Neutral currents and the neutrino emission from stars

S. S. Gershteĭn, V. N. Folomeshkin, M. Yu. Khlopov, and R. A. Éramzhyan

Institute for High Energy Physics, Serpukhov

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The possibility that $\nu_e\tilde{\nu}_e$ and $\nu_\mu\tilde{\nu}_\mu$ pairs are emitted in nucleon collisions or in nuclear transitions is considered. The emission of neutrino pairs in neutron collisions turns out to be essential for the cooling of neutron stars. The emission of neutrino pairs in nuclear transitions turns out to be effective immediately prior to the implosion of the nucleus of a hot massive star and in the initial stage of the implosion (until nuclei are completely dissociated into nucleons).

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1. INTRODUCTION

As is well known, neutrino emission plays an important role in the process of stellar evolution (particularly during the late stages of evolution, when the rate of evolution is practically completely determined by neutrino energy losses. This refers both to the stage of quiescent burning preceding the implosion of the stellar nucleus and to the process of catastrophic compression of the nucleus and the cooling down the neutron star formed as a result of this.

The existence of weak neutral hadronic currents which manifest themselves in processes of observed neutrino-nucleon scattering has as a result the existence of additional effective mechanisms for neutrino emission by stars. (This fact was pointed out long before the neutral currents were observed[1-3].) The presence of the neutral currents manifests itself, first, in a quantitative change[4] of the intensity of emission of electronic neutrino-antineutrino pairs calculated earlier and due to the $(\nu_e e)(\nu_e e)$ interaction, second, it leads to the emission of pairs of muonic neutrinos on account of the $(\nu_\mu\nu_\mu)$ (ee) interaction, and third, it opens up the possibility of the emission of neutrino pairs in nucleon collisions or in nuclear transitions (and even in photoproduction reactions $\gamma N \to N\nu\tilde{\nu}$).

In the present paper we consider the third of the enumerated mechanisms for neutrino emission on account of neutral currents (the contribution of the photoproduction process to the neutrino emission from stars is small[5,6]). The emission of neutrino pairs in neutron collisions turns out to be essential for the cooling down of neutron stars (Sec. 2).

At relatively low temperatures ($T \leq 10^8$K) the emission of neutrino pairs in nuclear transitions was considered in[7]. Under such conditions the neutrino emission can occur on account of nuclear transitions between low-lying levels of some distinguished isotopes, and the contribution of this process to the total neutrino flux is small[8] (even if one does not take into account the smallness of the corresponding transition matrix elements). This mechanism becomes considerably more efficient immediately prior to the implosion of the nucleus of massive hot stars and during the initial stage of implosion (up to the time when the nuclei dissociate completely into nucleons). Under these conditions its contribution becomes comparable to the contribution from the Urca-process on nuclei (Sec. 3).

2. NEUTRINO EMISSION FROM NEUTRON STARS

The rate of cooling of neutron stars determines the time during which such stars exist in a hot state, when they are intensive sources of x rays. The following conditions are characteristic for a neutron star: the Fermi energy of the degenerate neutron gas μ_n is approximately equal to the Fermi energy of the degenerate electron gas, $\mu_n \simeq \mu_e \simeq 100$ MeV. Then for the protons $\mu_p \simeq 5$ MeV and the density of matter is about 10^{14}–10^{15} g/cm^3.

The reactions $nn \to npe\tilde{\nu}$ and $epn \to nn\nu$ have been considered as one of the possible mechanisms of cooling down of neutron stars[8-14]. It was assumed that the rate of the inverse reaction $epn \to nn\nu$ is comparable to the rate of the direct reaction $nn \to npe\tilde{\nu}$ and only the probability of the direct reaction was estimated. In distinction from the two-stage character of reactions involving charged currents the process $nn \to nn\nu\tilde{\nu}$ considered here occurs only in one stage.

A self-consistent treatment of these processes would require the use of the theory of the neutron Fermi-fluid, with account taken of possible pion condensation in nuclear matter[15]. However, as an initial approximation we limit our attention to the simplest model of a degenerate Fermi gas.

A. The Cross Section for the Reaction nn → nn$\nu\tilde{\nu}$

The amplitude of the process

$$nn \to nn\nu\tilde{\nu} \tag{1}$$

is of the form $M = 2^{-1/2}Gl_\alpha H_\alpha$, where $l_\alpha = \nu\gamma_\alpha(1+\gamma_5)\nu$, and $H_\alpha = V_\alpha + A_\alpha$ is the matrix element of the neutral hadronic current assumed to be the sum of the vector and axial-vector terms. We denote by p_1, p_2 and p_3, p_4 the momenta of the initial and final neutrons, by k_1, k_2 the momenta of the neutrinos, and by E_1, E_2, E_3, E_4, ω_1, ω_2 the energies of the corresponding particles; also $k = k_1 + k_2$ and $\omega = \omega_1 + \omega_2$. The cross section for the reaction (1) describing the emission of the pairs $\nu_e\tilde{\nu}_e$ and $\nu_\mu\tilde{\nu}_\mu$ can be written in the form

