STRANGENESS PRODUCTION IN NEUTRON STARS

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Abstract

Production of strange quarks in neutron stars is investigated in this work. Three cases, one in which the energy and neutrinos produced in the strangeness production reactions are retained in the reaction region, second in which the neutrinos are allowed to escape the reaction region but the energy is retained and the third in which both the energy and neutrinos escape the reaction region are considered. It is shown that the nonleptonic weak process dominates strange quark production while semileptonic weak processes, which produce neutrinos, lead to the cooling if the neutrinos escape the reaction region. It is found that the time required for the saturation of the strangeness fraction is between $10^{-7}$ and $10^{-5}$ sec, with the shorter time corresponding to the first two cases. About 0.2 neutrinos/baryon are emitted during the process in the first two cases where as the neutrino emission is somewhat suppressed in the last case. The average energy of the neutrinos produced in all the three cases is found to be several hundred $MeV$. 

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We also find that a large amount of energy is released during the strangeness production in the first two cases and this leads to the heating of the reaction region. Implications of the neutrino production are investigated.
1 Introduction

The lowest energy state of the quark matter should contain a significant amount of strange quarks. For example, if we assume equal mass $u$, $d$ and $s$ quarks, the strangeness fraction (defined as the ratio of strange quark and baryon densities) in the quark matter would be unity. Even if one considers a realistic value of $s$ quark mass (about 150-200 MeV larger than $u$ and $d$ quark masses\textsuperscript{[1]}), one can show that the strangeness fraction in a chemically equilibrated quark matter is close to unity for large enough baryon densities. Furthermore, it has been conjectured\textsuperscript{[2]} that the quark matter with nonzero strangeness fraction may even be the ground state of the dense strongly interacting matter. This conjecture is supported by the bag model calculations\textsuperscript{[3]} for a certain range of $s$ quark mass and strong coupling constant.

On the other hand, the strangeness fraction in hadronic matter (essentially the ratio of strange baryon and total baryon densities) is expected to be small. Most of the hadronic equations of state do not include strange baryons in the hadronic matter\textsuperscript{[4]} and the strangeness fraction for these equations of state is zero. Nonzero strangeness fraction in the hadronic matter can be generated by including strange baryons (and their interactions) in the calculations and/or by considering the possibility of kaon condensation. Strange baryons have been introduced by considering a Walecka model Lagrangian density which includes hyperons and their interactions with $\sigma$, $\omega$ and $\rho$ mesons\textsuperscript{[5]}. For a reasonable values of hyperon-meson coupling constants, the strangeness fraction of hadronic matter is found to be between 0.3 and 0.5\textsuperscript{[6]} for baryon densities between 0.3 and 0.6 $fm^{-3}$. The kaon condensation has been considered by a number of authors\textsuperscript{[7, 8, 9]}. The results of ref.\textsuperscript{[9]} show that, for baryon densities between 0.4 and 1 $fm^{-3}$, the $K^-$ fraction (which is same as the strangeness fraction) varies from 0.4 to 0.9
as as one of the parameters ($a_s m_s$) is varied from -134 MeV to -310 MeV. This parameter depends on the strangeness content of the nucleon (varying from 0 to 0.2). Now, the neutrino scattering experiments\[10\] indicate that the strangeness content of the nucleon is $\sim 0.06$. It therefore appears that, for reasonable value of the strangeness content of the nucleon, the strangeness fraction due to the kaon condensate could be about 0.5, a value similar to the one obtained in Walecka model calculation\[6\]. In this regard, one must note that hyperons are not included in the kaon condensation calculations and for a reliable estimate of the strangeness fraction in the presence of kaon condensate, this must be done. Here we would like to point out that total kaon strangeness fraction comes not only from the kaon itself but also from the kaon-nucleon interaction term as suggested by Fuji et al.\[11\]. They find a monotonic increase of strangeness number density with baryon density. But, here again the strangeness fraction obtained remains uncertain due to uncertainty inherent in the kaon-nucleon sigma term.

One expects that, if the baryon density in neutron stars is large enough, the interior of the neutron star may consist of the quark matter. If Witten’s conjecture\[2\] is correct, the whole star will eventually become a strange star having significant amount of the strangeness fraction. Otherwise, the star will be a hybrid star with a core of strange quark matter. Another interesting possibility, investigated by Glendenning\[12\], is that, due to the presence of two conserved charges (the electronic and baryonic charges) the hybrid star may consist of a mixed phase region consisting of a mixture of quark and hadronic matter. In any case, the quark matter may be produced in the neutron star during the evolution of the star, if the baryon density in the neutron star is large enough. And when this occurs, significant amount of strange quarks will be produced. In the first case, the whole star will eventually become a strange star. Even in case of the mixed phase\[12\], macroscopic quark matter objects (spheres, rods or sheets\[13\])
will be formed and strange quarks will be produced in these objects.

