilibration time, change in the temperature and pressure of the quark matter and the number of neutrinos produced during equilibration are calculated. In our calculations the reaction rates are computed using standard weak interaction theory and we have assumed that the constituents of the quark matter are in thermal equilibrium during the chemical equilibration process. This is a reasonable assumption since the chemical equilibration process is due to weak interaction whereas the thermal equilibration is achieved by strong and electromagnetic interactions which have larger reaction rates.

The paper is organized as follows. In §2, the reaction rates for different weak interactions are computed and the evolution equations for densities of different constituents of the quark matter are defined. The expression for neutrino emission rates, rate of change of pressure, internal energy and energy liberation into neutrinos are also given in §2. In §3 the results of the computations are presented and discussed. Finally in §4 the implications of these results on supernova collapse is discussed.

2. Weak interaction rates

As mentioned in the preceding section, when the transition from hadron to quark matter takes place in stellar object (a neutron star or a proto-neutron star formed during the collapse of a white dwarf), the quark matter predominantly consists of u and d quarks, apart

from some electrons and gluons if the temperature of the star is large. Particularly, the s quark density is small when the transition takes place. Generally, the temperature is a few tens of MeV in a proto-neutron star and less than 0.1 MeV for neutron stars at the transition. As a result, the gluons are not expected to play an important role. To begin with, we assume the baryon density (ρ_B) to be same as that before the phase transition [4b]. The u and d quarks and electron densities are determined from baryon density, charge neutrality and β -equilibrium (among u , d quarks and electrons):

$$\begin{aligned} \frac{1}{3}(\rho_d + \rho_u) &= \rho_B, \\ \frac{2}{3}\rho_u - \frac{1}{3}\rho_d - \rho_e &= 0, \\ \mu_d &= \mu_u + \mu_e. \end{aligned} \tag{1}$$

Here μ_i is the chemical potential of the particle species i and the particles are assumed to have Fermi distribution $F(\epsilon_i, \mu_i, T) = \frac{1}{e^{(\epsilon_i - \mu_i)/T} + 1}$ with ϵ_i and μ_i being the energy and chemical potential of the particle of species i and T the temperature. If the strange particle density is assumed to be nonzero before the transition, the initial strange quark density is determined so that the strangeness fraction after the transition is same as that before the transition. Then the charge conservation and baryon number density conservation equations above get modified to include s quarks.

The chemical equilibration is reached by the weak interactions among the quarks and electrons. These are:



The first reaction above is nonleptonic weak reaction and it does not involve neutrino emission. The neutrinos are emitted in other two reactions. Note that both electrons and positrons are included in the reactions above since the temperature of the matter is generally larger than the electron mass and generally the electron chemical potential is less than the temperature. In addition, one also has reactions which have three body final state:



It turns out that the reaction rates of the last two reactions are much smaller. We therefore do not include these reactions in our calculations.

Using the standard V-A theory of the weak interactions [7], the transition matrix elements for these reactions can be calculated. One can then compute the reaction rates by integrating the square of the transition matrix element over the momenta of the particles involved in the reaction, average over the spins of incident particles and sum over the spins of product particles. After some integrations the reaction rates can be written in the form

$$\begin{aligned} R_{d \rightarrow s}(t) &= \frac{18G_F^2 \sin^2 \theta_c \cos^2 \theta_c}{(2\pi)^5} \int dp_d dp_{u_1} dp_{u_2} dp_s p_d p_{u_1} p_{u_2} p_s \delta(\epsilon_d + \epsilon_{u_1} - \epsilon_s - \epsilon_{u_2}) \\ &F(\epsilon_d, \mu_d, T) F(\epsilon_{u_1}, \mu_u, T) \left(1 - F(\epsilon_s, \mu_s, T)\right) \left(1 - F(\epsilon_{u_2}, \mu_u, T)\right) \end{aligned}$$

$$\int_{\max\{|p_d-p_{u_1}|, |p_s-p_{u_2}|\}}^{\min\{p_d+p_{u_1}, p_s-p_{u_2}\}} dP \left(1 + \frac{p_d^2 + p_{u_2}^2 - P^2}{2\epsilon_d\epsilon_{u_2}}\right) \left(1 + \frac{p_s^2 + p_{u_1}^2 - P^2}{2\epsilon_s\epsilon_{u_1}}\right), \quad (7)$$

