Diffusion of Neutrinos in Proto-Neutron Star Matter with Quarks

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Abstract

Neutrino opacities important in the evolution of a proto-neutron star containing quark matter are studied. The results for pure quark matter are compared with limiting expressions previously derived, and are generalized to the temperatures, neutrino degeneracies and lepton contents encountered in a proto-neutron star’s evolution. We find that the appearance of quarks in baryonic matter drastically reduces the neutrino opacity for a given entropy, the reduction being sensitive to the thermodynamic conditions in the mixed quark-hadron phase.

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A general picture of the early evolution of a proto–neutron star (PNS) is becoming well established. Neutrinos are produced in large quantities by electron capture as the progenitor star collapses, but most are temporarily prevented from escaping because their mean free paths are considerably smaller than the radius of the star. During this trapped-neutrino era, the entropy per baryon $s$ is about 1 through most of the star and the total number of leptons per baryon $Y_L = Y_e + Y_{\nu e} \simeq 0.4$. The neutrinos trapped in the core strongly inhibit the appearance of exotic matter, whether in the form of hyperons, a Bose (pion or kaon) condensate or quarks, due to the large values of the electron chemical potential. As the star cools, the neutrino mean free path increases, and the neutrinos eventually leak out of the star, on a timescale of 20-60 s. During deleptonization, neutrino diffusion heats the matter to an approximately uniform entropy per baryon of 2. If the strongly interacting components consist only of nucleons, the maximum supportable mass increases. In the case that hyperons, a Bose condensate...
(pion, kaon) or quarks appear in the core as the neutrinos leave, the maximum mass decreases with decreasing leptonic content. Neutron stars which have masses above the maximum mass for completely deleptonized matter are thus metastable, and will collapse into a black hole during deleptonization. Alternatively, if the mass of the neutron star is sufficiently small, the star remains stable and cools within a minute or so to temperatures below 1 MeV as the neutrinos continue to carry energy away from the star.

The way in which this picture is modified when the core of a PNS contains deconfined quark matter is only beginning to be investigated \cite{2,7–9}. In his seminal paper, Iwamoto \cite{10} noted that the non-degenerate $\nu$ mean free path in cold quark matter is about ten times larger than in nucleonic matter. We find that in PNS matter, in which quarks appear towards the end of deleptonization, similarly large enhancements persist even up to the largest relevant temperatures ($\sim 30 - 40$ MeV \cite{9}), inasmuch as quarks remain largely degenerate. On this basis, it can be anticipated that the presence of quark matter increases the neutrino fluxes while simultaneously decreasing the deleptonization time, relative to matter without quarks. In work to be reported elsewhere, we explore the possibility that such a change might be detected from a Galactic supernova in current and planned neutrino detectors. This would have direct implications for the theoretical understanding of the high-density regime of QCD which is inaccessible to high energy Relativistic Heavy-Ion Collider experiments, and, currently, to lattice QCD calculations at finite baryon density.

To perform detailed simulations of the neutrino signal from a PNS containing quark matter, as has already been done for matter containing nucleons, hyperons and/or a kaon condensate \cite{1–6}, consistent calculations of neutrino interactions in hot lepton-rich matter containing quarks are required. It is most likely that quarks exist in a mixed phase with hadrons \cite{7,9,11}. Steiner, et. al. \cite{9}, recently showed that the temperature of an adiabat decreases as a function of density in a mixed phase of quarks and nucleons. Because $\nu -$cross sections usually scale with $T^2$, this suggests that the presence of quark matter might influence the neutrino signal of a PNS with quarks.