Some of the mechanisms for the production of the strange quark matter in neutron stars have been investigated by Alcock et al.\cite{14}. These authors have assumed that Witten’s conjecture\cite{2} holds and proposed that the production of the strange quark matter is initiated by an introduction of a stable strange matter seed in the neutron star. This seed then grows by ‘eating up’ baryons in the hadronic matter, eventually converting the neutron star to a star containing strange quark matter. The speed at which the ‘conversion front’, the boundary between quark and hadronic matter, moves in a neutron star has been calculated by Olinto\cite{15}, Olesen and Madsen\cite{16} and Heiselberg et al.\cite{17}. These calculations suggest that the speed of the conversion front is between $10 \text{ m/sec}$ and $100 \text{ km/sec}$. This means that the time required for the conversion of the neutron star to the quark star is between $0.1 \text{ sec}$ to $10^3 \text{ sec}$. In this scenario, the strange quark production takes place in the conversion front, which has a microscopic thickness (of few tens to few hundreds of fm) in comparison with the size of the star.

Collins and Perry\cite{18}, on the other hand, have assumed that the hadronic matter first gets converted into the (predominantly) two-flavour quark matter, which later decays into the three-flavour quark matter by weak processes. Presumably, this is what happens when the mixed phase\cite{12} is formed. That is, when the mixed phase is formed, the quark matter objects are spontaneously generated and strangeness production takes place in these objects. If the size of these objects is large enough, one can use plane wave states to calculate the strangeness production. Further more, Lugones et al.\cite{19} have argued that, even when one considers the production of the strange matter by seeding\cite{14}, the conversion process may proceed as a detonation instead of being a slow combustion process as assumed in the preceding paragraph. This is partly due to the instabilities of the conversion front under perturbations\cite{20}. In fact, it has been argued
that such a detonation may be responsible for the type II supernova explosions\cite{21}. In such situations, the strangeness production would be occurring in an extended volume of the star.

Although, in both of these scenarios, the weak interactions are responsible for the strangeness production, the detailed evolution of the strangeness fraction is expected to be quite different. In the former case, the production occurs in the conversion front, a thin shell having a thickness of few tens of fm, whereas in the later it occurs over an extended volume. Thus, in the former case, the reaction products, the neutrinos, and the energy generated during the strangeness production are likely to escape the reaction region. On the other hand, in the latter case, the heat generated may be trapped in the reaction region if the thermal conductivity of the quark matter is not large enough. This would lead to the heating of the reaction region. Also, the neutrinos produced in the reaction region may be trapped, as their mean free path is rather small in comparison with the dimensions of the reaction region. This means that the reaction rates are expected to be different for the two scenarios.

Recently, Dai et al.\cite{22} have calculated the time required for the strangeness production in quark matter. Unfortunately, their results are not reliable as incorrect reaction rates have been used in these calculations. Also, these authors do not consider the trapping of energy and neutrinos in the reaction region. In this paper, we want to present a detailed calculation in which these aspects are included. In our calculation, the reaction rates are determined from the basic weak interactions and the time required for the chemical equilibration of the quark matter has been calculated. We have also estimated the number of neutrinos produced and the energy liberated during chemical equilibration process. Our calculations show that the saturation of the strangeness fraction is reached in $10^{-7} \sim 10^{-5}$ sec. We also find that approximately 0.2 neutrinos/baryon are emitted.
during the equilibration process and the average energy of these neutrinos is between 150 and 200 MeV. If we assume that the energy generated during the strangeness production is trapped in the reaction region, the temperature of the reaction region increases to about 50 MeV.

The paper is organised as follows. The reaction rates are calculated in Section II. The results of the calculation are presented and discussed in Section III. Section IV is devoted to the conclusions.

