Direct URCA Process in Neutron Stars

James M. Lattimer
Earth and Space Sciences Department, State University of New York at Stony Brook, Stony Brook, New York 11794

C. J. Pethick
NORDITA, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark
and Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

Madappa Prakash
Physics Department, State University of New York at Stony Brook, Stony Brook, New York 11794

Pawel Haensel
Copernicus Astronomical Center, 00-716 Warszawa, Poland

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We show that the direct URCA process can occur in neutron stars if the proton concentration exceeds some critical value in the range (11–15)%. The proton concentration, which is determined by the poorly known symmetry energy of matter above nuclear density, exceeds the critical value in many current calculations. If it occurs, the direct URCA process enhances neutrino emission and neutron star cooling rates by a large factor compared to any process considered previously.

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Neutron stars are born with interior temperatures of order 20–50 MeV, but rapidly cool via neutrino emission to temperatures of less than 1 MeV within minutes.[1] The long-term cooling of a neutron star consists of two periods: a neutrino cooling epoch which lasts until 10^5–10^6 yr and a subsequent photon cooling epoch. Although neutrino emission from a young neutron star was undoubtedly observed from SN 1987A, this kind of emission becomes undetectable from even close-by neutron stars after about 100 s. In the standard model, the surface temperatures of neutron stars, however, remain above 10^6 K for about 10^5 yr, so they are potentially observable in the x-ray or UV bands. Nevertheless, the thermal radiation from a neutron star has yet to be identified unambiguously. All positive observations to date[2] are for pulsars, and it is unclear how much of the observed emission is due to the pulsar phenomenon, to a synchotron-emitting nebula, or to the neutron star itself.

The so-called standard model of neutron star cooling is based upon neutrino emission from the interior that is dominated by the modified URCA process

$$(n,p)+p+e^- \rightarrow (n,p)+n+\nu_e\,,$$
$$(n,p)+n \rightarrow (n,p)+p+e^-+\bar{\nu}_e\,. \qquad (1)$$

The direct URCA process

$$n \rightarrow p+e^-+\bar{\nu}_e,\quad p+e^- \rightarrow n+\nu_e \qquad (2)$$

is not usually considered because the proton abundance is thought to be too small to allow simultaneous energy and momentum conservation.[3,4] If a pion[4,5] or kaon condensate,[6] or quark matter,[7] is present, neutrino emission is faster than by the modified URCA process. In this Letter we show that it is possible the direct URCA process occurs, and demonstrate that it would lead to more rapid cooling than any other process.

The minimum proton fraction for which the direct URCA process can occur is determined by the fact that at tempertures well below typical Fermi temperatures ($T_F \sim 10^{12}$ K), fermions participating in the process must have momenta close to the Fermi momenta p_{Fi}, where subscripts $i=n$, p, and e correspond to neutrons, protons, and electrons, respectively. Since neutrino and antineutrino momenta are $\sim kT/c \ll p_{Fi}$, the condition for momentum conservation is $p_{Fp}+p_{Fe} > p_{Fn}$. If matter consists only of neutrons, protons, and electrons, charge neutrality requires that $n_p = n_e$, where $n_i \propto p_{Fi}^3$ are the particle densities, and thus the condition becomes $2p_{Fp} > p_{Fn}$, or $n_n = 8n_p$, and the proton fraction $x = n_p/(n_p+n_n)$ at threshold is $x_c = \frac{1}{9}$.

To explore the dependence of the proton fraction on nuclear properties, we consider a schematic model. The energy per baryon ϵ may be expanded quadratically in the proton concentration x about its value for symmetric matter ($x=\frac{1}{2}$):

$$\epsilon(n,x) = \epsilon(n,\tfrac{1}{2}) + S_v(n)(1-2x)^2 + \cdots\,, \qquad (3)$$