$$R_{s \rightarrow d}(t) = \frac{18G_F^2 \sin^2 \theta_c \cos^2 \theta_c}{(2\pi)^5} \int dp_d dp_{u_1} dp_{u_2} dp_s dp_{p_{u_1} p_{u_2}} dp_s \delta(\epsilon_s + \epsilon_{u_1} - \epsilon_d - \epsilon_{u_2}) \\ F(\epsilon_s, \mu_s, T) F(\epsilon_{u_1}, \mu_{u_1}, T) \left(1 - F(\epsilon_d, \mu_d, T)\right) \left(1 - F(\epsilon_{u_2}, \mu_{u_2}, T)\right) \\ \int_{\max\{|p_s-p_{u_1}|, |p_d-p_{u_2}|\}}^{\min\{p_s+p_{u_1}, p_d-p_{u_2}\}} dP \left(1 + \frac{p_s^2 + p_{u_2}^2 - P^2}{2\epsilon_s\epsilon_{u_2}}\right) \left(1 + \frac{p_d^2 + p_{u_1}^2 - P^2}{2\epsilon_d\epsilon_{u_1}}\right), \quad (8)$$

$$R_{d \rightarrow u}(t) = \frac{6G_F^2 \cos^2 \theta_c}{(2\pi)^5} \int dp_d dp_{e^+} dp_u dp_\nu dp_d p_{e^+} p_u p_\nu \delta(\epsilon_d + \epsilon_{e^+} - \epsilon_u - \epsilon_\nu) \\ F(\epsilon_d, \mu_d, T) F(\epsilon_{e^+}, \mu_{e^+}, T) \left(1 - F(\epsilon_u, \mu_u, T)\right) \\ \int_{\max\{|p_d-p_{u_1}|, |p_s-p_{u_2}|\}}^{\min\{p_d+p_{u_1}, p_s-p_{u_2}\}} dP \left(1 + \frac{p_d^2 + p_{u_2}^2 - P^2}{2\epsilon_d\epsilon_{u_2}}\right) \left(1 + \frac{p_s^2 + p_{u_1}^2 - P^2}{2\epsilon_s\epsilon_{u_1}}\right), \quad (9)$$

$$R_{s \rightarrow u}(t) = \frac{6G_F^2 \cos^2 \theta_c}{(2\pi)^5} \int dp_s dp_{e^+} dp_u dp_\nu p_s p_{e^+} p_u p_\nu \delta(\epsilon_s + \epsilon_{e^+} - \epsilon_u - \epsilon_\nu) \\ F(\epsilon_s, \mu_s, T) F(\epsilon_{e^+}, \mu_{e^+}, T) \left(1 - F(\epsilon_u, \mu_u, T)\right) \\ \int_{\max\{|p_d-p_{u_1}|, |p_s-p_{u_2}|\}}^{\min\{p_d+p_{u_1}, p_s-p_{u_2}\}} dP \left(1 + \frac{p_d^2 + p_{u_2}^2 - P^2}{2\epsilon_d\epsilon_{u_2}}\right) \left(1 + \frac{p_s^2 + p_{u_1}^2 - P^2}{2\epsilon_s\epsilon_{u_1}}\right), \quad (10)$$

$$R_{u \rightarrow d}(t) = \frac{6G_F^2 \sin^2 \theta_c}{(2\pi)^5} \int dp_d dp_{e^+} dp_u dp_\nu p_d p_{e^+} p_u p_\nu \delta(\epsilon_u + \epsilon_{e^+} - \epsilon_d - \epsilon_\nu) \\ F(\epsilon_u, \mu_u, T) F(\epsilon_{e^+}, \mu_{e^+}, T) \left(1 - F(\epsilon_d, \mu_d, T)\right) \\ \int_{\max\{|p_d-p_{u_1}|, |p_s-p_{u_2}|\}}^{\min\{p_d+p_{u_1}, p_s-p_{u_2}\}} dP \left(1 + \frac{p_d^2 + p_{u_2}^2 - P^2}{2\epsilon_d\epsilon_{u_2}}\right) \left(1 + \frac{p_s^2 + p_{u_1}^2 - P^2}{2\epsilon_s\epsilon_{u_1}}\right), \quad (11)$$