2 Reaction Rates

The dominant reaction mechanism for the strange quark production in quark matter is the nonleptonic weak interaction process;

\[ u_1 + d \leftrightarrow u_2 + s. \]  

(1)

Initially, when the quark matter is formed, the d-quark chemical potential is much larger than s-quark chemical potential and the reaction in eq(1) converts d quarks into s quarks, releasing energy. The amount of energy released depends on the difference between d and s quark chemical potentials. When the two chemical potentials are almost equal, the net reaction rate due to the nonleptonic reaction becomes vanishingly small. The nonleptonic reaction alone cannot produce the chemical equilibrium since the chemical equilibration requires that the d-quark chemical potential must be equal to the sum of u-quark and electron chemical potentials. Thus semileptonic weak interactions,

\[ d(s) \rightarrow u + e^- + \nu_e \]  

(2)

and

\[ u + e^- \rightarrow d(s) + \nu_e, \]  

(3)
must be included. In addition, we find that semileptonic processes involving positrons,

\begin{equation}
    d(s) + e^+ \rightarrow u + \nu_e;
\end{equation}

and

\begin{equation}
    u \rightarrow d(s) + e^+ + \nu_e,
\end{equation}

must also be included. The reason being that, near the chemical equilibrium, the electron chemical potential is rather small (few MeV) and the temperature of the reaction region is expected to rise to few tens of MeV during the equilibration process. So the electrons are not degenerate and therefore, the processes involving the positrons must be included. It turns out that the semileptonic reactions do not contribute much to the strangeness production as such but these are responsible for the neutrino production. In the following, the constituents of the reaction region (u, d and s quarks and electrons) are assumed to be in thermal equilibrium at all times. This is reasonable since the strong and electromagnetic interactions are responsible for the thermal equilibration and their time scales are much smaller than the weak interaction time scale.

Before we go on to the calculation of the reaction rates, let us first consider the implications of the two scenarios of the strangeness production. If the strangeness production occurs in a thin boundary between quark and hadronic matter, the energy and neutrinos produced in weak reactions will leave the reaction region. Thus, the reaction will occur at constant temperature. When the strangeness production takes place in an extended volume, the situation is much more complicated. Depending on the thermal conductivity of the quark matter, the size of the reaction region and the strangeness saturation time scale, part of the energy produced will escape from the reaction region. As we shall see later, the strangeness-fraction saturation time is less than $10^{-5}$ sec. We
therefore expect that most of the energy produced during the strangeness production will be trapped in the reaction region and this would lead to heating of the reaction region. As for the neutrinos, their mean free path $\lambda_\nu$, in the quark matter of three times the nuclear matter density is estimated to be $0.5/E_\nu^2 \text{ km}$ where $E_\nu$ is the neutrino energy in $MeV$. Thus, except for the low energy neutrinos ($E_\nu < \text{ few tenth of MeV}$), the neutrinos will be stopped in the reaction region. This means that the weak reactions would occur in a neutrino background. Therefore following three cases of strangeness production are considered for a detailed calculation.

1. The energy and neutrinos produced in the reaction are retained in the reaction region. The momentum distribution of the neutrinos is assumed to be that of noninteracting Fermi gas.

2. The energy produced in the reaction is retained in the reaction region but the neutrinos are assumed to escape.

3. All the energy produced is assumed to be lost to the surroundings and the temperature of the reaction region is maintained at a fixed value.

It should be noted that in the first case, the internal energy of the system remains constant. Thus, in this case, the temperature of the reaction region increases monotonically during equilibration process. We have assumed a noninteracting Fermi gas distribution function for the neutrinos in case 1. Strictly speaking, this is not correct since the neutrinos are not expected to reach thermal equilibrium quickly, as they interact through weak interactions. Further more, the low energy neutrinos can leave the reaction region, thus altering the distribution function. However, as we shall find later, the results for

\footnote{The mean free path is estimated using formula $\lambda_\nu = \frac{1}{n_B \sigma}$, where $n_B$ the baryon density and $\sigma$ is the scattering cross section ($q\nu \rightarrow q\nu$).}
the cases 1 and 2 are almost identical. In the second case, part of the internal energy is lost to the escaping neutrinos. In this case, the nonleptonic weak reaction leads to heating and semileptonic weak reactions lead to cooling of the reaction region.