where $n = n_n + n_p$ is the baryon density and S_v is the bulk symmetry-energy parameter, which is density dependent. At nuclear saturation density, $n_s \simeq 0.16$ fm^{-3}, this parameter can be estimated from nuclear masses[8] and has the value $S_v(n_s) \equiv S_0 \approx 27$–$36$ MeV. The matter we are concerned with is degenerate and therefore the temperature dependence of Eq. (3) may be neglected. The condition for β equilibrium is $\mu_e = \mu_n - \mu_p = -\partial\epsilon/\partial x$. Studies of pure neutron matter strongly suggest that the expansion (3) with only the quadratic term is a good approximation for all x, at any density.[9] If muons and other charged species are ignored, x is then given by[10]

$$\hbar c(3\pi^2 nx)^{1/3} = 4S_v(n)(1-2x)\,, \qquad (4)$$

where the electrons are assumed ultrarelativistic and degenerate. The density n_c at which x equals the critical value $x_c = \frac{1}{9}$ is found from

$$S_v(n_c) = 51.2(n_c/n_s)^{1/3}\ \text{MeV}\,. \qquad (5)$$

Assuming for simplicity that $S_v \propto n^q$, we find n_c/n_s

$=[1.71(30\text{ MeV})/S_0]^{1/(q-1/3)}$. The cases $q=\frac{1}{2}$, $\frac{2}{3}$, 1, and $\frac{4}{3}$ would give $n_c/n_s=25$ (9.7), 5.0 (3.1), 2.2 (1.8), and 1.71 (1.46), respectively, where $S_0=30$ (35) MeV is assumed. Clearly, the critical density is sensitive to the magnitude of the symmetry energy.

Muons will be present when $\mu_e > m_\mu c^2 = 105.7$ MeV, which generally is the case for $n \gtrsim n_s$, and then p_{Fe} and p_{Fp} will be unequal and Eq. (4) will be modified. To estimate the effects of muons, we consider the case $\mu_e \gg m_\mu c^2$. In this case, the electron and muon concentrations are each equal to $x/2$. The threshold condition $p_{Fn}=p_{Fp}+p_{Fe}$ then implies $(1-x_c)^{1/3}=x_c^{1/3}+(x_c/2)^{1/3}$, or $x_c \simeq 0.148$. Although x_c is now larger than before, the critical density is smaller, provided $q>\frac{1}{3}$: The equation determining x, Eq. (4), has the x on its left-hand side replaced by $x/2$ and the critical density becomes $n_c/n_s=[1.65(30\text{ MeV})/S_0]^{1/(q-1/3)}$, in the case of a power-law symmetry energy and ultrarelativistic muons. We also note that if $p_{Fn}<p_{Fp}+p_{F\mu}$, the direct URCA process with muons will occur. The threshold proton concentration and density for this process are higher than those for electron since $m_\mu > m_e$.

We now consider models of dense matter. The calculation most firmly grounded in available nuclear data is that of Wiringa, Fiks, and Fabrocini,[11] which is based on a two-body potential fitted to nucleon-nucleon scattering, and a three-body term whose form is suggested by theory and whose parameters are determined by the binding of few-body nuclei and the saturation properties of nuclear matter. The symmetry energies for two choices of the three-body forces are shown in Fig. 1(a). Because of Eq. (4), suitably modified to include muons, x mimics the behavior of $S_v(n)$, as displayed in Fig. 1(b). The proton concentration attains values very close to those required for the direct URCA process to occur, but never quite reaches them. Note, however, the large spread in x which is consistent with available data. This largely reflects uncertainties in the three-body interaction. Also shown in Fig. 1 are results for two other types of models: a field-theoretical model[12] with baryon and meson degrees (σ-ω-ρ) of freedom calculated up to the one-loop level, and the relativistic Dirac-Brueckner approach,[10,13] in which the matrix elements of the boson-exchange potentials are calculated using in-medium nucleon spinors and the effects of correlations are calculated using the Bethe-Goldstone equation. In these models, x can be large enough for the direct URCA process to occur. It is evident that the more rapidly the symmetry energy increases with density, the lower the density at which the direct URCA process begins to operate.

For the direct URCA process to occur in a neutron star, its central density, which depends on the pressure rather than on the symmetry energy, must exceed the critical density. Figure 1(b) shows the central densities of a neutron star with a mass of $1.4M_\odot$ and of a neutron star with the maximum mass for the particular equation of state. Of the models selected, only that of Ref. 13 allows the direct URCA process in a $1.4M_\odot$ star. However, in each of the models displayed in Fig. 1, the central density of the maximum-mass neutron star considerably exceeds that for the $1.4M_\odot$ star.