$$d\sigma_\nu = \frac{F d^4k}{2^{13} I \pi^8} \frac{d^3p_3\, d^3p_4}{E_3 E_4} \delta^4(p_1+p_2-p_3-p_4-k), \tag{2}$$

$$F = \int \overline{|M|^2} \frac{d^3k_1\, d^3k_2}{\omega_1\omega_2} \delta^4(k-k_1-k_2) = {}^2/_3\pi G^2[|k_\alpha H_\alpha|^2 - k^2|H|^2],$$

$$I = [(p_1p_2)^2 - m^4]^{1/2}. \tag{3}$$

The probability of the reaction (1) with emission of neutrino pairs can be estimated by making use of the low-energy theorems[16,17]. The terms of order k^{-1} in the expansion of the matrix element, terms which give the main contribution in the low energy limit, appear on account of the emission of $\nu\tilde{\nu}$ pairs from the external lines of the diagram describing the process of elastic neutron-neutron scattering. In the energy region of interest (corresponding to laboratory energies in the interval $0 \leq E \leq 400$ MeV) the nn scattering is practically isotropic. Therefore, for estimates one can limit oneself to s-wave neutron-neutron scattering. Writing the vertex of the weak interaction (nn) $(\nu\nu)$ in the form $l_\alpha\{\bar{n}\gamma_\alpha(g_V + g_A\gamma_5)n\}$ and taking into account the emission of $\nu\tilde{\nu}$ pairs from external lines, we obtain for F in the indicated approximation the expression

$$F={}^1/_3\cdot 2^{11}\pi^2G^2g_A{}^2\sigma_{nn}[(kp_1-kp_2)^2+(kp_3-kp_4)^2](\omega^2+2k^2)/\omega^4, \tag{4}$$

where σ_{nn} is the cross section for elastic nn scattering.

In the nonrelativistic approximation the contribution of the weak vector interaction to the emission of $\nu\tilde{\nu}$ pairs in nn collisions vanishes. This result is analogous to the absence of electromagnetic dipole radiation in the collision of charged particles with the same e/m ratio. If one takes into account only one diagram, as was done, e.g., by Finzi[9], there is no compensation of the vector part of the interaction and the result is excessive. We note that such a compensation obviously does not occur in neutron-nucleus scattering.

For the total cross section of the reaction (1) we obtain the expression

$$\sigma_\nu=\frac{2^8G^2m^4g_A{}^2\sigma_{nn}}{3^45^27\pi^4}\left(\frac{E}{m}\right)^5, \tag{5}$$

where $E = (\mathbf{p}_1 - \mathbf{p}_2)^2/4m$ is the relative kinetic energy of the nucleons.

We note that in the soft-pion limit (when $m_\pi = 0$) the cross section (1) can be related to the cross section for pion production in nucleon-nucleon collisions. Indeed, in the nonrelativistic approximation for the nucleons there is the relation

$$g(\bar{N}\gamma_5N)\varphi_\pi=(g/2m)\varphi_\pi(\bar{N}\hat{\mathbf{k}}\gamma_5N),$$

where $g^2/4\pi = 14.6$, k_α is the pion momentum, and the cross section of the reaction $nn \to nn\pi$ can be written in the form

$$\sigma_\pi=\frac{g^2/4\pi}{2^{12}\pi^4m^2I}\int|k_\alpha A_\alpha|^2\frac{d^3k\,d^3p_3\,d^3p_4}{\omega E_3E_4}\delta^4(p_1+p_2-p_3-p_4-k). \tag{6}$$

Comparing in the soft-pion limit the expressions (2), (3) and (6) and assuming that $\sigma_\pi(k^2 = 0) = \sigma_\pi(k^2 = m_\pi^2)$, we obtain

$$\sigma_\nu=\frac{4G^2g_A{}^2m^2}{3(2\pi)^3(g^2/4\pi)}E^2\sigma_\pi(E). \tag{7}$$

B. The Reaction nn → nn$\nu\tilde{\nu}$ in the Conditions of a Neutron Star

In the conditions prevalent in a neutron star the neutron gas is strongly degenerate and only a small number of neutrons can be emitted near the Fermi surface. The corresponding energy of the $\nu\tilde{\nu}$ pair is $\omega \ll \mu_n$. Up to terms of the order $\beta^{-1} = T/\mu_n$ the expression (4) can be written in the form

$$F={}^1/_3\cdot 2^{12}\pi^2G^2g_A{}^2\sigma_{nn}(kp_1-kp_2)^2(\omega^2+2k^2)/\omega^4. \tag{8}$$

The specific luminosity of the neutrino losses on account of the emission of $\nu_e\tilde{\nu}_e$ and $\nu_\mu\tilde{\nu}_\mu$ pairs is

$$L_\nu=\frac{1}{2^5\pi^2}\int d^4k\,\omega SF\delta^4(p_1+p_2-p_3-p_4-k), \tag{9}$$

$$S=S_1S_2S_3S_4,\qquad S_i=d^3p_i/E_i(2\pi)^3\left(1+\exp\left(\pm\frac{E_i-\mu}{T}\right)\right), \tag{10}$$

where the plus sign is to be taken for incident neutrinos (i = 1, 2) and the minus sign for emitted neutrinos (i = 3, 4).