The reaction rates of the strangeness production reactions are calculated using standard weak interaction Lagrangian\[^{23}\]. For the second and third case mentioned above, these rates are,

\[
R_{d \rightarrow s} = C_{ds} \int p_d p_u p_v d p_d d p_u d p_v \delta(\epsilon_d + \epsilon_u - \epsilon_u - \epsilon_s) \\
\times \frac{1}{e(\epsilon_d - \mu_d)/T + 1} \frac{1}{e(\epsilon_u - \mu_u)/T + 1} \frac{1}{e(\epsilon_u - \mu_u)/T + 1} \frac{1}{e(\epsilon_u - \mu_u)/T + 1} \\
\times \int_{\min{\{|p_d + p_u|, |p_u + p_v|\}}}^{\max{\{|p_d - p_u|, |p_u - p_v|\}}} dP \left(1 + \frac{p_u^2 + p_v^2 - P^2}{2\epsilon_d \epsilon_u}\right) \left(1 + \frac{p_v^2 + p_\nu^2 - P^2}{2\epsilon_d \epsilon_\nu}\right)
\]

\[
R_{u \rightarrow d (u \rightarrow s)}(e^-) = C_{ud} C_{us} \int p_u p_v p_u p_d d p_v d p_u d p_v d p_d d p_\nu \delta(\epsilon_u + \epsilon_e - \epsilon_\nu - \epsilon_d(s)) \\
\times \frac{1}{e(\epsilon_u - \mu_u)/T + 1} \frac{1}{e(\epsilon_e - \mu_e)/T + 1} \frac{1}{e(\epsilon_d(s) - \mu_d(s))/T + 1} \\
\times \int_{\min{\{|p_u + p_v|, |p_d(s) + p_\nu|\}}}^{\max{\{|p_u - p_v|, |p_d(s) - p_\nu|\}}} dP \left(1 + \frac{p_u^2 + p_\nu^2 - P^2}{2\epsilon_u \epsilon_\nu}\right) \left(1 + \frac{p_d(s)^2 + p_\nu^2 - P^2}{2\epsilon_d(s) \epsilon_\nu}\right)
\]

\[
R_{d \rightarrow u (s \rightarrow u)}(e^-) = C_{du} C_{us} \int p_d(s) p_u p_v p_u d p_d d p_v d p_\nu \delta(\epsilon_d(s) - \epsilon_u - \epsilon_e - \epsilon_\nu) \\
\times \frac{1}{e(\epsilon_d(s) - \mu_d(s))/T + 1} \frac{1}{e(\epsilon_u - \mu_u)/T + 1} \frac{1}{e(\epsilon_\nu - \mu_\nu)/T + 1} \\
\times \int_{\min{\{|p_d(s) + p_v|, |p_d(s) + p_\nu|\}}}^{\max{\{|p_d(s) - p_v|, |p_d(s) - p_\nu|\}}} dP \left(1 - \frac{p_d(s)^2 + p_\nu^2 - P^2}{2\epsilon_d(s) \epsilon_\nu}\right) \left(1 - \frac{p_d(s)^2 + p_\nu^2 - P^2}{2\epsilon_d(s) \epsilon_\nu}\right)
\]

where \(C_{ds} = \frac{18 G_F^2 \sin^2 \theta_C \cos^2 \theta_C}{(2\pi)^2}\), \(C_{ud} = C_{du} = \frac{6 G_F^2 \cos^2 \theta_C}{(2\pi)^2}\), \(C_{su} = C_{us} = \frac{6 G_F^2 \sin^2 \theta_C}{(2\pi)^2}\), \(G_F\) is the weak decay constant and \(\theta_C\) is the Cabibbo angle and \(\epsilon_i\) and \(\mu_i\) are energies and chemical potentials of the \(i\)-th species \((i = u, d, s, e)\). We have taken quark-gluon interaction upto first order in strong coupling constant\[^{23}\]. The rate \(R_{s \rightarrow d}\) is calculated by interchanging \(d\) and \(s\) quarks and the rates involving positrons are calculated by replacing \(\mu_e\) by \(-\mu_e\) in the Fermi functions. In the presence of the neutrino background,
case 1, the rate equations are modified by multiplying neutrino and antineutrino Fermi distribution functions in eq(7) and eq(8) respectively.

Approximate analytic results for these rates have been obtained for the massless particles and for temperatures small compared with chemical potentials appearing in eqs(6,7,8) above. For the massive quarks and when the strong interaction between quarks are included, such approximate rates are not available. In this regard, we would like to note that Dai et al. [22] use reaction rates obtained by generalizing Iwamoto formulae for the non-equilibrium cases [25]. Thus, the reaction rates in [22] are proportional to $T^5$, where as, when $\mu_d \neq \mu_s$, then for the small $T$ the reaction rates should depend on the chemical potential difference and should not vanish in $T \to 0$ limit. As we shall see later, the difference between our reaction rates and those of Dai et al. lead to different conclusions regarding neutrino emission. To compute the reaction rates on has to perform the integrals in the eqs(6,7,8). In these equations the $P$-integral can be done analytically. The energy delta function is used to perform one of the remaining four integrals. As a result the eqs(6,7,8) reduce to three dimensional integrals. These are evaluated numerically using extended Simpson’s rule. We have ensured that the numerically calculated results agree with the approximate analytic results for massless particles at small temperatures. Note that the energy carried away by the neutrinos and antineutrinos (the neutrino emissivities $\epsilon_\nu$ and $\epsilon_\bar{\nu}$) is calculated by including the neutrino energy in the integrands of eq(7) and eq(8) respectively.