$$R_{u \rightarrow s}(t) = \frac{6G_F^2 \sin^2 \theta_c}{(2\pi)^5} \int dp_s dp_{e^+} dp_u dp_\nu p_s p_{e^+} p_u p_\nu \delta(\epsilon_u + \epsilon_{e^+} - \epsilon_s - \epsilon_\nu) \\ F(\epsilon_u, \mu_u, T) F(\epsilon_{e^+}, \mu_{e^+}, T) \left(1 - F(\epsilon_s, \mu_s, T)\right) \\ \int_{\max\{|p_d-p_{u_1}|, |p_s-p_{u_2}|\}}^{\min\{p_d+p_{u_1}, p_s-p_{u_2}\}} dP \left(1 + \frac{p_d^2 + p_{u_2}^2 - P^2}{2\epsilon_d\epsilon_{u_2}}\right) \left(1 + \frac{p_s^2 + p_{u_1}^2 - P^2}{2\epsilon_s\epsilon_{u_1}}\right). \quad (12)$$

Here the Fermi distribution function F ensures that the particles before the reaction are in the Fermi sea and the produced particles are above the Fermi sea. The constants G_F and θ_c

are the weak interaction (Fermi) constant and Cabibo angle respectively. In the calculation of the reaction rates we have assumed that the neutrinos produced in the reaction leave the reaction region and therefore their chemical potential is taken to be zero. The knowledge of the reaction rates allows us to compute the rate of change of densities of various particle species:

$$\frac{d\rho_d}{dt} = R_{sd} - R_{ds} + R_{ud} - R_{du}, \quad (13)$$

$$\frac{d\rho_u}{dt} = R_{du} - R_{ud} + R_{su} - R_{us}, \quad (14)$$

$$\frac{d\rho_s}{dt} = -R_{sd} + R_{ds} + R_{us} - R_{su}, \quad (15)$$

$$\frac{d\rho_{e^-}}{dt} = R_{du} - R_{ud} + R_{su} - R_{us}. \quad (16)$$

In addition, the internal energy of the matter changes as the escaping neutrinos carry energy. The rate of change of the internal energy is given by the neutrino emissivities ϵ_ν and $\epsilon_{\bar{\nu}}$ which are essentially the equations similar to the rate equations above with the neutrino (antineutrino) energy included in the momentum integrations. In the rate equations above, ρ_{e^-} implies the difference of electron and positron densities. It is straight forward to verify that baryon number and charge conservation is satisfied by these equations.

Given the reaction rates and the neutrino emissivities, one can compute the densities of different species and the total internal energy after a small time interval dt . Using these one can then determine the temperature and chemical potentials of different species by assuming thermal equilibrium. From these one can compute new rates and hence the evolution of the constituents of the quark matter as a function of time. The computation is carried out till the chemical equilibrium is reached, that is when the chemical potentials of d and s quarks become equal or when the strangeness fraction (defined as the ratio of strangeness density to baryon density) saturates.

In addition to the evolution of number densities of different species one would like to know the number of neutrinos emitted and the energy carried by the neutrinos during the equilibration process. These are obtained by integrating the reaction rates and neutrino emissivities:

$$n_\nu = \int dt(R_{ud}(t) + R_{us}(t)), \quad (17)$$

$$n_{\bar{\nu}} = \int dt(R_{du}(t) + R_{su}(t)), \quad (18)$$

$$E_\nu = \int dt(\epsilon_{ud}(t) + \epsilon_{us}(t)), \quad (19)$$

$$E_{\bar{\nu}} = \int dt(\epsilon_{du}(t) + \epsilon_{su}(t)), \quad (20)$$

where $\epsilon(t)$ is the neutrino emissivity computed by including the neutrino energy in the integration defining the corresponding reaction rate. Note that even after the chemical equilibrium is reached, ($R_{ud}(t) = R_{du}(t)$ and $R_{us}(t) = R_{su}(t)$), the neutrino emission still continues. This is essentially thermal emission of neutrinos and is actually responsible