After the integrations the expression (9) takes the form

$$L_\nu=\frac{11\cdot 2^5}{3^3\cdot 5\cdot 7\cdot\pi^8}G^2g_A{}^2p_F{}^3\langle\sigma\rangle T^8J, \tag{11}$$

$$J=\int\limits_{-\beta}^{\infty}dx_1\int\limits_{-\beta}^{\infty}dx_2\int\limits_{-\beta-x_1-x_2}^{\beta}dx_3\int\limits_{-x_1-x_2-x_3}^{\beta}dx_4(x_1+x_2+x_3+x_4)^4Q\approx 540, \tag{12}$$

$$Q^{-1}=(1+e^{x_1})(1+e^{x_2})(1+e^{x_3})(1+e^{x_4}), \tag{13}$$

$p_F^2 = 2\mu m$, $\langle\sigma\rangle$ is the energy average of the nn-scattering cross section

$$\langle\sigma\rangle=\frac{1}{E_{max}}\int\limits_0^{E_{max}}\sigma(E)\,dE.$$

for $\mu = 100$ MeV the cross section $\langle\sigma\rangle$ is approximately 42 mb. For the quantity L_ν we obtain the value

$$L_\nu=4\cdot 10^4g_A{}^2T_9{}^8\ \mathrm{erg\cdot g^{-1}\ sec^{-1}} \tag{14}$$

where T_q is the temperature in units of 10^9K. This value is close to the intensity estimated for the reaction $nn \to npe\tilde{\nu}$[8-12]. We arrive at the conclusion that the neutral currents may play a noticeable role in the cooling down of neutron stars.

As was noted above, an important role in the neutrino luminosity of neutron stars may be played by pion condensation effects. The emission of a $\nu\tilde{\nu}$ pair by a pion in the process of pion-nucleon scattering will be enhanced on account of the smaller pion mass and the absence of suppression due to the Pauli principle in the degenerate neutron gas.

3. NEUTRINO EMISSION FROM HOT "IRON" STARS

The fundamental processes of neutrino emission during the late stages of stellar evolution (before the implosion and possible supernova flare-up) are the Urca-processes and the annihilation of electron-positron pairs[18-24]. The weak neutral hadronic currents lead to the possibility of exciting nuclei by neutrino scattering[2,25,26] and, correspondingly, to the possibility of $\nu\tilde{\nu}$ pair emission in transitions from higher to lower nuclear levels[1,3,7].

The main contribution to the process $(A, Z)^* \to (A, Z) + \nu\tilde{\nu}$ is determined by an allowed transition and is caused by the axial-vector part of the weak current (both by the isoscalar part, if it exists, and by the isovector part). The probability of emission of $\nu_e\tilde{\nu}_e$ and $\nu_\mu\tilde{\nu}_\mu$ pairs by an excited nucleus has the form

$$W(E)=\frac{G^2E^5}{30\pi^3}g_A{}^2|\langle\sigma\rangle|^2,$$

and the intensity of neutrino radiation is

$$L_\nu=W(E)Ee^{-E/kT}.$$

If $|\langle\sigma\rangle|^2$ does not depend on the energy, the maximum intensity corresponds to levels with excitation energies of $E = 6kT$ and the intensity of emission from levels in the interval $3.5kT \leq E \leq 9.5kT$ is not smaller than half the intensity of neutrino radiation from levels with E = 6kT.

During the "iron" stage of stellar evolution their isotopic composition is determined by elements of the type Fe, Co, or Mn. In this nuclear region intensive Gamow-Teller transitions are situated in the excitation energy region from 5 to 12 MeV[27]. In particular, for ^{56}Fe they are situated in the region 11–12 MeV, for ^{57}Fe, in the region 7 MeV, and for ^{58}Ni in the 5–8 MeV region (isoscalar branch) and 10–12 MeV region (isovector branch).