In this work, we calculate the diffusion coefficients of neutrinos in a mixed phase of hadrons and quarks for the temperatures, neutrino degeneracies, and lepton contents likely to be encountered in the evolution of a PNS with quarks. We demonstrate that the cross sections for scattering and absorption
of neutrinos by nucleons, leptons, and quarks are reduced to two integrals, whose integrands are products of simple polynomials and thermal distribution functions. The limiting behaviors of the cross sections, for non-degenerate and degenerate neutrinos, respectively, are compared with previous calculations [10] in the case of pure quark matter. For simulations of PNS evolution using the diffusion approximation, diffusion coefficients, which are energy weighted averages of neutrino cross sections, are required for matter in which quarks exist in a mixed phase with hadrons. We examine the relevant diffusion coefficients for two thermodynamic conditions especially germane to PNS evolution. The first situation is when neutrinos are trapped, \( s \approx 1 \), and the total lepton content of the matter \( Y_L = Y_e + Y_{\nu e} \) (which measures the concentrations of the leptons per baryon) is approximately 0.4. We also consider the situation when neutrinos have mostly left the star and the matter has been diffusively heated \( (Y_\nu \approx 0, s \approx 2) \). We discuss the impact these results might have upon the evolution of a PNS which contains quarks in a mixed phase.

For the \( \nu \)–energies of interest, the neutral and charged current \( \nu \)–interactions with the matter in a PNS are well described by a current-current Lagrangian [12]

\[
\mathcal{L} = \frac{G_F^2}{\sqrt{2}} \left( \overline{\psi}_\nu (1 - \gamma_5) \psi_p (3) \right) \left( \overline{\psi}_p (2) (\mathcal{V} - \mathcal{A} \gamma_5) \psi_p (4) \right) + \text{H.C.},
\]

where \( \mathcal{V} \) and \( \mathcal{A} \) are the vector and axial–vector coupling constants (See Table 1) and \( G_F \approx 1.17 \text{ GeV}^{-2} \) is the Fermi weak coupling constant. The subscripts \( i = 1, 2, 3, \) and \( 4 \) on the four-momenta \( p_i \) denote the incoming neutrino, the incoming lepton, baryon or quark, the outgoing neutrino (or electron), and the outgoing lepton, baryon or quark, respectively. The charged current reactions contribute to absorption of neutrinos by baryons or quarks and scattering of neutrinos with leptons of the same generation.

The neutral current interactions contribute to scattering of neutrinos with leptons and baryons or quarks. The charged current contribution to neutrino–lepton scattering in the same generation can be transformed into the neutral current form, which modifies the constants \( \mathcal{V} \) and \( \mathcal{A} \) for that case. For completeness, the values of \( \mathcal{V} \) and \( \mathcal{A} \) for electron neutrinos are given in Table 1. The corresponding values for reactions with electron anti-neutrinos are obtained by the replacement \( \mathcal{A} \rightarrow -\mathcal{A} \).

From Fermi’s golden rule, the cross section per unit volume (or inverse mean free path) is

\[
\sigma = g \int \frac{d^3 p_2}{(2\pi)^3} \int \frac{d^3 p_3}{(2\pi)^3} \int \frac{d^3 p_4}{(2\pi)^3} W_{f_1 f_2} (1 - f_3) (1 - f_4) (2\pi)^4 \delta^4 (p_1 + p_2 - p_3 - p_4) ,
\]

where...
where the degeneracy factor \( g \) is 6 (3 colors \( \times 2 \) spins) for reactions involving quarks while it is 2 (2 spins) for baryons of a single species. The Fermi–Dirac distribution functions are denoted by \( f_i = \left[ 1 + \exp \left( \frac{E_i - \mu_i}{T} \right) \right]^{-1} \), where \( E_i \) and \( \mu_i \) are the energy and chemical potential of particle \( i \). The transition probability \( W_{fi} \), summed over the initial states and averaged over the final states, is

\[
W_{fi} = \frac{G_F^2}{E_1 E_2 E_3 E_4} \left[ (\mathcal{V} + \mathcal{A})^2 (p_1 \cdot p_2) (p_3 \cdot p_4) + (\mathcal{V} - \mathcal{A})^2 (p_1 \cdot p_4) (p_3 \cdot p_2) - (\mathcal{V}^2 - \mathcal{A}^2) (p_1 \cdot p_3) (p_4 \cdot p_2) \right]. \tag{3}
\]

