S173 ... 2

INSTITUTE FOR HIGH ENERGY PHYSICS

ИФВЭ
ОТФ 75-45

S.S. Gershtein, V.N. Folomeshkin, M.Yu. Khlopov
R.A. Eramzhyan

A15, A22

NEUTRAL CURRENTS AND NEUTRINO EMISSION OF STARS

Serpukhov 1975

S.S. Gershtein, V.N. Folomeshkin, M.Yu. Khlopov
R.A. Eramzhyan

NEUTRAL CURRENTS AND NEUTRINO EMISSION OF STARS

Аннотация

Герштейн С.С., Фоломешкин В.Н., Хлопов М.Ю., Эрамжян Р.А.
Нейтральные токи и нейтринное излучение звезд. Серпухов, 1975.
14 стр. (ИФВЭ СТФ 75-45).
Библиогр. 28.

Рассматривается возможность излучения пар $\nu_e \tilde{\nu}_e$ и $\nu_\mu \tilde{\nu}_\mu$ при столкновении нуклонов или ядерных переходах. Испускание нейтринных пар при столкновении нейтронов оказывается существенным для охлаждения нейтронных звезд. Излучение нейтринных пар при ядерных переходах оказывается эффективным непосредственно перед имплозией ядра горячей массивной звезды и на начальной стадии имплозии (до полной диссоциации ядер на нуклоны).

Abstract

Gershtein S.S., Folomeshkin V.N., Khlopov M.Yu., Eramzhyan R.A.
Neutral Currents and Neutrino Emission of Stars. Serpukhov, 1975.
p. 14. (IHEP 75-45)
Ref. 28.

Possible emission of $\nu_e \tilde{\nu}_e$ and $\nu_\mu \tilde{\nu}_\mu$ pairs in nucleon collisions or nuclear transitions has been studied. Neutrino pair emission in neutron collision turns out to be essential for cooling of neutron stars. Neutrino pair emission in nuclear transitions is effective just before the core implosion of a hot massive star and at the initial stage of implosion (till a full dissosiation of nuclei into nucleons).

Introduction

As is known neutrino emission plays an important role in the process of star evolution (especially, at the last stages of evolution when its rate is practically fully determined by neutrino losses of energy). It is true for the stage of smooth burning, prior to the star core implosion, as well as for the processes of core implosion and cooling of the produced neutron star.

Weak neutral hadronic currents, that manifest themselves in the observed neutrino scattering on nucleons, provide grounds for additional effective mechanisms of emitting neutrinos by stars. (This fact had been pointed out long before neutral currents were discovered /1-3/). Presence of neutral currents leads firstly to quantitative changes /4/ of the earlier calculated intensity of electronic neutrino-antineutrino pair emission, caused by $(\nu_e e)(\nu_e e)$ interaction. Second, it leads to emission of muonic neutrino in $(\nu_\mu \nu_\mu)(e e)$ interaction, and finally it opens possibilities for neutrino pair emission in nucleon collisions or nuclear transitions (as well as in photoproduction $\gamma N \to N \nu\nu$).

In the present paper we consider the latter mechanism of neutrino emission due to neutral currents(contribution of $\gamma N \to N \nu \tilde{\nu}$ process to the neutrino emission of stars is very small[5,6]). Emission of neutrino pairs in neutrino collisions is important for cooling of neutrino stars (§2).

Emission of neutrino pairs from nuclear transitions at comparatively low temperatures ($T < 10^8$ °K) was considered in ref.[8]. Under these conditions neutrino emission may take place due to nuclear transitions between the low levels of some selected isotopes. The contribution of this mechanism to the total neutrino flux is small[8] (even if the small values of the corresponding matrix elements are not taken into account).This mechanism should be effective just before the core implosion of massive stars and at initial stage of implosion (till a total dissosiation of nuclei into nucleons).Under these conditions its contribution is comparable with the one from the Urca-process on nuclei (§3).

2. Neutrino Emission of Neutron Stars

The cooling rate of neutron stars determines the life time of such stars in hot stage, when they are intensive sources for x-rays.

The following conditions are characteristic for neutron stars: the Fermi energy of the degenerated neutron gas μ_n is approximately equal to the one of the generated electron gas $\mu_n \approx \approx \mu_e \approx 100$ MeV. In this case $\mu_p \approx 5$ MeV for protons, and the matter density is about 10^{14}-10^{15} g/cm^3.