For low-lying levels the quantity $|\langle\sigma\rangle|^2$ is small (in particular, the matrix elements for transitions with E = 14 keV for ^{57}Fe and E = 67 keV for ^{61}Ni discussed in[7], are small). The main contribution to the Gamow-Teller matrix element in the region of nuclei discussed here is due to the one-particle transition ${}^1f_{5/2} \to {}^1f_{7/2}$, for which $|\langle\sigma\rangle|^2 = 2.3$. For the intensity of neutrino emission per nucleus for $0.1\ E \leq kT \leq 0.3\ E$ we obtain the estimate

$$l_\nu \geqslant \frac{1}{2}\left(\frac{G^2}{30\pi^3}\right)(6kT)^6 e^{-6} g_A^2 2.3.$$

The luminosity of the star is

$$L_\nu \approx 10^8 (T_9)^6 g_A^2\ \mathrm{erg}\cdot\mathrm{g}^{-1}\cdot\mathrm{s}^{-1}.$$

This estimate is too low, since we have taken into account only the transition from one of the levels into the ground state. For $T_9 = 5$ we have $L_\nu = 1.5 \times 10^{12} g_A^2\ \mathrm{erg}\cdot\mathrm{g}^{-1}\mathrm{sec}^{-1}$. For comparison we note that the Urca-process on nuclei for $T_9 = 5$ and $\rho = 10^7\,\mathrm{g/cm}^3$ yields a neutrino luminosity $L_\nu = 5 \times 10^{11}\ \mathrm{erg}\cdot\mathrm{g}^{-1}\cdot\mathrm{sec}^{-1}$[22], i.e., there exists a region of temperatures and densities in which the emission of neutrino pairs in nuclear transitions may make a noticeable contribution to the neutrino luminosity of a star.

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[1] B. Pontecorvo, Phys. Lett. 1, 287 (1962).
[2] S. S. Gershteĭn, Nguyen Van Hieu, and R. A. Eramzhyan, Zh. Eksp Teor. Fiz. 43, 1554 (1962) [Sov. Phys. JETP 16, 1097 (1963)].
[3] S. Sakashita and M. Nishida, Prog. Theor. Phys. 31, 727 (1964).
[4] D. Dicus, Phys. Rev. D6, 941 (1972).
[5] L. Desrosiers and P. J. O'Donnel, Phys. Rev. D2, 403 (1970).
[6] S. N. Biswas, R. N. Chaudhuri, and J. K. S. Taank, J. Phys. A: 6, 1751 (1973).
[7] J. N. Bahcall, S. B. Treiman, and A. Zee, Phys. Lett. B52, 275 (1974).
[8] H. Y. Chiu and E. E. Salpeter, Phys. Rev. Lett. 12, 413 (1964).
[9] A. Finzi, Astrophys. J. 139, 1398 (1964); Phys. Rev. B137, 472 (1965).
[10] D. G. Ellis, Phys. Rev. B139, 754 (1965).
[11] J. N. Bahcall and R. A. Wolf, Phys. Rev. B140, 1453 (1965).
[12] A. Finzi and R. A. Wolf, Astrophys. J. 153, 835 (1968).
[13] N. Itoh and T. Tsuneto, Prog. Theor. Phys. 48, 1849 (1972).
[14] E. Flowers, Astrophys. J. 180, 911 (1973).
[15] A. B. Migdal, Phys. Lett. B45, 448 (1973); B47, 96 (1973).
[16] F. E. Low, Phys. Rev. 110, 974 (1958).
[17] S. L. Adler and Y. Dothan, Phys. Rev. 151, 1267 (1966).
[18] V. S. Pinaev, Zh. Eksp. Teor. Fiz. 45, 548 (1963) [Sov. Phys. JETP 18, 377 (1964)].
[19] Ya. B. Zel'dovich and O. Kh. Khuseĭnov, Dokl. Akad. Nauk SSSR 162, 791 (1965) [Sov. Phys. Dokl. 10, 524 (1965)].
[20] O. Kh. Khuseĭnov, Astron. Zh. 43, 772 (1966); 45, 985 (1968) [Sov. Astron. 10, 613 (1967); 12, 783 (1969)].
[21] V. S. Imshennik, D. K. Nadezhdin, and V. S. Binaev, Ibid. 44, 768 (1967) [11, 617 (1968)].
[22] D. K. Nadezhdin and V. M. Chechetkin, Ibid. 46, 270 (1969) [13, 213 (1969)].
[23] H. Y. Chiu and R. Stabler, Phys. Rev. 122, 1317 (1961).
[24] H. Y. Chiu and P. Morrison, Phys. Rev. 5, 573 (1960).
[25] T. W. Donnely, D. Hitlin, and M. Schwartz, et al., Phys. Lett. B49, 8 (1974).
[26] R. A. Eramzhyan, V. N. Folomeshkin, S. S. Gershtein, and M. Yu. Khlopov, JINR Preprint E2-8305, Dubna, 1974.
[27] S. S. Hanna, Proc. Intern. Conf. on Nuclear Structure and Spectroscopy, Amsterdam, 1974, p. 249.

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