Utilizing \( d^3 p_i = p_i^2 \, dp_i d\Omega_i = p_i E_i \, dE_i d\Omega_i \) and integrating over \( E_4 \), Eq. (2) may be cast in the form

\[
\frac{\sigma}{V} = \frac{g G_F^2}{32 \pi^5} \int_{M_2}^\infty dE_2 \int_0^\infty dE_3 \int_0^\infty d\vec{p}_2 \, |\vec{p}_2| \left[ (\mathcal{V} + \mathcal{A})^2 I_a + (\mathcal{V} - \mathcal{A})^2 I_b + (\mathcal{V}^2 - \mathcal{A}^2) I_c \right], \tag{4}
\]

where \( S = f_2 (1 - f_3) (1 - f_4) \), \( M_i \) is the mass of particle \( i \), and

\[
I_a = \int d\Omega_2 d\Omega_3 d\Omega_4 \, \delta^3 (p_1 + p_2 - p_3 - p_4) (p_1 \cdot p_2) (p_3 \cdot p_4). \tag{5}
\]

The integrals \( I_b \) and \( I_c \) are defined similarly to \( I_a \), and all can be performed analytically. Explicitly,

\[
I_a = \frac{\pi^2}{3 p_1 p_2 p_3 p_4} \left[ 3 \left( P_{\text{max}}^5 - P_{\text{min}}^5 \right) - 10 (A + B) \left( P_{\text{max}}^3 - P_{\text{min}}^3 \right) + 60 AB (P_{\text{max}} - P_{\text{min}}) \right], \tag{6}
\]

where

\[
2A = 2E_1 E_2 + p_1^2 + p_2^2, \quad 2B = 2E_3 E_4 + p_3^2 + p_4^2,
\]

\[
P_{\text{min}} = \max \left( |p_1 - p_2|, |p_3 - p_4| \right), \quad P_{\text{max}} = \min (p_1 + p_2, p_3 + p_4). \tag{7}
\]

In the above expression, \( p_i \equiv \vec{p}_i \). \( I_b \) and \( I_c \) are defined to be the same as \( I_a \), but with appropriate replacements:

\[
I_b \equiv I_a (p_2 \leftrightarrow p_4, E_2 \leftrightarrow -E_4), \quad I_c \equiv I_a (p_2 \leftrightarrow p_3, E_2 \leftrightarrow E_3). \tag{8}
\]

In Eqs. (7) and (8), \( E_4 = E_1 + E_2 - E_3 \) and \( |\vec{p}_4| = \sqrt{(E_1 + E_2 - E_3)^2 - M_4^2} \). Eqs. (4) through (8) are the principal results of this work and enable us to compute, for arbitrary conditions of neutrino degeneracy and matter’s temperature, the neutrino diffusion coefficients required in simulations of PNSs containing quark matter. We note that similar techniques were employed to calculate \( \nu \)-emissivities in cold catalyzed neutron stars in Refs. [13][14].
In limiting cases when the neutrinos are either degenerate or non-degenerate, and the quarks, which are always degenerate in PNSs, are massless, simple analytical expressions for the cross section may be obtained by replacing momenta by Fermi momenta and energies by chemical potentials in the integrals $I_a$, $I_b$, and $I_c$. For the sake of comparing such limits with the general results obtained from Eq. (4), we record various limiting forms obtained earlier in Refs. [10,15].

(1) **Scattering of degenerate neutrinos:** The result is the same as for neutrino-electron scattering:

$$\frac{\sigma_S}{V} = \frac{G_F^2 \mu_2^3}{5\pi^3} \left[ \frac{2(xE_1)}{\mu_2} \right] \left[ (E_1 - \mu_1)^2 + \pi^2 T^2 \right] \left[ (\nu^2 + A^2) (10 + x^2) + 5 (2\nu A) x \right],$$

where $x = \min(E_1, \mu_2)/\max(E_1, \mu_2)$. Here, and in the following, we have removed the factor $1 - f_1 = \left( 1 + e^{-(E_1 - \mu_1)/T} \right)^{-1}$ from [10,15] to obtain transport mean free paths.