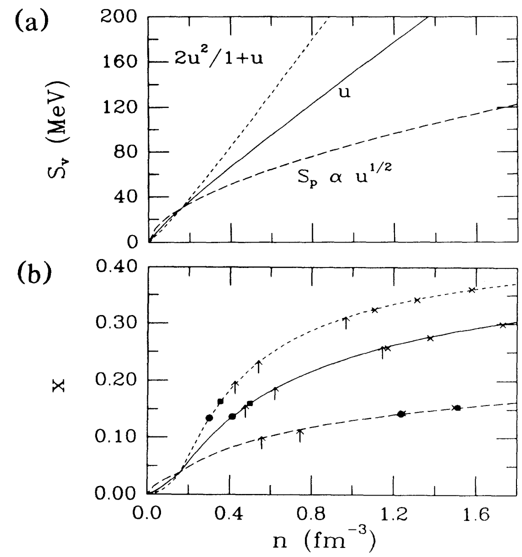

FIG. 1. (a) Nuclear symmetry energy as a function of density for several recent equations of state. (b) Equilibrium proton fraction for the equations of state shown in (a), including the presence of muons. Solid circles (squares) denote the critical density for the direct URCA process for electrons (muons). Arrows (crosses) denote the central density of $1.4M_\odot$ (maximum-mass) neutron stars.

To illustrate the relationships of $S_v(n)$ and the stiffness of the equation of state to the possible occurrence of the direct URCA process, we have also considered the simple parametrization of dense matter proposed by Prakash, Ainsworth, and Lattimer.[9] This parametrization can simulate the results found in many microscopic calculations. We conservatively take $S_0=30$ MeV and choose the density dependence of the potential contributions to S_v to vary as u, $2u^2/(1+u)$, and $u^{1/2}$, where $u=n/n_s$. The functions $S_v(n)$ and x for matter in equilibrium with electrons and muons are shown in Fig. 2. The overall stiffness and the central density of neutron stars are primarily determined by the incompressibility parameter K_s in this model. Figure 2(b) displays the critical proton concentration and density necessary for the occurrence of the direct URCA process, as well as the central densities of $1.4M_\odot$ and maximum-mass stars with $K_s=120$, 180, and 240 MeV. Clearly, with the assumed extrapolations, many realistic combinations of S_v and K_s allow the direct URCA process to occur.

The emissivity due to the direct URCA process may be derived from Fermi's golden rule. The antineutrino energy emission rate from neutron decay is given by

$$\epsilon_\beta=\frac{2\pi}{\hbar}2\sum_i G_F^2\cos^2\theta_C(1+3g_A^2)n_1(1-n_2)(1-n_3)\times\epsilon_4\delta^{(4)}(p_1-p_2-p_3-p_4)\,, \qquad (6)$$

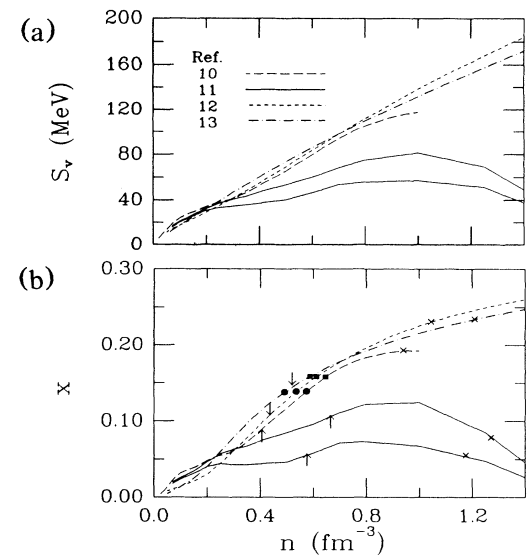

FIG. 2. Same as Fig. 1, but for equations of state from Prakash, Ainsworth, and Lattimer (Ref. 9), which have the indicated forms for the potential contributions S_p to S_v. The assumed values of the nuclear incompressibility K_s are irrelevant for calculations of $x(n)$, but do determine central densities of neutron stars. For each S_p curve, the arrows (crosses), from left to right, correspond to central densities of $1.4M_\odot$ (maximum-mass) stars for $K_s=240$, 180, and 120 MeV, respectively.

