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Plasma neutrino energy loss due to the axial-vector current at the late stages of stellar evolution*

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Abstract Based on the Weinberg-Salam theory, the plasma neutrino energy loss rates of vector and axial-vector contributions are studied. A ratable factor of the rates from the axial-vector current relative to those of the total neutrino energy loss rates is accurately calculated. The results show that the ratable factor will reach a maximum of 0.95 or even more at relatively higher temperature and lower density (such as $\rho/\mu_e < 10^7$ g/cm^3). Thus the rates of the axial-vector contribution cannot be neglected. On the other hand, the rates of the axial-vector contribution are on the order of ~0.01% of the total vector contribution, which is in good agreement with Itoh's at relatively high density (such as $\rho/\mu_e > 10^7$ g/cm^3) and a temperature of $T \leqslant 10^{11}$ K.

Key words Weinberg-Salam theory, plasma neutrino energy loss, stellar evolution

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1 Introduction

Neutrino astrophysics has entered a new important stage of development. In recent years, considerable progress has been made in the studies of neutrino energy loss, and neutrino reactions at the stages of stellar evolution have been a subject of interest in astrophysics. Neutrinos interact so weakly with matter, and can escape with lots of messages and energy which are taken away from the star unhindered in circumstances where photons are trapped. Therefore, research on the neutrino and neutrino energy loss (hereafter referred to as NEL) rates has been a hotspot and frontier issue in astrophysics and particle-physics.

It is well known that the neutrino energy loss is important during the stellar evolution, for instance, in the red giant stages of stellar evolution; the cooling of white dwarfs and neutron stars; the X-ray burst models, as well as during supernova collapse. The energy loss rate due to neutrino emission receives a contribution from both the weak nuclear reactions and purely leptonic processes. However, for the rather large values of density and temperature which characterize the final stages of stellar evolution, the latter one is largely dominant. The leading leptonic processes are the following: pair annihilation; ν-photoproduction; plasmon decay and bremsstrahlung on nuclei. One of the crucial parameters which strongly affect the stellar evolution is the cooling rate. An accurate determination of neutrino emission rates is therefore eassential in order to perform a careful study of the final branches of star evolutionary tracks. In particular, a change in the cooling rates at the very late stages of massive star evolution could sensibly affect the evolutionary time scale and the iron core configuration at the onset of a supernova explosion, whose triggering mechanism still lacks a full theoretical understanding. Thus some authors, such as Hirata K et al.[1]; Bionta R M et al.[2]; Fuller, Flower and Newman[3]; S. Esposito et al.[4]; and Liu and Luo[5—9], have studied extensively the neutrino energy loss rates and obtained plenty of results.

Adams, Ruderman, and Woo[10], and also Dicus[11] remarked that the contribution of the axial-vector current to the plasma neutrino process is much smaller than that of the vector current. The plasma NEL was also investigated by Naoki Itoh et al.[12, 13] based on the Weinberg-Salam theory. It is found that the axial-vector contribution to the plasma neutrino energy loss rate is at most on the order of 0.01% of the vector contribution for $T \leqslant 10^{11}$ K. In this paper,

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based on the Weinberg-Salam theory, according to the method of Beaudet G, Petrosian V and Salpeter E E,(hereafter referred to as BPS) the plasma NEL due to the axial-vector current will be reinvestigated. We will consider the axial-vector contribution and the vector contribution to the plasma NEL rates at the density-temperature range of 10^2 g/cm^3 $\leqslant \rho/\mu_e \leqslant$ 10^{13} g/cm^3 and $T \leqslant 10^{11}$ K.

2 The NEL rates

The NEL rates per unit volume per unit time due to the plasma neutrino process are written as[14, 15]

$$Q_{\rm plasma} = \left(C_{\rm V}^2 + nC_{\rm V}^{\prime 2}\right) Q_{\rm V} + \left(C_{\rm A}^2 + nC_{\rm A}^{\prime 2}\right) Q_{\rm A}\,, \quad (1)$$

where

$$C_{\rm V} = \frac{1}{2} + 2\sin^2\theta_{\rm W};\ \ C_{\rm A} = \frac{1}{2};\ \ C'_{\rm V} = 1 - C_{\rm V};\ \ C'_{\rm A} = 1 - C_{\rm A}$$

and $\sin^2\theta_{\rm W} = 0.23$. $\theta_{\rm W}$ is the Weinberg angle and n is the number of the neutrino flavors other than the electron neutrino, whose masses can be neglected compared with $K_{\rm B}T$. Corresponding to the vector and axial-vector contributions in Eq. (1), we order

$$Q_1 = \left(C_{\rm V}^2 + nC_{\rm V}^{\prime 2}\right) Q_{\rm V}, Q_2 = \left(C_{\rm A}^2 + nC_{\rm A}^{\prime 2}\right) Q_{\rm A}.$$