(2) **Scattering of non-degenerate neutrinos:** The inverse scattering mean free path is

$$\frac{\sigma_S}{V} = \frac{G_F^2 \mu_1^3}{5\pi^3 \mu_2^2},$$

when it is additionally assumed that $\mu_2$ is large compared to $E_1$.

(3) **Absorption of degenerate neutrinos:**

$$\frac{\sigma_A}{V} = \frac{2G_F^2 \mu_3^3}{5\pi^3 \mu_1^4} \left[ 10\mu_4^2 + 5\mu_4 \mu_3 + \mu_3^2 \right] \left[ (E_1 - \mu_1)^2 + \pi^2 T^2 \right].$$

(4) **Absorption of non-degenerate neutrinos:** The general result is greatly simplified by additionally assuming that the quark chemical potentials are modified by perturbative gluon exchange:

$$\frac{\sigma_A}{V} = \frac{16}{\pi^4} \alpha_s G_F^2 p_{F_2} p_{F_3} p_{F_4} \left[ E_1^2 + \pi^2 T^2 \right].$$

Representative cross sections from Eq. (4) are compared with the limiting forms in Eqs. (9)–(12) in Fig. 1. Degenerate neutrinos are assumed in this figure to have $\mu_\nu >> T$ and non-degenerate neutrinos are assumed to have $\mu_\nu \approx 0$. In the regions where they were expected to be valid, namely $E_\nu/T >> 1$ for degenerate absorption and scattering, and also non-degenerate scattering, and $E_\nu \approx T$ for non-degenerate absorption, the limiting forms give adequate representations of the general results. However, significant deviations occur in the cases of non-degenerate absorption when $E_\nu \neq T$, and for degenerate absorption and non-degenerate scattering when $E_\nu << T$. The deviation for non-degenerate absorption is due to the neglect of $p_\nu$ in the momentum conservation condition in Eq. (2) in
Ref. [10] (which is appropriate for cold catalyzed stars, but not for hot matter in PNSs), which limits its applicability to the region $E_{\nu} \approx T$. The other two deviations are simply due to the assumption in Ref. [10] that $E_{\nu} >> T$.

The weak interaction timescales of neutrinos are much smaller than the dynamical timescale of PNS evolution, which is on the order of seconds. Thus, until neutrinos enter the semi-transparent region, they remain close to thermal equilibrium in matter. Hence, neutrino propagation may be treated in the diffusion approximation with the differential equations for the flux of energy ($F_{\nu}$) and lepton number ($H_{\nu}$) [5]:

$$H_{\nu} = -\frac{T^2 e^{-\Lambda - \phi}}{6\pi^2} \left[ D_4 \frac{\partial}{\partial r} \left( T e^\phi \right) + \left( T e^\phi \right) D_3 \frac{\partial \eta(r)}{\partial r} \right] \quad \text{and} \quad F_{\nu} = -\frac{T^3 e^{-\Lambda - \phi}}{6\pi^2} \left[ D_3 \frac{\partial}{\partial r} \left( T e^\phi \right) + \left( T e^\phi \right) D_2 \frac{\partial \eta(r)}{\partial r} \right],$$

where $\Lambda$ and $\phi$ are general relativistic metric functions, $\eta = \mu_{\nu}/T$ and $D_2$, $D_3$, and $D_4$ are diffusion coefficients decomposed as

$$D_2 = D_2^{e\nu} + D_2^{\bar{e}\nu}, \quad D_3 = D_3^{e\nu} - D_3^{\bar{e}\nu}, \quad D_4 = D_4^{e\nu} + D_4^{\bar{e}\nu} + 4D_4^{\mu\tau}. \quad (13)$$