The reactions $nn \to npe\nu$, $epn \to nn\nu$ /9-15/ was considered as one of the possible mechanisms of neutron star cooling. It was assumed that probability for a transverse reaction $epn \to nn\nu$ is comparable with the probability of the direct reaction $nn \to npe\nu$ and the probability for the latter one only was considered. On the contrary with the two-step character of the reaction with charged currents the considered process $nn \to nn\nu\nu$ is one-step.

A step by step consideration of the processes should follow the theory of the neutron Fermi liquid and with account of possible effects of pion condensation in nuclear matter /16/. However we will limit ourselves with the simplest model of degenerated Fermi gas as a first approximation.

A. Cross Section for Reaction $nn \to nn\nu\tilde{\nu}$

The amplitude for the process

$$nn \to nn\nu\tilde{\nu} \qquad (1)$$

has the form $M = \frac{G}{\sqrt{2}} \ell_a H_a$ where $\ell_a = \tilde{\nu}\gamma_a(1+\gamma_5)\nu$, $H_a = V_a + A_a$ is the matrix element of neutral neutrino hadronic current, assumed in the form of the sum of vector and axial interactions. Let us denote the momenta of the initial and final neutrons as p_1, p_2 and p_3, p_4 and k_1, k_2 stand for neutrino momentum. E_1, E_2, E_3, E_4, ω_1, ω_2 are the energies of the corresponding particles, $k = k_1 + k_2$, $\omega = \omega_1 + \omega_2$. The cross section of reaction (1) for emission of pairs $\nu_e \tilde{\nu}_e$ and $\nu_\mu \tilde{\nu}_\mu$ may be written in the form

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

$$F = \int \overline{|M|^2} \frac{d^3k_1\, d^3k_2}{\omega_1 \omega_2} \delta^4(k - k_1 - k_2) =$$

$$= \frac{2}{3} \pi G^2 [\, |k_\alpha H_\alpha|^2 - k^2 |H|^2], \qquad I = \sqrt{(p_1 p_2)^2 - m^4}. \qquad (3)$$

The probability for reaction (1) with emission of soft $\nu\tilde{\nu}$-pairs may be estimated with using the low energy theorems /17-18/. The expansion terms of the matrix element of the order of k^{-1}, that make the main contribution in the limits of low energies, arise due to emission of $\nu\tilde{\nu}$-pairs from the outer lines of the diagram which describes elastic neutron-neutron scattering. In the energy region we are interested in (corresponding to $0 < E_n < 400$ MeV in the lab.system), elastic nn-scattering is practically isotropic. Therefore for estimations we can restrict ourselves with S-wave neutron-neutron scattering. Having written down the vertex of weak interaction $(nn)(\nu\nu)$ in the form $\ell_\alpha[\bar{n}\,\gamma_\alpha(g_V + g_A\gamma_5)n]$ and taken into account the emission of $\nu\tilde{\nu}$-pairs from all the outer lines, we will obtain the expression

$$F = \frac{1}{3} 2^{11} \pi^2 G^2 g_A^2 \sigma_{nn} [(kp_1 - kp_2)^2 + (kp_3 - kp_4)^2](\omega^2 + 2k^2)/\omega^4 \qquad (4)$$

for the magnitude F. Here σ_{nn} is the cross section for elastic nn → nn scattering. In nonrelativistic approximation the contribution of weak vector interaction to the emission of $\nu\tilde{\nu}$-pairs in nn collisions is equal to zero. This result is similar to the absence of dipole electromagnetic emission for collision of the charged particles with equal ratio e/m. If the contribution of one diagram only is taken into account, e.g. in ref./10/, then the vector part of the interaction is not compensated, and the result turns out to be higher. It worth noticing that such a compensation seems not to occur in neutrino scattering on nuclei.

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

$$\sigma_\nu = \frac{2^8 G^2 m^4 g_A^2 \sigma_{nn}}{3^4 5^2 7 \pi^4} (E/m)^5 \tag{5}$$

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

We would note that in the soft-pion limit (when $m_\pi = 0$) cross section (1) may be related to the cross section for pion production in nucleon-nucleon collisions. Indeed in nonrelativistic approximation the following relation takes place for nucleons

$$g(N\gamma_5 N)\phi_\pi = \frac{g}{2m}\phi_\pi(\bar{N}\hat{k}\gamma_5 N),$$

where $g^2/4\pi = 14.6$, k_α is pion momentum and the cross section for reaction may be presented in the form

$$\sigma_\pi = \frac{g^2/4\pi}{2^{12}\pi^4 m^2 I}\int |K_\alpha A_\alpha|^2 \frac{d^3k\, d^3p_3\, d^3p_4}{\omega E_3 E_4}\delta^4(p_1 + p_2 - p_3 - p_4 - k). \tag{6}$$

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

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

Unfortunately this expression can hardly be used in the energy range of our interest, as the experimental data on $\sigma_\pi(E)$ are known only above the production threshold of real pion.