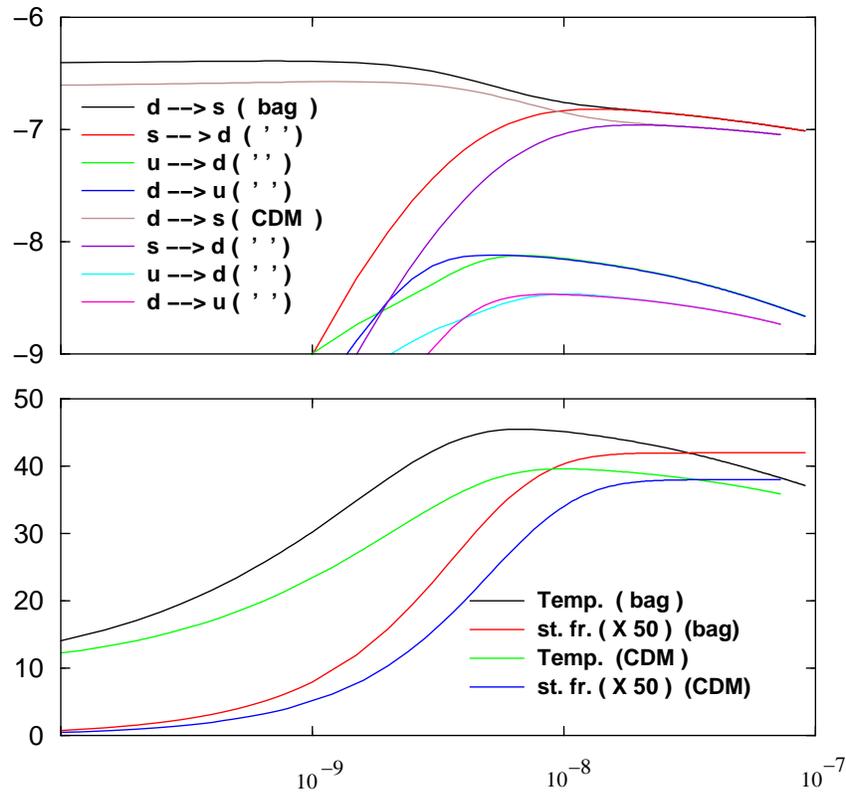


Figure 2. Results for bag and CCD models. The lower panel displays the evolution of temperature and strangeness fraction and the upper panel shows the reaction rates.

for the cooling of the star. In our calculation, we stop when the chemical equilibration is reached. Thus, in our calculation, the number of neutrinos emitted and the energy carried by the neutrinos is only during the equilibration. It is expected that many more neutrinos will be emitted after the chemical equilibration.

3. Results

The calculations described in the previous section have been performed for a number of initial conditions (baryon density, temperature and strangeness content). The qualitative behavior of the results is similar. We therefore will consider one set of the results of our calculation for detailed discussion. The behavior of the temperature, strangeness fraction and reaction rates is displayed in figure 2. The calculation has been done for initial quark matter temperature of 10 MeV and baryon density of $3 \times \rho_{NM}$. The strangeness fraction at the time of quark matter formation is assumed to be zero. The lower panel of figure 2 shows the evolution of temperature and strangeness fraction and the upper panel shows the different reaction rates as a function of time. The results for bag model [8] where u, d and

s quark masses are chosen to be 0, 0 and 150 MeV respectively and for the CCD model [9] these masses are 100, 100 and 210 MeV. In some sense, the bag model represents the situation when one has asymptotic freedom, so that the quark masses are the current quark masses. On the other hand, the lattice calculations suggest that the matter after the phase transition does not have asymptotic freedom. Thus, one would expect that the quark masses will be similar to the constituent masses just after the transition, which is the case for the CCD model.

These results show that the chemical equilibrium is reached in a very short time (less than 10^{-7} seconds). This time period, being of the order of typical weak interaction time scale, should not be surprising. But it is much smaller than the time scales of supernova collapse or initial evolution of the proto-neutron star [10]. The chemical equilibration time is more or less same for the bag and CDM models. This means that, if the quark matter is formed in neutron stars, the chemical equilibrium in the quark matter will be reached very quickly. As expected, the value of the strangeness fraction is close to unity when the chemical equilibrium is reached.

The calculations show that the temperature of the quark matter rises sharply during the chemical equilibration process and reaches the peak value in about 10^{-8} sec. At that stage, the strangeness fraction has reached about 80% of its saturation value. Depending on the initial temperature and, to some extent on the model, the rise in the temperature is between 30–40 MeV. This implies that the reactions leading to chemical equilibration are exothermic. The rise in the temperature is because the d quarks having large momenta and kinetic energies are converted to s quarks. Since the s quark chemical potential is small to begin with, their energy is used up in heating of the quark matter. Note that beyond 10^{-8} seconds, the temperature of the quark matter starts dropping. This decrease is because the neutrinos emitted in semi-leptonic weak reactions carry away the energy from the quark matter and as a result there is cooling of the matter. Neutrino emission is believed to be the most efficient process for the cooling of neutron stars when the temperatures are larger than 1 MeV. We do find that the neutrino emission leads to a rapid cooling of the quark matter. The calculations, when continued to larger time, show that the temperature of the quark matter drops to 10 MeV or lower in $\sim 10^{-4}$ seconds.