The rate of change of densities of the constituents (u, d, s quarks and electrons) are obtained from the reaction rates given above. These are,

$$\frac{dn_u(t)}{dt} = R_{d\to u}(e^-) + R_{s\to u}(e^-) - R_{u\to d}(e^-) - R_{u\to s}(e^-)$$

$$+ R_{d\to u}(e^+) + R_{s\to u}(e^+) - R_{u\to d}(e^+) - R_{u\to s}(e^+)$$

\[ (9) \]
\[
\frac{dn_d(t)}{dt} = R_{s \to d} - R_{d \to s} - R_{d \to u}(e^-) + R_{u \to d}(e^-) \\
- R_{d \to u}(e^+) + R_{u \to d}(e^+) 
\]

(10)

The reactions in eqs(6,7,8) satisfy charge and baryon number conservation. Thus the rate of change of s quark and electron densities are known from eq(9,10). In addition, when the neutrinos are allowed to escape the reaction region, the internal energy of the system decreases and the rate of decrease of the internal energy is given by,

\[
\frac{d\epsilon}{dt} = -\epsilon_\nu - \epsilon_\tau 
\]

(11)

The calculation of the evolution of the constituent densities proceeds as follows. Initially, ( time $t = 0$ ), we assume that the quark matter having same chemical composition as that of the hadronic matter is formed. This gives the initial condition on quark and electron densities and their chemical potentials. The initial temperature is varied between 5 and 20 MeV. The internal energy and number densities of the constituents at later time are calculated by integrating the rate equations(eqs(9,10,11)) numerically using Runge-Kutta method. Assuming the thermal equilibrium, the chemical potentials of the constituents and the temperature are determined at each instant of time. Note that these are required for the calculation of the reaction rates and neutrino emissivities. The calculation is continued till the strangeness fraction saturates. The results of the calculation are discussed in the following section.

3 Results And Discussions

The calculations have been performed for a range of baryon densities ( 0.4 - 0.8 fm$^{-3}$), strange quark masses ( 150 - 200 MeV ) and strong coupling constants ( 0.1 - 0.5 ).
For a detailed discussion, the strange quark mass of 150 MeV and the strong coupling constant of 0.1 has been chosen. The results for other parameter sets are similar. The parameter set used by Dai et al.\cite{22} \((n_B = 0.4 f m^{-3}, \text{strange quark mass of 200 MeV and strong coupling constant 0.17})\) has also been included in the discussion. This baryon density corresponds to the baryon density at the center of the neutron star of 1.4 M\(_{\odot}\).

The knowledge of the initial and final values of energy/baryon (or equivalently, the energy density) could be of interest. For example, for the parameter set \((n_B = 0.4 f m^{-3}, \text{strange quark mass = 150 MeV, strong coupling constant of 0.1 and } B^{1/4} = 150 \text{ MeV})\) the initial and final energy/baryon is 1100 MeV and 970 MeV respectively\footnote{The bag pressure term does not affect the difference in the energy densities. In any case, the bag energy is a small fraction of the total energy density at these baryon densities}. Thus, 130 MeV of energy/baryon is liberated during the strangeness production. Part of this energy is carried by the neutrinos and rest is used in heating of the reaction region. The latent heat produced during the hadron-quark phase transition is, however, not included in our calculation.