where n_i is the Fermi function and the subscripts $i=1$–4 refer to the neutron, proton, electron, and antineutrino, respectively. The p_i's are four-momenta and ϵ_4 is the antineutrino energy. The sum over states is to be performed only over three-momenta $\mathbf{p}_i$ and the prefactor 2 takes into account the initial spin states of the neutron. The square of the neutron β-decay matrix element, summed over spins of final particles and averaged over angles, is $G_F^2\cos^2\theta_C(1+3g_A^2)$, where $G_F \simeq 1.436 \times 10^{-49}$ erg cm^{-3} is the weak coupling constant, $\theta_C = 0.239$ is the Cabibbo angle, and $g_A \simeq -1.261$ is the axial-vector coupling constant. The factors $1-n_2$ and $1-n_3$ are final-state blocking factors. The phase-space sums in Eq. (6) may be simply performed using the methods of Fermi-liquid theory. Electron capture gives the same luminosity as neutron decay, but in neutrinos, and thus the total luminosity for the URCA process is $\epsilon_{\rm URCA}=2\epsilon_\beta$ or

$$\epsilon_{\rm URCA}=\frac{457\pi}{10080}G_F^2\cos^2\theta_C(1+3g_A^2)\frac{m_n m_p \mu_e}{\hbar^{10}c^5}(kT)^6\Theta_t$$
$$=4.00\times10^{27}(Y_e n/n_s)^{1/3}T_9^6\Theta_t \ \text{erg cm}^{-3}\text{s}^{-1}, \quad (7)$$

where T_9 is the temperature in units of 10^9 K, $n_s=0.16$ fm^{-3}, and $\Theta_t=\theta(p_{Fe}+p_{Fp}-p_{Fn})$ is the threshold factor, $\theta(x)$ being $+1$ for $x>0$ and zero otherwise. If the muon URCA process can occur, the emissivity is increased by a factor of 2, irrespective of the value of $\mu_e/m_\mu c^2$.

The estimates above were made assuming the participating particles are free. Interactions give rise to a number of changes. First, the neutron and proton densities of states at the Fermi surfaces are renormalized, which results in the factor $m_n m_p$ in Eq. (7) being replaced by $m_n^* m_p^*$, where m^* is the effective mass (in the sense of Landau Fermi-liquid theory). This factor may well be of order 0.5–0.2. A second effect is that in a nuclear medium the effective value of $|g_A|$ is quenched.[14] At the saturation density $|g_A|\simeq 1$ and it is expected to remain at approximately this value at higher densities (Brown and Rho[15]). Third, final-state interactions will modify the effective weak-interaction matrix element, but this is a small effect since n-p interactions are small at the momentum transfers of importance ($\sim p_{Fp}$). Thus the total reduction of the URCA rates due to interaction effects may amount to a factor of 10, but similar factors must be applied to other neutrino emission processes involving nucleons.

Let us now compare the rate of the direct URCA process with that of other processes. The neutrino emissivity from the modified URCA process, Eq. (1), for free particles, is[16]

$$\epsilon_{\rm mod\,URCA}\approx 10^{22}(Y_e n/n_s)^{1/3}T_9^8 \ \text{erg cm}^{-3}\text{s}^{-1}. \quad (8)$$

A small correction to this result should be applied to take into account reactions in which the bystander nucleon is a proton. From Eqs. (7) and (8) we find $\epsilon_{\rm URCA}/\epsilon_{\rm mod\,URCA}\approx 5\times10^5 T_9^{-2}$. Roughly speaking, this is a factor $(T/T_F)^{-2}$, reflecting the fact that the bystander particles in the initial and final states of the modified URCA process each lead to a factor T/T_F. This indicates that the rate of the modified URCA process would be comparable to that of the direct URCA process at $T\simeq T_F\simeq 10^{12}$ K. (We note in passing that the modified URCA process may be regarded as a correction to the direct URCA process due to damping of participating nucleon states by collisions.)

