Neutrino luminosity of the bubble phase layer in a hot neutron star

L. B. Leinson
Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation RAS, 142092 Troitsk, Moscow Oblast'

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A new mechanism of neutrino emission is suggested for a newly born neutron star cooling. Nucleons emit neutrino pairs due to collisions with bubbles which exist inside the spherical layer of stellar matter from half nuclear to nuclear density. During the earliest stages of the nascent neutron star cooling the $\nu_\mu\tilde{\nu}_\mu$ pair luminosity of this rather thin spherical layer is on the order of 10^{53} ergs/s.

A highly degenerate, lepton-rich nuclear matter of the average density $0.5\rho_0 \leqslant \rho \leqslant \rho_0$ resembles Swiss cheese consisting of a denser phase with isolated regions of less dense nuclear matter (bubbles).[1-5] Here $\rho_0 = 2.6 \times 10^{14}$ g $\cdot$ cm^{-3} is the nuclear density.

A nucleon can emit, through the weak neutral current, a single neutrino-antineutrino pair by the collision with the bubble.

$$n + \text{bubble} \to n + \text{bubble} + \nu + \tilde{\nu}, \tag{1}$$

$$p + \text{bubble} \to p + \text{bubble} + \nu + \tilde{\nu}. \tag{2}$$

Here the total lepton energy ω is on the order of the medium temperature T. All neutrino species can be produced by this mechanism. However, electron neutrinos are trapped in the core of a hot neutron star and are highly degenerate, as β equilibrium requires. Since the electron neutrino production is hardly suppressed in this case, we will consider here the muon neutrinos which are not degenerate and which therefore can be generated rapidly.[1)]

To describe the weak interaction, we employ the Weinberg-Salam model and consider the single bubble as a field acting on the nucleon. Here we would like to make several observations. It is well known that in the Brueckner theory the nucleon in a uniform nuclear matter is described as a plain wave propagating in the uniform medium with a self-consistent, uniform, negative potential $U_{\text{eff}} = -W$, while the nucleon energy $\epsilon(\mathbf{p}) = -W + \mathbf{p}^2/2m^*$, where m^* is the effective mass. The magnitude of W depends significantly on the nuclear matter density. Assuming that the nuclear matter that fills the volume between the bubbles has the density $\rho = \rho_0$ from Brueckner's theory,[8] we obtain $W = 45$ MeV. In a first approximation one can assume the bubble to be a nuclear matter of density $\rho = 0$, i.e., inside the bubble $W = 0$ identically. This means that the nucleon-bubble interaction can be considered as an incoming nucleon

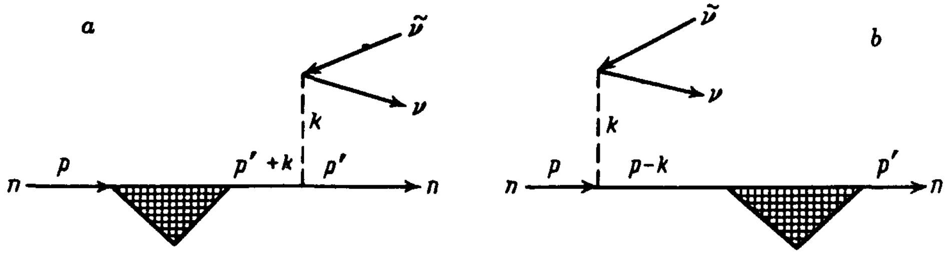

FIG. 1. These Feynman diagrams contribute mainly to the matrix element of the neutrino-pair emission due to the neutron collision with the bubble. Here the dashed line represents the Z boson and the triangle denotes the sum of the diagrams corresponding to the nucleon scattering by the bubble.

scattering from the central potential field, $V(r)=W\theta(R_A-r)$, produced by the bubble. Of course, the spin-orbit nucleon interaction with the bubble's surface should also be taken into account.

Let us assume that the block enclosed by the triangle represents the sum of diagrams corresponding to the nucleon scattering from the bubble. Since $\omega \lesssim T \ll \epsilon_{\mathbf{p}}$, and since the total lepton momentum $k \ll \omega \ll p$, the main contribution to the matrix element of reaction (1) or (2) comes from the diagrams shown in Figs. 1a and 1b, because the nonrelativistic nucleon propagator in these diagrams is near the pole $G(\mathbf{p}\pm\mathbf{k},\ \epsilon_{\mathbf{p}}\pm\omega) \approx \pm\omega^{-1}$. The contribution of diagram 1(b) to the matrix element differs from that of diagram 1(a) only in the order of interaction and in the sign of the nucleon propagator. When we sum these two diagrams, the vector part of the weak interaction therefore vanishes. The axial part of the weak interaction does not cancel because the Pauli spin matrices $\hat{\sigma}_i$ do not commute with the spin-orbit part of the scattering amplitude $\hat{f}$. This yields the following matrix element of the reaction:

$$M=\frac{g_A G_F}{2\sqrt{2}}\frac{2\pi}{m^*\omega}j_i\chi_1^+[\hat{\sigma}_i\hat{f}(\mathbf{p},\mathbf{p}')-\hat{f}(\mathbf{p},\mathbf{p}')\hat{\sigma}_i]\chi_2. \tag{3}$$