Let us now consider the first two cases. The time dependence of the temperature and strangeness fraction are shown in Fig 1. The figure shows that for both the cases the strangeness fraction attains its saturation value in a very short time \((\sim 10^{-7} \text{ sec})\). The time required for the chemical equilibration as well as the strangeness saturation time is about the same for the two cases. Although not shown here, the reaction rates for the two cases are also almost same. This implies that the strangeness production does not depend very much on whether the neutrinos are stopped in the reaction region or not. As for the temperature, the figure shows that, the temperature of the reaction region rises to about 50 MeV in \(\sim 10^{-7} \text{ sec}\) for case 1. After chemical equilibration, the temperature of the reaction region remains constant. For the second case, the temperature reaches
a peak value of about 45 $MeV$ after about $10^{-8} \ sec$ and later it continues to fall. The peak value of the temperature is about 10% smaller than the temperature obtained in case 1. Initially, the time dependence of the temperature is similar for the two cases. The smaller rise of the temperature and the decrease of the temperature at later times in the second case is because of the loss of the internal energy to the neutrinos which are assumed to escape the reaction region.

The reaction rates for the case 2 are plotted in Fig 2. We do not show the reaction rates for the case 1 as these are practically same as those of case 2. This figure shows that the reaction rate of the nonleptonic weak process is several orders of magnitude larger than the semileptonic rates. Thus, the nonleptonic weak process dominates the strangeness production till the strangeness fraction reaches saturation value. Afterwards the nonleptonic weak rate drops sharply. It is interesting to note that initially, the rates $R_{u \rightarrow d}(e^-)$ and $R_{u \rightarrow s}(e^-)$ are much larger than other semileptonic rates. This is because of the large initial value of the electron chemical potential. At later times, when the temperature reaches the peak value, $R_{d \rightarrow u}(e^+)$ and $R_{s \rightarrow u}(e^+)$ are comparable to $R_{u \rightarrow d}(e^-)$ and $R_{u \rightarrow s}(e^-)$ respectively. The behaviour of the reaction rates clearly shows that the semileptonic processes do not contribute much to the strangeness production. Initially, the primary mechanism of the strangeness production is the nonleptonic process in which $d$ quarks are converted to $s$ quarks. Later, when the semileptonic rates are comparable to the nonleptonic rate, the semileptonic reactions do not alter the $s$ quark density very much since the strangeness fraction has already saturated. In other words, the primary mechanism of $s$ quark production is the nonleptonic weak process with semileptonic weak processes playing a minor role. The semileptonic processes, however, contribute to the neutrino production. This also leads to the cooling of the reaction region in case 2.
The reaction rates and strangeness fraction when temperature is kept at 10 \( MeV \) are plotted in Fig 3. In this case also the nonleptonic weak interaction dominates. The figure shows that the time required for the saturation of strangeness fraction is larger ( \( \sim 10^{-5} \) sec ). Furthermore, the time required for the chemical equilibration is even larger ( about 0.1 sec ). This is because of the small values of the rates \( R_{u \rightarrow d} \) and \( R_{u \rightarrow s} \). Thus we find that the chemical potentials of \( d \) and \( s \) quarks become equal earlier but the chemical equilibrium ( \( \mu_d(\mu_s) = \mu_u + \mu_e \) ) is reached at much later time. Similar results are obtained for the temperature of the reaction region ranging between 5 and 20 \( MeV \). It must be noted that the choice of the temperature in this case is somewhat uncertain.

We have noted earlier that, when the energy is retained in the reaction region, the initial rise in the temperature of the reaction region is rapid. For example, figure 1 shows that the temperature rises to 20 \( MeV \) in \( 10^{-9} \) sec. Therefore, it is reasonable to assume a temperature of 10 - 20 \( MeV \) in the reaction region. The calculations show that the strangeness saturation time decreases with the increase in the temperature.

The results for different baryon densities, and for different values of the initial strangeness fraction are summarised in Table I. Case I and II correspond to zero and nonzero initial strangeness fraction respectively. The initial value of strangeness fraction in case II is obtained from Walecka model calculations [3]. Case III corresponds to the parameter set of [22] and the case IV corresponds to the situation when temperature is held fixed. Table I shows that the saturation time increases by orders of magnitude when the temperature of the reaction region is held constant. The time required for the saturation decreases when the initial strangeness fraction is nonzero and when the baryon density is increased. From the results displayed in Table I, one can conclude that the time required for the saturation of strangeness fraction varies between \( 10^{-7} \) and \( 10^{-5} \) sec, with the larger time corresponding to the constant temperature case.
The number of neutrinos emitted during the strangeness production and their average energy is also shown in Table I. We find that 0.07 to 0.25 neutrinos/baryon are emitted during strangeness production and average energy per neutrino is between 150 and 200 MeV. The neutrino emission is smaller for the constant temperature case and at lower temperatures, the neutrino production further decreases. However, in constant temperature case, the neutrinos emitted after the saturation of the strangeness fraction are not included in the table. Thus, the actual neutrino number, in this case, would be somewhat larger than the values shown in Table I. The average energy of neutrinos appears to be rather large. This is because the neutrino energy is essentially related to the difference between $|\mu_u + \mu_e - \mu_d(\mu_s)|$, which is few hundred MeV in the beginning. In contrast to our results, Dai et al.\[22\] predict much more copious neutrino production with each neutrino carrying about 0.1 MeV of energy on the average. In their calculations, they use Iwamoto like formulae\[25\] in which the average neutrino energy is proportional to the temperature. Since they choose a temperature of 0.1 MeV, the average energy of the neutrinos in their calculations is $\sim 0.1 \text{ MeV}$.