B. Reaction $nn \to nn\nu\tilde{\nu}$ under Conditions of Neutron Star

Under conditions of a neutron star the neutron gas is highly degenerated, and it can effectively emit only a small number of neutrons near the Fermi surface. In this case the energy of pair $\omega \ll \mu_n$. With an accuracy up to the terms of the order of $\beta^{-1} = T/\mu_n$ expression (4) may be presented in the form

$$F = \frac{1}{3} 2^{12} \pi^2 G^2 g_A^2 \sigma_{nn} (kp_1 - kp_2)^2 (\omega^2 + 2k^2)/\omega^4. \tag{8}$$

Specific luminosity of neutrino energy losses with emission of $\nu_e \tilde{\nu}_e$ and $\nu_\mu \tilde{\nu}_\mu$ pairs is equal to

[illegible] $$_{\nu} = \int d^4 k \, \omega \, S \, F \, \delta^4 (p_1 + p_2 - p_3 - p_4 - k)/(2^5 \pi^2), \tag{9}$$

$$S = S_1 S_2 S_3 S_4, \qquad S_i = d^3 p_i \,/[E_i (2\pi)^3 (1 + \exp(\pm \frac{E_i - \mu}{T}))], \tag{10}$$

the sign "+" stands for initial neutrons ($i = 1,2$) and the sign "−" stands for final neutrons ($i = 3,4$).

After integration expression (9) takes the form

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

$$J = \int_{-\beta}^{\infty} dx_1 \int_{-\beta}^{\infty} dx_2 \int_{-\beta-x_1-x_2}^{\beta} dx_3 \int_{-x_1-x_2-x_3}^{\beta} dx_4 \, (x_1 + x_2 +$$

$$+ x_3 + x_4)^4 Q \simeq 540, \tag{12}$$

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

$p_F^2 = 2\mu m$, $\langle\sigma\rangle$ - cross section for nn-scattering averaged in energy,

$$\langle\sigma\rangle = \frac{1}{E_{max}} \int_0^{E_{max}} \sigma(E)\, dE.$$

When $\mu = 100$ MeV, $\langle\sigma\rangle \simeq 42$ mbn. For the magnitude L_ν we obtain

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

This value is close to the emission intensity, estimated for reaction $nn \to npe\nu$ /9-13/. Thus we come to a conclusion that neutral currents may play an important role in cooling of neutron stars.

As it was mentioned above, the effects of pion condensation may also play an important role in neutrino luminosity of neutron stars. Emission of $\nu\tilde{\nu}$ pair by pions in pion-nucleon scattering will be enlarged due to a smaller mass of pion and absence of its suppression at the account of the Pauli principle in degenerated neutron gas.

3. Neutrino Emission of Hot "Iron" Stars

Urka-processes and processes of electron-positron pair annihilation are the main processes of neutrino emission at the latest stage of star evolution (before implosion and possible burst of a supernew star). Weak neutral hadronic currents make possible nuclear exitation in neutrino scattering /2,26,27/, and correspondingly, $\nu\tilde{\nu}$ pair emission in transition from higher to lower nuclear levels.

The main contribution to the process $(A,Z)^* \to (A,Z)$ is determined by the permitted transition and is caused by the axial part of a weak current (by isoscalar if it exists at all, as well as by isovector). The probability of emitting $\nu_e\tilde{\nu}_e$ and $\nu_\mu\tilde{\nu}_\mu$ pairs by exited nucleus may be presented in the form

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

and emission intensity is

$$L_\nu = W(E)\, E \exp(-E/kT)\,.$$

If $|\langle\sigma\rangle|^2$ is independent of energy then the emission maximum corresponds to the levels with exitation energy of E=6kT and the intensity of emission within the interval 3,5 kT< E <9,5 kT, is not less than one half of the intensity from levels with $E = 6$ kT.

At the "iron" stage of star evolution their isotopic composition is determined by the elements Fe, Mn, Co. In this domain intensive Gamov-Teller transitions are in the region of exitation energy from 5 up to 12 MeV /28/. In particular, for ^{56}Fe they are within the range from II up to 12 MeV. For ^{57}Fe in the region of 7 MeV of and in the case of ^{58}Ni this domain is (5-8)MeV(isoscalar branch) and 10-12 MeV (isovector one).

The magnitude $|\langle\sigma\rangle|^2$ for lower levels is small (in particular the value of matrix elements for transition from 14 KeV for ^{57}Fe ΔE=67 KeV for ^{61}Ni discussed in ref. /8/ is small).