The transport of $\mu$ and $\tau$ neutrinos and anti-neutrinos are well approximated [1] by assuming that they contribute equally to $D_4$ and are represented by $D_4^{\mu\tau}$. These coefficients are defined in terms of the energy dependent diffusion coefficient $D^p(E_{\nu})$ by

$$D^p_n = \int_0^\infty dx \ x^n D^p(E_1) f(E_1) [1 - f(E_1)], \quad (14)$$

where $x = E_1/T$, and the superscript $p$ denotes either the electron neutrino, the anti-electron neutrino, or the $\mu$ and $\tau$ neutrinos and their antineutrinos. In turn, the energy dependent diffusion coefficient is obtained directly from the cross sections per unit volume through

$$(D^p(E_1))^{-1} = \frac{1}{1 - f_1} \left[ \sum_{r=(p,L)} \frac{\sigma_r}{V} + \chi \sum_{r=(p,H)} \frac{\sigma_r}{V} + (1 - \chi) \sum_{r=(p,Q)} \frac{\sigma_r}{V} \right], \quad (15)$$

where the $(p, L)$, $(p, H)$, and $(p, Q)$ represent the sum over all the reactions of particle $p$ with leptons, hadrons, or quarks, respectively. The factor $(1 - f_1)^{-1}$ ensures detailed balance, and $\chi$ is the volume fraction of matter in the hadronic phase.
Note that in the case of scattering, the Pauli blocking factor corresponding to the outgoing neutrino is omitted, since the neutrino distribution function is not always known a priori unless a full transport scheme is employed. It is possible, however, to devise a simplified scheme \cite{5} in which the dependence on the neutrino distribution function is minimized. Such a scheme is valid only when scattering from light particles (either electrons or quarks) does not dominate the opacity. Our results below show that this requirement is indeed met, because absorption dominates over scattering by a factor of 2 to 5 at all densities interior to the central densities of PNSs investigated here.

We describe neutron star matter at finite density and temperature using the Gibbs phase rules \cite{9,11}. The conditions of baryon number density and charge conservation in the mixed phase are

\[
    n_B = \chi n_B^H + (1 - \chi) n_B^Q, \quad 0 = \chi n_c^H + (1 - \chi) n_c^Q + n_c^L,
\]

where \(n_B\) and \(n_c\) are the baryon number and charge densities, respectively; \(H\), \(Q\), and \(L\) denote hadrons, quarks, and leptons. Since the dynamical time scale is much longer than the weak interaction time scale, beta equilibrium implies that the various chemical potentials satisfy the relations

\[
    \mu_e - \mu_{\nu_e} = \mu_\mu - \mu_{\nu_\mu}; \quad \mu_B = b_i \mu_n - q_i (\mu_e - \mu_{\nu_e}), \quad (16)
\]

where \(b_i\) and \(q_i\) are the baryon number and electric charge of the hadron or quark of species \(i\). When the neutrinos are trapped, the electron lepton number \(Y_L = (n_e + n_{\nu_e})/n_B\) is initially fixed at a value \(\simeq 0.4\) as suggested by collapse calculations.

Hadronic matter is described using a field-theoretical description in which nucleons interact via the exchange of \(\sigma\), \(\omega\), and \(\rho\) mesons. The meson-nucleon couplings and the couplings of the \(\sigma\) self-interaction terms are determined by reproducing the empirical properties of nuclear matter, \(E_B = -16.0\) MeV, \(M^*/M = 0.6\), \(K = 250\) MeV, \(a_{sym} = 32.5\) MeV, and \(n_0 = 0.16\) fm\(^{-3}\). Quark matter is described using the MIT Bag model, with a bag constant of \(B = 200\) MeV/fm\(^3\). (Similar results are obtained with four-quark interactions in the Nambu–Jona-Lasinio model \cite{9}.) The mixed phase is assumed to be homogeneous. For more details of the calculation of the EOS, see Ref. \cite{9}.