Let us now consider the consequences of strangeness production in a neutron star. Consider the scenario in which the strangeness production takes place in a thin conversion front. Assuming that the whole star of mass 1.4 $M_\odot$ is converted into a strange star (a typical mass of a neutron star), about $10^{56}$ neutrinos will be produced during the conversion and the energy carried by these neutrinos will be about $2.5 \times 10^{52}$ ergs. In addition, a significant amount of energy will be produced in the form of heat during the conversion process. A rough estimate suggests that this would be about the same order of magnitude. Now, the time during which these neutrinos are produced is not given by the strangeness production time displayed in Table I, but is related to the time taken by the conversion front to traverse the star. This time has been estimated to be
between 0.1 and $10^3$ sec $^{[15, 16, 17]}$. The neutrinos produced during the conversion process cannot leave the star as their mean free path is much smaller than the radius of the star. For example, the mean free path of neutrinos in neutron and quark matter of three time nuclear matter density is about $0.1/E^2_{\nu}$ km$^{[26]}$ and $0.5/E^2_{\nu}$ km respectively. Thus, these neutrinos will lose their energy while percolating out of the star and during the process, more neutrino-antineutrino pairs will be produced. The situation is similar to what happens during the supernova explosion$^{[27]}$. The supernova calculations suggest that roughly 10 pairs of neutrinos are produced during percolation. Since the energy of neutrinos produced during the strangeness production is much larger ($\sim 200$ MeV vs $\sim 15$ MeV in supernova collapse), many more neutrino pairs will be produced. Thus, the number of neutrinos eventually escaping the star may be $10^{57}$ or larger.

Now consider the scenario in which the strangeness production takes place in an extended volume. In this case, only a part of the star is likely to be converted into the strange matter. As an example, let us assume that the mass of the strange quark matter formed in such a process is about 0.7 $M_\odot$. Then about $2 \times 10^{56}$ neutrinos will be emitted in $10^{-7}$ sec. The energy carried by these neutrinos will be about $5 \times 10^{52}$ ergs. Also, the quark matter will be heated to about 50 MeV of temperature. In this case also, the neutrinos produced will percolate outwards, producing neutrino-antineutrino pairs in the process. In contrast, the standard supernova calculations, in which quark matter formation is not included, predict that $\sim 10^{57}$ neutrinos produced and the average energy of these neutrinos is about 15 MeV$^{[27]}$. So, if quark matter is formed during the supernova collapse, the number of neutrino produced and the energy carried by these neutrinos will possibly be larger by an order of magnitude. Now, it is known that the prompt shock model$^{[29]}$, which is based on the hydrodynamical bounce, does not produce sufficient bounce for the supernova explosion$^{[30]}$. Hence, a delayed mechanism,
in which heating by an intense neutrino flux coming from the collapsed core\cite{28}, has been proposed as one of the mechanisms of supernova explosions. If the strange matter is formed during supernova collapse, the neutrinos produced during strangeness production would provide a significant addition to the neutrino flux, thus enhancing the delayed mechanism. Such a scheme has been proposed by Benvenuto and Hovarth\cite{21}.

From the preceding discussion, one can conclude that the strangeness production in a dense star will be followed by copious production of neutrinos and release of large amount of energy. It may be possible to observe the neutrinos produced in the strangeness production process. Particularly, if the strangeness production occurs in a collapsing supernova, the neutrinos produced may help in generating the shock required for the supernova explosion. However, it must noted that a detailed calculation of neutrino transport in quark and nuclear matter is required before quantitative estimates can be made.