Here χ_2 and χ_1^+ are the Pauli spinors which represent the nonrelativistic incoming nucleon and the outgoing nucleon, respectively; m^* is the effective nucleon mass, $G_F=8.7\times10^{-5}$ Mev $\cdot$ fm^3 is the weak Fermi coupling constant, $g=1.26$ is the axial vector normalization factor, and $\mathbf{j}$ is the three-dimensional Lepton neutral current. The nucleon operator of the scattering amplitude in the bubble field $\hat{f}$ can be written in the general form

$$\hat{f}(\mathbf{p},\mathbf{p}')=A(p,\theta)+B(p,\theta)e_{ijk}\hat{\sigma}_i\hat{p}_j\hat{p}'_k, \tag{4}$$

where e_{ijk} is the completely antisymmetric tensor of rank 3, $\hat{\mathbf{p}}=\mathbf{p}/p$ is the unit vector in the initial nucleon momentum direction, and $\mathbf{p}'$ is the same for the final nucleon. We assume $|\mathbf{p}|=|\mathbf{p}'|$, because the scattering is quasielastic for neutrons near the Fermi surface. The scattering amplitude in this case depends only on the angle θ between the incoming and outgoing neutron momenta. The bubble radius is $R_A = r_0 A^{1/3}$ (as that for a nucleus with A nucleons, $r_0 = 1.4$ fm). Since $pR_A \gg 1$, the bubble scatters neutrons only at a small angle, $\theta \sim (pR_A)^{-1}$.

The neutrino emissivity per unit volume is the integral

$$\varepsilon_\nu = 2\pi n_b \int \frac{d^3p d^3p' d^3k d^3k'}{(2\pi)^{12}} \delta(\epsilon - \epsilon' - \omega) \frac{\omega}{4\omega_1\omega_2} \sum_{\rm spin} \overline{|M|^2} f_{\mathbf{p}}(1 - f_{\mathbf{p}'}), \qquad (5)$$

where ϵ and ϵ' are respectively the energies of the incoming neutron and the outgoing neutron, $\delta(\epsilon - \epsilon' - \omega)$ is the energy conservation δ-function, $\omega = \omega_1 + \omega_2$ is the total neutrino energy; $f_{\mathbf{p}}$ is the Fermi-Dirac distribution function of highly degenerate neutrons, and n_b is the bubble number density. Thus, we obtain

$$\varepsilon^\nu = \frac{23}{1870} g_A^2 G_F^2 p_F^2 n_b T^6 \sigma_{tr}^{sl}, \qquad (6)$$

where

$$\sigma_{tr}^{sl} = 2\pi \int d(\cos\theta) \, |B(p_F, \theta)|^2 (1 - \cos\theta). \qquad (7)$$

The neutrino pair emissivity is proportional to the transport cross section (7) of the nucleon scattering from the bubble via the spin-orbit interaction. The simplest model of such an interaction $\hat{V}(r) = W(a/R_A)\delta(r - R_A)\hat{\sigma}_i \hat{l}_i$ gives the following expression for $2p_F R_A \gg 1$:

$$\sigma_{tr}^{sl} = \frac{1}{(1 + g_0)^2} (2Wm^* a)^2 \pi R_A^2 \frac{1}{2} [\ln(4p_F R_A) + \gamma - 1]. \qquad (8)$$

Here $\gamma = 0.577$ is Euler's constant, and $a = 3.5 \times 10^{-27}$ cm^2 is the spin-orbit coupling constant known from nuclear data.[9] The factor $1/(1 + g_0)^2$ is a correction which takes into account the polarization of the nucleon medium around the bubble.[10] For pure neutron matter at the nuclear density the theory of nuclear matter gives[11] $g_0 = 0.97$.