The top panel of the figure shows different reaction rates. The rate for $d + u \rightarrow s + u$ is the largest and clearly dominates the equilibration process. On the other hand, the reaction rates of semi-leptonic weak reactions are smaller by more than an order of magnitude. This means that the chemical equilibrium in the quark matter is primarily reached by the conversion of d quarks to s quarks. When the reaction time reaches 10^{-8} seconds, the reaction rates of $d \rightarrow s$ and $s \rightarrow d$ reactions become almost equal. This implies that the d and s quark chemical potentials have become almost equal but this does not yet imply chemical equilibration. However, the chemical equilibrium is soon established. The weak reactions continue after the chemical equilibration but these do not alter the composition of the quark matter. One important point is that the semi-leptonic reactions, which contribute to the production of neutrinos, continue after equilibration. This gives rise to copious production of neutrinos as well as cooling of the matter because of the loss of the energy to the produced neutrinos.

It is clear from the reaction rates that the semi-leptonic reactions play only a minor role in the process of chemical equilibration as such. Nevertheless, these reactions do take place during the chemical equilibration process and afterwards. As discussed above, this leads to a release of energy from the quark matter in the form of neutrinos. In order to get

some idea about the number of neutrinos emitted and the energy carried by them, we have plotted the number of neutrinos/baryon and energy/baryon emitted since the start of the equilibration process in figure 3. This figure shows that about 0.03 neutrinos/baryon are emitted during the chemical equilibration and the per baryon energy released in neutrinos is about 3 MeV. That means the average energy carried by the neutrinos is of the order of 100 MeV. Thus, although the number of neutrinos is not large, the energy carried away by these neutrinos is quite large. Further, the neutrino emission continues after equilibration and a lot more neutrinos are emitted. For example, by 10^{-6} seconds since the beginning of the equilibration process, about 1 neutrino/baryon is emitted and the per baryon energy carried by the neutrinos is larger than 50 MeV. Thus, the chemical equilibration leads to emission of large number of neutrinos and also enormous amount of energy in form of neutrino kinetic energy. Implication of this on dense stellar objects will be discussed in the following section.

4. Dense stellar objects

It is well-known that neutron stars are formed after supernova collapse if the mass of pre-supernova star is not too large. The evolution of the stellar object from pre-supernova stage

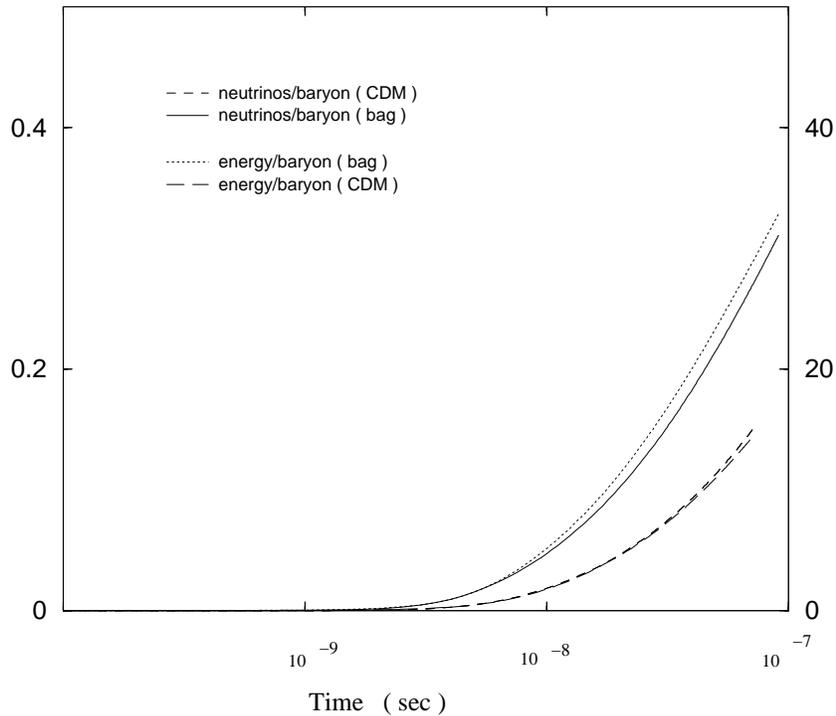


Figure 3. Plot of number of neutrinos/baryon and neutrino energy/baryon emitted during chemical equilibration and after. Note that the strangeness fraction saturates around 10^{-8} seconds.