The cross sections per unit volume (or inverse mean free paths) for \(\nu_e\) scattering and absorption are shown in Fig. \cite{2} for the two stages of PNS evolution described before. It is important to recall
that these curves are drawn under conditions of fixed entropy. (Constant entropy adiabats shown in Fig. 3 of Ref. \[9\] are helpful to gain insights into the behavior of the cross sections shown here.) The individual contributions from the different reactions in the pure nucleon and quark phases (thin lines) and in the mixed phase (thick lines) are marked in this figure. The vertical dashed lines show the central densities of 1.4\( M_{\odot} \) and the maximum mass configurations, respectively. Notice that quarks exist only in the mixed phase; the pure quark phase occurs at densities above the central densities of maximum mass stars in all cases shown here.

In general, for a given density and temperature, the pure quark-phase opacity (or equivalently the cross section per unit volume) is less than that of hadrons due to the former’s smaller matrix elements sampled by a relativistic phase space. In addition, for a given entropy and density, pure quark matter favors a lower temperature than hadronic matter \[9\]. It is natural, therefore, that within the mixed phase region of hadrons and quarks, the net cross section per unit volume either flattens or decreases with increasing density. The reduction of opacities from that of the pure hadronic phase is enhanced in the \( \nu \)-free case, reflecting the more extreme decrease of temperature across the mixed phase region in that case \[9\]. The precise density dependence of the net neutrino opacity depends upon the details of the mixed phase.

Note that the total absorption cross section is larger than the scattering cross section for both degenerate and nondegenerate situations. As discussed above, this justifies our approximate treatment of scattering in the calculation of the diffusion coefficients.

The diffusion coefficients most relevant for the PNS simulations, in matter with and without a mixed phase of hadrons and quarks, are \( D_2 \) and \( D_4 \), and these are shown in Fig. 3. Insofar as absorption dominates scattering, the behavior of these coefficients can be understood qualitatively by utilizing the limiting forms for neutrino absorption in the degenerate (Eq. (11)) and nondegenerate (Eq. (12)) cases, respectively. The actual behavior is somewhat more complicated, but this assumption will suffice for a qualitative interpretation of Fig. 3. In this case, the leading behaviors may be extracted to be

\[
D_2 \propto \lambda(\mu_\nu/T)(\mu_\nu/T)^2 \quad \text{and} \quad D_4 \propto \lambda(\mu_\nu/T = 0),
\]

where the mean free path \( \lambda = (\sigma/V)^{-1} \). In these equations, \( D_2 \) is evaluated under conditions of
extreme neutrino degeneracy and $D_4$ is evaluated assuming that $\mu_\nu = 0$. Thus, both $D_2$ and $D_4$ should simply reflect the inverse behavior of the cross section per unit volume, which decreases with increasing density in the pure phases, but increases within the mixed phase region.

Concerning the evolution of a PNS, we expect that the initial star, which is lepton rich, will not have an extensive mixed phase region. Only after several seconds of evolution will quark matter appear. In the newly-formed mixed phase region, the neutrino opacity will be substantially smaller than in the case in which a mixed phase region does not appear. However, due to the large $\nu -$optical depth of the PNS, neutrinos remain trapped, and no significant effect on emergent neutrino luminosities is expected at early times. As the star evolves, however, the relatively larger increase in opacity (note the increases in $D_4$ relative to $D_2$) and the growing extent of the mixed phase region eventually allows a larger flux of neutrinos, and thereby a more rapid evolution.

In summary, we have calculated neutrino opacities for matter containing quarks for the temperatures, neutrino degeneracies and lepton contents relevant for PNS simulations, employing Gibbs phase rules to construct a mixed hadron-quark phase. We find that, in the presence of quarks, neutrinos have a significantly smaller opacity and hence larger diffusion coefficients than those in purely hadronic matter at similar densities. These differences may have an observable impact on the neutrino flux from PNSs containing quark matter, but these differences are not expected to become apparent until the PNS is 10–20 s old. Simulations of PNSs with a mixed phase of hadrons and quarks are under investigation [16]. The influence of heterogeneous structures [17,18] and superfluidity [8] in matter will be addressed in future work.

