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NEUTRINO LUMINOSITY OF THE BUBBLE PHASE LAYER IN A HOT NEUTRON STAR

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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 somewhat thin spherical layer is of the order of 10^{53} ergs/s.

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

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

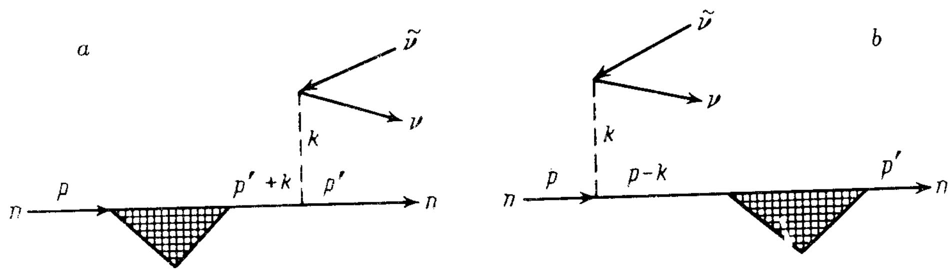
$$n + bubble \rightarrow n + bubble + \nu + \tilde{\nu}, \qquad (1)$$

$$p + bubble \rightarrow p + bubble + \nu + \tilde{\nu}. \qquad (2)$$

Here the total lepton energy ω is of 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 enforces. The electron neutrino production is hardly suppressed in this case. So, we consider here the muon neutrino which are not degenerate and therefore can be generated very intensively[1)].

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

To describe the weak interaction, we employ the Weinberg-Salam model and consider the single bubble as a field acting on the nucleon. Here several notes are in order. It is well known that within 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 $U_{eff} = -W$, while the nucleon energy $\varepsilon(\mathrm{p}) = -W + \mathrm{p}^2/2m^*$, where m^* is the effective mass. The magnitude of W depends significantly on the nuclear matter density. Supposing that the nuclear matter filling the volume between the bubbles has the density $\rho = \rho_0$ from the Brueckner theory [8] we get $W = 45$ MeV. As a first approximation one can consider the bubble as 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 scattering from the central potential field $V(r) = W\theta(R_A - r)$, produced by the bubble. Of course, the spin-orbital nucleon interaction with the bubble surface should also be taken into account.



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

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

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

Here χ_2 and χ_1^+ are the Pauli spinors representing the nonrelativistic incoming nucleon and outgoing one respectively; m^* is the effective nucleon mass; $G_F = 8.7 \cdot 10^{-5}$ Mev·fm^3 is the weak Fermi coupling constant; $g = 1.26$ is the axial vector renormalization factor, and j is the three-dimension lepton neutral current. The nucleon operator of the scattering amplitude in the bubble field $\hat{f}$ can be written in the following 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 quasi-elastic 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

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

where correspondingly ϵ and ϵ' are energies of the incoming and 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 Fermi-Dirac distribution function of highly degenerate neutrons; n_b is the bubble number density. Thus, we obtain:

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

where

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

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

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

Here $\gamma = 0.577$ is Eiler constant; $a = 3.5 \cdot 10^{-27}$ cm^2 is the spin-orbital coupling constant known from nuclear data [9]. Factor $1/(1 + g_0)^2$ is a correction taking into account polarization of the nucleon medium arround the bubble [10]. For pure neutron matter at the nuclear density the theory of nuclear matter gives $g_0 = 0.97$ [11].

The most frequent bubbles are of the radius $R_A = r_0 A^{1/3}$ with [4]

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

Here

$$\phi(x) = 1 - \frac{3}{2} x^{\frac{1}{3}} + \frac{1}{2} x, \tag{10}$$

$u = n/n_0$ is the ratio of the average nucleon number density to the nuclear number density $(0.5 \leq u \leq 1)$; the bubble number density equals $n_b = (1 - u) A^{-1} n_0$ with $n_0 = 1.55 \cdot 10^{38}$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 ($erg \cdot cm^{-3} \cdot s^{-1}$) :

$$\varepsilon_{\nu_\mu}^{nb} = 3 \cdot 10^{29} T_{10}^6 (1-u)[\phi(1-u)]^{\frac{1}{3}}[1.79 - 1/6 \ln \phi(1-u) + 1/2 \ln(1-Y_e)] \quad (11)$$

and the one due to the proton-bubble collisions:

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

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

According to the conventional model [12-14] the initial cooling phase of a nascent neutron star lasts of the order of 10 seconds. Muon neutrinos are nondegenerate at this stage and can be produced in the bubble phase layer very intensively. 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 mainly be caused by a coherent neutrino scattering from nuclei in the outer crust. However, Coulomb interaction between the crust nuclei reduses significantly this scattering [15,16]. The neutrino mean free path in this case can be written as follows:

$$l \sim \frac{2 \cdot 10^8}{\rho_{12}} \left[\frac{1 \mathrm{Mev}}{E_\nu} \right]^2 \frac{E_{\mathrm{Fe}}}{T} \frac{Y_e}{(1-Y_e)^2}, \quad (13)$$

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

To evaluate the neutrino luminosity from the bubble phase spherical layer of the thickness d one should perform integral over total layer volume. One can estimate the derivative $|du/dr| \sim |\Delta u/\Delta r| \sim 0.5/d$ to be constant and replace approximately integration over dr by integration over du in the interval $(0.5, 1)$. Neglecting small logarithmic terms in Eqs.(11) and (12) one has:

$$L_\nu \sim 1.4 \cdot 10^{30} T_{10}^6 R^2 d \left[1 + \left(\frac{Y_e}{1-Y_e} \right)^{2/3} \right]. \quad (14)$$

Using the inner core radius $R \sim 30$ km, the bubble phase thickness $d \sim 3 \times 10^4$ cm and supposing that $Y_e \approx 0.3$ and $T_{10} \approx 10$ one obtains the $\nu_\mu \bar{\nu}_\mu$ pair luminosity of 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 $\nu_\mu \bar{\nu}_\mu$ pairs with the luminosity $\sim 10^{53}$ 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 leads to the lower temperature of the collapsing matter [17]. If this is the case (the so-called 'cold' collapse with $T_{10} \leq 15$) the bubble phase of nuclear matter can occupy the large central volume in a nascent condition of a neutron core. It seems clear that the additional $\nu_\mu \bar{\nu}_\mu$ emission discussed here should be incorporated into detailed numerical models of the early phase of the neutron star cooling.

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