Emission from pion and kaon condensates and quark matter all have the same temperature dependence as the direct URCA process because the phase-space considerations are essentially identical. For a pion condensate, the effective β-decay matrix elements contain a factor θ^2, where θ, the pion condensate angle, is expected to be considerably less than unity. Estimates[5] of the pion emissivity are typically at least a factor of 10 less than that of the direct URCA process. Emission from kaon condensates also contains a factor of $\sin^2\theta_C$, where θ_C is the Cabbibo angle, in addition to the square of the kaon condensate angle. The kaon emissivity[6] is estimated to be less than the direct URCA process by a factor of 1000. Quark matter, if present, would give rise to direct URCA processes involving u and d quarks with an emissivity[7]

$$\epsilon_{q\,\rm URCA}=8.8\times10^{26}\alpha_c(n/n_s)Y_e^{1/3}T_9^6 \ \text{erg cm}^{-3}\text{s}^{-1}.$$

With the standard value of the QCD coupling constant $\alpha_c\simeq 0.1$, and choosing $n=4n_s$ and $Y_e=10^{-4}$ (the equilibrium electron fraction in quark matter would be zero if quarks were massless), one finds that $\epsilon_{q\,\mathrm{URCA}}/\epsilon_{\mathrm{URCA}} \sim 10^{-3}$. Although quark bremsstrahlung has the same T dependence as direct URCA, it is considerably less efficient.[17]

Dense neutron-star matter ($n > 2n_s$) may contain a significant fraction of hyperons, beginning with Σ^-, Λ, and Ξ^-.[18] Hyperons provide additional sources of neutrino emissivity via direct URCA processes. Even if the direct nucleon URCA process is not permitted, the direct URCA processes involving hyperons appear to be allowed above the threshold density for the appearance of hyperons (Prakash, Prakash, Pethick, and Lattimer[19]). The characteristic luminosity of the hyperon direct URCA process is comparable to that for nucleons, but generally somewhat less because of reduced matrix elements. The luminosities will greatly exceed those of hyperon-modified URCA processes.[20]

At some densities neutrons may be superfluid and/or protons superconducting. The direct URCA rate is then reduced by a factor $\sim\exp(-\Delta/kT)$, since for the process to occur, the total energy of particles in the initial or final state must exceed Δ, the larger of the neutron and proton gaps. Calculated gaps are uncertain but are typically of the order of a few hundred keV.[21] Thus, when $\Delta \gg kT$, neutrino emission rates are significantly reduced. However, it should be remembered that the modified URCA rates are reduced by a factor $\sim\exp(-2\Delta/kT)$.

The time for a star's center to cool by the direct URCA process Eq. (7) to a temperature T_9 may be estimated to be $\sim 20 T_9^{-4}$ s. Cooling simulations[22] for the case of enhanced emissivity (compared to the standard model) from the neutron star's core show that the surface temperature remains high until a cooling wave reaches the surface. After this, the surface temperature plunges abruptly below 5×10^5 K and the star becomes virtually invisible. This takes from 1 to 100 yr, depending upon the relative sizes of the neutron star's crust and core, and thus upon the equation of state, and not upon the cooling mechanism. There is, therefore, little to distinguish observationally the effects of the direct URCA process, pion and kaon condensates, and quark matter. X-ray or UV observations of neutron stars cannot be used to demonstrate unequivocably the existence of Bose condensates or quark matter.

When the direct URCA process can occur, the bulk viscosity of neutron-star matter will be increased by a factor $(T_F/T)^2$ compared with that for the modified URCA process (Haensel and Schaeffer[23]). This would strongly damp radial pulsations and increase the stability of rapid rotation in very young neutron stars. We further observe that the threshold for the direct URCA process is expected to lie in the range of central densities for neutron stars. In view of the step-function character of the threshold, neutron stars rather close in mass could have very different cooling histories.

To determine if the direct URCA process can occur, it is important to make more precise estimates of the symmetry energy and equation of state at densities above that of nuclear matter. The continuing attempts to observe thermal radiation from neutron stars will have important implications for these properties of nuclear matter.

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