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TABLE 1: The standard model charged and neutral current vector and axial–vector couplings of neutrinos to leptons, baryons, and quarks; $\theta_C$ is the Cabbibo angle ($\cos \theta_C = 0.973$), $\theta_W$ is the weak mixing angle ($\sin \theta_W = 0.231$), and $g_A = 1.23$ is the baryon axial–vector coupling constant.

| 1 + 2 $\rightarrow$ 3 + 4 | $V$ | $A$ |
|---------------------------|-----|-----|
| $\nu_e + \mu^- \rightarrow \nu_\mu + e^-$ | 1 | 1 |
| $\nu_l + n \rightarrow l^- + p$ | $\frac{1}{2} \cos \theta_C$ | $\frac{1}{2} g_A \cos \theta_C$ |
| Charged current | $\nu_l + d \rightarrow l^- + u$ | $\cos \theta_C$ | $\cos \theta_C$ |
| | $\nu_l + s \rightarrow l^- + u$ | $\sin \theta_C$ | $\sin \theta_C$ |
| | $\nu_e + e^- \rightarrow \nu_e + e^-$ | $\frac{1}{2} + 2 \sin^2 \theta_W$ | $\frac{1}{2}$ |
| | $\nu_e + \mu^- \rightarrow \nu_e + \mu^-$ | $-\frac{1}{2} + 2 \sin^2 \theta_W$ | $\frac{1}{2}$ |
| | $\nu_e + n \rightarrow \nu_e + n$ | $-\frac{1}{2}$ | $-\frac{1}{2} g_A$ |
| Neutral current | $\nu_e + p \rightarrow \nu_e + p$ | $\frac{1}{2} + 2 \sin^2 \theta_W$ | $\frac{1}{2} g_A$ |
| | $\nu_e + u \rightarrow \nu_e + u$ | $\frac{1}{2} - \frac{4}{3} \sin^2 \theta_W$ | $\frac{1}{2}$ |
| | $\nu_e + d \rightarrow \nu_e + d$ | $\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W$ | $-\frac{1}{2}$ |
| | $\nu_e + s \rightarrow \nu_e + s$ | $\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W$ | $-\frac{1}{2}$ |

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FIGURE CAPTIONS

Figure 1: $\nu_e$ cross sections per unit volume in pure quark matter, for $T = 5$ MeV. Solid lines show complete results from Eq. (4), and dashed lines indicate limiting forms from [10]. The labels “Degenerate” and “Non-Degenerate” refer to neutrinos. Upper panels show results for two times nuclear matter density, and the lower panels show results for a neutrino energy of 50 MeV ($\mu$ is the chemical potential of the incoming quark).

Figure 2: $\nu_e$ cross sections with various particles in matter containing a mixed phase of quarks and hadrons ($n_0 = 0.16$ fm$^{-3}$). The left panels show scattering cross sections for neutrinos with the indicated incoming hadrons, quarks, or leptons. Thick lines show the extent of the mixed phase region. The right panels show absorption cross sections on nucleons and quarks. The upper panels correspond to the neutrino-trapped era when $s = 1$ and $Y_L = 0.4$, and the lower panels to the time following deleptonization when $s = 2$ and $Y_\nu = 0$. The vertical dashed lines labelled $u_{1.4}$ and $u_{max}$ indicate the central densities of a $M_G = 1.4$ M$_\odot$ star and the maximum mass star ($M_G = 2.22$ M$_\odot$ for the upper panels and $M_G = 1.89$ M$_\odot$ for the lower panels), respectively.

Figure 3: Diffusion coefficients for the neutrino-trapped era (left panel) and hot deleptonized era (right panel). Thick lines show the extent of the mixed phase. Solid lines correspond to matter with a mixed phase, and dashed lines to matter containing only nucleons. The vertical dashed lines have the same meaning as in Fig. 2.
FIG. 1.
FIG. 2.