The most frequently encountered bubbles have the radius $R_A = r_0 A^{1/3}$, with[4]

$$A = \frac{193(1 - Y_e)^2}{\phi(1 - u)}. \qquad (9)$$

Here

$$\phi(x) = 1 - \tfrac{3}{2} x^{1/3} + \tfrac{1}{2} x, \qquad (10)$$

$u = n/n_0$ is the ratio of the average nucleon number density to the nuclear number density $(0.5 \leqslant u \leqslant 1)$; the bubble number density is $n_b = (1 - u) A^{-1} n_0$ with $n_0 = 1.55 \times 10^{38}$ cm^{-3}, and Y_e is the number of electrons per unit baryon in the medium. Thus, from Eq. (6) we obtain the muon neutrino emissivity by means of the neutron-bubble collisions $(\text{erg} \cdot \text{cm})^{-3} \cdot \text{s}^{-1})$:

$$\epsilon_{\nu_\mu}^{nb} = 3 \times 10^{29} T_{10}^6 (1 - u) [\phi(1 - u)]^{1/3} [1.79 - \tfrac{1}{6} \ln\phi(1 - u) + \tfrac{1}{2} \ln(1 - Y_e)] \qquad (11)$$

and the one due to the proton-bubble collisions:

$$\epsilon_{\nu_\mu}^{pb}=3\times10^{29}T_{10}^6(1-u)\left[Y_e^2\frac{\phi(1-u)}{(1-Y_e)^2}\right]^{1/3}[1.79-\tfrac{1}{6}\ln\phi(1-u)+\tfrac{1}{3}\ln(1-Y_e)+\tfrac{1}{6}\ln Y_e] \quad (12)$$

with $T_{10}=T/10^{10}K$. Here we take into account that $P_F=[3\pi^2 n_0(1-Y_e)]^{1/3}$ for neutrons and $P_F=(3\pi^2 n_0 Y_e)^{1/3}$ for protons.

According to the conventional model,[12–14] the initial cooling phase of a nascent neutron star lasts on the order of 10 seconds. Muon neutrinos are nondegenerate at this stage and can be produced very rapidly in the bubble phase layer. Since the bubble phase layer is situated at the edge of the inner core, the neutron star opacity for the muon neutrinos emitted from it can be caused mainly by a coherent neutrino scattering from nuclei in the outer crust. However, Coulomb interaction between the crust nuclei reduces this scattering significantly.[15,16] The neutrino mean free path in this case can be written as follows:

$$l\sim\frac{2\times10^8}{\rho_{12}}\left[\frac{1\text{Mev}}{E_\nu}\right]^2\frac{E_{\text{Fe}}}{T}\frac{Y_e}{(1-Y_e)^2}, \quad (13)$$

where ρ is the matter density, and $\rho_{12}=\rho/10^{12}$ g·cm^{-3}. For $E_\nu\approx T$ one has $l\sim10^6$–10^7 cm. Thus, for ν_μ generated in the bubble phase layer the low-energy window is widened.

The neutrino luminosity from the bubble phase spherical layer of thickness d can be determined by integration over the total layer volume. The derivative $|du/dr|\sim|\Delta u/\Delta r|\sim0.5/d$ is assumed to be constant and integration over dr can be replaced approximately by integration over du in the interval $(0.5,1)$. Disregarding small logarithmic terms in Eqs. (11) and (12), we have

$$L_\nu\sim1.4\times10^{30}T_{10}^6R^2d\left[1+\left(\frac{Y_e}{1-Y_e}\right)^{2/3}\right]. \quad (14)$$

Using the inner core radius $R\sim30$ km, the bubble phase thickness $d\sim3\times10^4$ cm, and assuming that $Y_e\approx0.3$ and $T_{10}\approx10$, we find that the $\nu_\mu\tilde{\nu}_\mu$ pair luminosity is on the order of 10^{53} ergs/s.

The nuclear matter in the bubble regime contributes significantly to the neutron star cooling at the earliest stage. The bubble phase layer of the nascent neutron star emits $\nu_\mu\tilde{\nu}_\mu$ pairs with the luminosity $\sim10^{53}$ ergs/s. The more intensive luminosity can occur during the short infall epoch of the collapsing matter. In the lepton-rich collapsing matter very heavy atomic nuclei could exist up to the half-nuclear density. This circumstance accounts for the lower temperature of the collapsing matter.[17] If this is the case (the so-called 'cold' collapse with $T_{10}\leqslant15$), the bubble phase of nuclear matter can occupy the large central volume in the nascent condition of the neutron core. It seems clear that the additional $\nu_\mu\tilde{\nu}_\mu$ emission discussed here should be incorporated into the detailed numerical models of the early phase of cooling of a neutron star.

[1]A degenerate sea of massive muon neutrinos can be rapidly populated through $\nu_e \leftrightarrow \nu_\mu$ oscillations only if the ν_μ mass is on the order of or greater than[6] 10 keV. The GALLEX experimental data exclude such a possibility.[7]

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