4 Conclusions

The strangeness production when a neutron star gets converted to a strange star is studied in this work. In our calculation we consider three cases. These are a) the neutrinos and energy produced during the strangeness production are retained in the reaction region, b) the energy is retained in the reaction region but the neutrinos are allowed to escape and c) both the energy and neutrinos are allowed to escape. The first two correspond to the scenario in which the strangeness production occurs in an extended volume where as the last case corresponds to the scenario in which the production takes place in a thin conversion front. We find that, the strangeness production occurs in $10^{-7}$ sec in the first two cases and $10^{-5}$ sec in the last case. A large amount of energy
is produced during the production and this may raise the temperature of the reaction region to about 50 $MeV$. Thus, quark matter formation in a neutron star is a violent process in which a large amount of energy is released. The main reason for this is the large difference in the strangeness fraction of nuclear and quark matter (0.0 - 0.5 for the nuclear matter vs $\sim 1.0$ for the quark matter). About 0.2 neutrinos/baryon are emitted during this process and the average energy of these neutrinos is hundreds of $MeV$. Although these neutrinos cannot escape the star as their mean free path in hadronic and quark matter is rather small, these will percolate out, loosing their energy and producing large number of neutrino-antineutrino pairs in the process. It may be possible to detect these neutrinos. But a detailed calculation of neutrino transport in quark and nuclear matter is required to estimate the flux of these neutrinos.
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Table 1: The values of time required for the strangeness fraction saturation, energy/neutrino (Av. Energy), total neutrinos per baryon \( N_{\nu B} \) and total neutrinos \( N_{\nu} \) emitted from a star of mass \( 1.4M_\odot \) for four different cases are displayed.

| \( n_B \) \( (fm^{-3}) \) | \( T \) \( (MeV) \) | \( Time \) \( (seconds) \) | \( Av.\text{Energy} \) \( (MeV) \) | \( N_{\nu B} \) | \( N_{\nu} \) \( (MeV) \) | \( Cases \) |
|---|---|---|---|---|---|---|
| 0.45 | – | \( 2.41 \times 10^{-7} \) | 168.5 | 0.24 | \( 3.75 \times 10^{56} \) | |
| 0.60 | – | \( 1.21 \times 10^{-7} \) | 194.0 | 0.27 | \( 4.22 \times 10^{56} \) | (I) |
| 0.45 | – | \( 2.47 \times 10^{-7} \) | 162.6 | 0.17 | \( 2.66 \times 10^{56} \) | |
| 0.60 | – | \( 1.12 \times 10^{-7} \) | 182.9 | 0.15 | \( 2.34 \times 10^{56} \) | (II) |
| 0.40 | – | \( 2.22 \times 10^{-7} \) | 176.1 | 0.25 | \( 3.91 \times 10^{56} \) | (III) |
| 0.60 | 20.0 | \( 3.14 \times 10^{-6} \) | 140.0 | 0.07 | \( 1.09 \times 10^{56} \) | |
| 0.60 | 10.0 | \( 6.70 \times 10^{-5} \) | 185.4 | 0.03 | \( 0.47 \times 10^{56} \) | (IV) |
| 0.60 | 5.0 | \( 6.82 \times 10^{-5} \) | 227.9 | 0.008 | \( 0.12 \times 10^{56} \) | |
Figure 1: Time dependence of temperature and strangeness fraction are shown for density $0.6\ fm^{-3}$, (a) and (c) correspond to temperature and strangeness fraction for case 2 and (b) and (d) for case 1 respectively.

Figure 2: The reaction rates of nonleptonic and semileptonic weak processes till the strangeness fraction reaches saturation value are shown in lower half, where (a) is $u + e^- \rightarrow d + \nu_e$, (b) is $u + e^- \rightarrow s + \nu_e$, (c) is $d \rightarrow s$, (d) is $d + e^+ \rightarrow u + \bar{\nu}_e$ and (e) is $s + e^+ \rightarrow u + \bar{\nu}_e$. Here $n_B = 0.6\ fm^{-3}$ with nonzero initial strangeness. The other semileptonic reaction rates are much lower and are not shown here.

Figure 3: The upper half of the figure is strangeness fraction for fixed temperature $10\ MeV$. The reaction rates of nonleptonic and semileptonic weak processes till the strangeness fraction reaches saturation value are shown in lower half, where (a) is $u + e^- \rightarrow d + \nu_e$, (b) is $u + e^- \rightarrow s + \nu_e$, (c) is $d \rightarrow s$ and (d) is $u \rightarrow s + e^+ + \nu_e$. Here $n_B = 0.6\ fm^{-3}$ with nonzero initial strangeness. The other semileptonic reaction rates are much lower and are not shown here.