The main contribution to the Gamov-Teller matrix element in the considered domain of nuclei is caused by the one particle transition $1f_{5/2} \to 1f_{7/2}$ for which $|\langle\sigma\rangle|^2 = 2.3$. For emission intensity per nucleus when $0.1\ E < kT < 0.3\ E$ we will obtain the estimation

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

The star luminosity is

$$L_\nu = 10^8\,(T_9)^6\, g_A^2 \quad \text{erg.g}^{-1}\text{.sec}^{-1}.$$

This estimation is slightly lowered, as we have taken into account a transition from one level only and to the ground state only.

When $T_9 = 5$ $L_\nu = 15 \cdot 10^{12} g_A^2$ erg.g.$^{-1}$.sec^{-1}. For comparison we would note that Urka process on nuclei when $T_9 = 5$ and $\rho = 10^7$ g/cm^3 leads to neutrino luminosity $L_\nu 5 \cdot 10^{11}$erg.g.$^{-1}$.sec^{-1}/23/. It means that there does exist a region of temperatures and densities, where emission of neutrino pairs in nuclear transitions may make a considerable contribution to the neutrino luminosity of stars.

In conclusion we express our gratitude to G.S.Bisnovaty-Kogan, G.V.Domogatsky, V.S.Imshennik, D.K.Nadezhin, V.M.Chechetkin for discussions of this paper.

References

1. B.Pontecorvo. Phys. Lett., 1, 287 (1962).
2. С.С.Герштейн, Нгуен Ван Хьеву, Р.А.Эрамжян. ЖЭТФ, 53, 1554 (1962).
3. S.Sakashita, M.Nishida. Progr.Theor.Phys., 31, 727 (1964).
4. D.Dicus. Phys.Rev., D6, 941 (1972).
5. L.Desrosiers, P.J.O'Donnel. Phys.Rev., D2, 403 (1970).
6. S.N.Biswas, R.N.Chandhuri, J.K.S.Taank. J. Phys. A: Math.Gen., 6, 1751 (1973).
7. J.N.Bahcall, S.B.Treiman, A.Zee. Phys. Lett., B52, 275 (1974).
9. H.Y.Chiu, E.E.Salpeter. Phys. Rev. Lett., 12, 413 (1964).
10. A.Finzi. Astroph. J., 139, 1398 (1964); Phys.Rev., B137, 472 (1965).
11. D.G.Ellis. Phys. Rev, B139, 754 (1965).
12. J.N.Bahcall, R.A.Wolf. Phys.Rev., B140, 1453 (1965).

13. A.Finzi, R.A.Wolf. Astroph. J., 153, 835 (1968).
14. N.Itoh, T.Tsuneto. Progr. Theor. Phys., 48, 1849) (1972).
15. E.Flowers. Astroph, J., 180, 911 (1973).
16. A.B.Migdal. Phys. Lett., B45, 448 (1973): B47, 96 (1973)
17. F.E.Low. Phys.Rev., 110, 974 (1958).
18. S.L.Adler, Y.Dothan. Phys. Rev., 151, 1267 (1966).
19. В.С.Пинаев. ЖЭТФ, 45, 548 (1963).
20. Я.Б.Зельдович, О.Х.Гусейнов. ДАН СССР, 162, 791 (1965).
21. О.Х.Гусейнов. Астрон. журнал, 43, 772 (1966); 45, 985 (1968).
22. В.С. Имшенник, Д.К. Надежин, В.С. Пинаев. Астрон. журнал, 44, 768 (1967).
23. Д.К.Надежин, В.М.Чечеткин. Астрон. журнал, 46, 270 (1969).
24. H.Y.Chiu, T.Stabler. Phys. Rev., 122, 1317 (1961).
25. H.Y.Chiu, P.Morrison. Phys.Rev.Lett., 5, 573 (1960).
26. T.W.Donnely, D.Hitlin, M.Schwartz et al. Phys. Lett., B49, 8, (1974).
27. R.A.Framzhyan, V.N.Folomeshkin, S.S.Gershtein, M.Yu.Khlopov. JINR, E2-8305, Dubna (1974).
28. S.S.Harna. Proc. Intern. Conf, on Nuclear Structure and Spectroscope. Amsterdam, p.249 (1974)

Received 24 March 1975.

Цена 7 коп.

Издательская группа И Ф В Э
Заказ 374. Тираж 290. 0,6 уч.-изд.л. Т-08927.
Апрель 1975. Редактор А.А. Антипова.