to proto-neutron star and later into a neutron star has been studied in detail [11]. Further, the constitution of neutron stars has also been studied using different equations of state of the nuclear matter [4,5]. These studies indicate that the matter density in the cores of proto-neutron stars as well as neutron stars could be several times ρ_{NM} . Thus, it is very much likely that the cores of these objects will consist of exotic states of matter such as strange matter, kaon condensate, quark matter etc. In this work we shall be concentrating on the last possibility, namely the quark matter. As discussed in the Introduction, the lattice calculations [1] as well as the recent experiments at CERN [12] indicate that the quark matter is likely to be formed when the energy density of the hot, small density matter reaches $600 \text{ MeV}/\text{fm}^3$ or more. Extrapolating this result to cold and dense nuclear matter, we can conclude that the formation of quark matter is very much likely to occur when the baryon number density is between 0.5 and 0.8 fm^{-3} . This corresponds to $3-5 \times \rho_{\text{NM}}$.

The neutron star calculations [4,5] show that, depending on the nuclear equation of state employed in the calculation and the assumed mass of the neutron star, a substantial fraction of the star core (between 0.5 and 1.5 times solar mass) will have sufficiently large baryon density for the matter to undergo quark-hadron phase transition. If we, as a conservative estimate, assume that the mass contained in the quark matter in the neutron star is half the solar mass, the total number of baryons contained in the quark matter is about 10^{57} . As mentioned in the previous section, about 0.03 neutrinos/baryon are emitted during the chemical equilibration process. Further, the neutrinos are also produced during the rapid cooling of the quark matter and in about first microsecond after the formation of quark matter, close to 1 neutrino/baryon is expected to be emitted. Thus, the total number of neutrinos emitted during and soon after the formation of quark matter can be estimated to be 10^{57} or larger. Note that these are high energy neutrinos and when they diffuse out from the core of the star, their numbers are expected to increase [13] (possibly) by a factor of 10 during their propagation from the core of the star to its surface [14]. Thus, the number of neutrinos released from the star during the process of quark matter formation could be $\sim 10^{58}$ or larger. Note that these numbers are of the order of the number of neutrinos emitted by standard nuclear β -decay processes during the collapse of the white dwarf. Thus, if the quark matter is formed during the collapse, our estimate suggests that the number of neutrinos emitted will be at least factor of two larger than the number expected to be emitted during the collapse.

One of the mechanisms for the supernova explosion is the reheating of the mantle of the star by out-streaming neutrinos which gives an extra outward push to the shock wave which is stalled. The neutrinos produced during the quark matter formation will add to the reheating of the mantle and therefore facilitate the explosion. Furthermore, the amount of energy carried by these neutrinos is quite large, since on the average, these neutrinos carry 100 MeV of energy. A crude estimate indicates that this energy will be about 10^{53} ergs, which is, again, comparable to the energy emitted during the supernova collapse. Actually, it is not surprising that such a huge amount of energy is liberated during quark matter formation. In the standard supernova mechanism, the energy release is primarily due to nuclear reactions and the gravitational energy. This energy release is expected to be few tens of $\text{MeV}/\text{nucleon}$, a typical energy scale of nuclear physics. In case of quark matter formation, the energy released is related to the difference in chemical potentials of d and s quarks. At the beginning of the quark matter formation, this difference is few hundred MeV . That is why the neutrinos produced during the chemical equilibration of the quark matter carry such a large amount of energy.

To conclude, we have argued that the nuclear matter having densities larger than $3-5 \times \rho_{\text{NM}}$ is likely to undergo phase transition from nuclear to quark matter. We have shown that after hadron-quark phase transition, the quark matter is not in chemical equilibrium in the beginning. The process of chemical equilibration, which is achieved by weak interactions, leads to production of s quarks. The dominant reaction for the equilibration is the nonleptonic weak process which converts d quarks into s quarks, although semi-leptonic weak processes also occur during and after chemical equilibration. The equilibration reaction is exothermic and therefore the temperature of the quark matter rises during the equilibration. A large number of neutrinos are produced during and after chemical equilibration. These neutrinos carry substantial amount of energy, thus cooling the quark matter. We also argue that, since the nuclear densities neutron stars are several times ρ_{NM} , it is likely that the quark matter is formed in these cores. We then conclude that the neutrinos produced during and after the formation of quark matter in these cores may help in the reheating of the mantle of the star during the supernova collapse.

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