So Eq. (1) will be written as

$$Q_{\rm plasma} = Q_1 + Q_2\,, \quad (2)$$

where Q_1 and Q_2 are the NEL rates due to the plasma neutrino process which correspond to the vector and axial-vector contributions. The vector contribution $Q_{\rm V}$ in Eq. (1) consists of two parts: the contribution of the longitudinal plasma $Q_{\rm L}$ and that of the transverse plasma $Q_{\rm T}$[13] and has been calculated by BPS as (we use the natural units in which $h = c = 1$ in this article unless specified explicitly),

$$Q_{\rm V} = Q_{\rm T} + Q_{\rm L}\,, \quad (3)$$

$$Q_{\rm T} = A_0 \left(\frac{h\omega_0}{mc^2}\right)^6 \left(\frac{1}{mc}\right)^3 \int_0^\infty \frac{|k|^2}{{\rm e}^{h\omega/kT} - 1} {\rm d}|k| = A_0 \gamma^6 \lambda^9 \int_\gamma^\infty \frac{x\left(x^2 - \gamma^2\right)^{1/2}}{{\rm e}^x - 1} {\rm d}x\,, \quad (4)$$

$$Q_{\rm L} = A_0 \left(\frac{h}{mc^2}\right)^9 \frac{1}{2} \left(\frac{5}{3}\right)^{7/2} \left(\frac{1}{\omega_1}\right)^7 \int_{\omega_0}^{a\omega_0} \frac{\omega^{10}\left(\omega^2 - a^2\right)^2 \left(\omega^2 - \omega_0^2\right)^{1/2}}{{\rm e}^{h\omega/kT} - 1} {\rm d}\omega = A_0 \gamma^6 \lambda^9 \left(\frac{\omega_0}{\omega_1}\right)^7 \frac{1}{2} \left(\frac{5}{3}\right)^{7/2} \int_1^a \frac{y^{10}\left(y^2 - a^2\right)^2 \left(y^2 - 1\right)^{1/2}}{{\rm e}^{\gamma y} - 1} {\rm d}y\,, \quad (5)$$

where

$$A_0 = \frac{g^2}{48\pi^4\alpha} mc^2 \left(\frac{mc^2}{h}\right) \left(\frac{mc}{h}\right)^3 = 3.001 \times 10^{21}\ {\rm ergs/(cm^3 \cdot s)}\,,$$

$$g = \frac{Gm^2c}{h^3},\ \gamma = \frac{h\omega_0}{KT},\ \lambda = \frac{KT}{mc^2},\ a = \left[1 + \frac{3}{5}\left(\frac{\omega_1}{\omega_0}\right)^2\right]^{1/2},$$

$$\left(\frac{h\omega_0}{mc^2}\right)^2 = \frac{4\alpha}{3\pi}\left[2G^+_{-1/2} + 2G^-_{-1/2} + G^+_{-3/2} + G^-_{-3/2}\right],$$

$$\left(\frac{h\omega_1}{mc^2}\right)^2 = \frac{4\alpha}{3\pi}\left[2G^+_{-1/2} + 2G^-_{-1/2} + G^+_{-3/2} + G^-_{-3/2} - 3G^+_{-5/2} - 3G^-_{-5/2}\right],$$

$$G_n^{\pm}(\lambda, \nu) = \lambda^{3+2n} \int_{\lambda-1}^\infty \frac{x^{2n+1}\left(x^2 - \lambda^{-2}\right)^{1/2}}{1 + {\rm e}^{x \pm \nu}} {\rm d}x$$

$$\nu = \frac{\mu}{KT},\ G = 1.02679 \pm 0.00002 \times 10^{-5} h^3/\left(M^2c\right)$$

where α is the fine-structure constant; G, the Fermi coupling constant[16]; M, the mass of a proton; ω_0, the plasma frequencies in units of the electron mass $m_{\rm e}$ and ω_1, the first order correction to the plasma frequencies. According to the calculations of BPS, the vector contribution $Q_{\rm V}$ is written as

$$Q_{\rm V} = \left(\frac{\rho}{\mu_{\rm e}}\right)^3 \frac{\left(a_0 + a_1\xi + a_2\xi^2\right){\rm e}^{-c\xi}}{\xi^3 + b_1\lambda^{-1} + b_2\lambda^{-2} + b_3\lambda^{-3}}\,, \quad (6)$$

where $\xi = \left(\frac{\rho/\mu_{\rm e}}{10^9\ {\rm gcm^{-3}}}\right)^{1/3} \lambda^{-1}$ and $\lambda = \frac{KT}{mc^2} = 0.1686T_9$, T_9 is the temperature in units of 10^9 K. The constants of a_0, a_1, a_2, b_1, b_2, b_3 and c will be found in Ref. [17], which were given by BPS.

The axial-vector contribution $Q_{\rm A}$ is given by Y. Kohyama et al[12].

$$Q_{\rm A} = 1.11 \times 10^{-9} \left(\frac{\rho}{\mu_{\rm e}}\right)^3 \xi^{-3} {\rm e}^{-0.555\xi} \times \left[\alpha_0 + \left(1.00 + \alpha_1\xi^{-1} + \alpha_2\xi^{-5}\right)^{-1}\right], \quad (7)$$

where

$$\alpha_0 = 3.40\times10^{-3}/(1.00+12.5\lambda^{-2}),$$

$$\alpha_1 = 7.76+0.055\lambda^{-1},\quad \alpha_2 = 0.50\lambda^{-0.50}+0.014\lambda^{-4},$$

μ_e is the electron mean molecular weight and ρ is measured in units of g/cm^{-3}. In order to compare the contribution of the axial-vector current with that of the vector current in the total plasma NEL process, a ratable factor is defined as

$$C = Q_2/Q_{\rm plasma} = Q_2/Q_1+Q_2 = \left[\left(C_{\rm A}^2+nC_{\rm A}'^2\right)Q_{\rm A}\right]/ \left[\left(C_{\rm V}^2+nC_{\rm V}'^2\right)Q_{\rm V}+\left(C_{\rm A}^2+nC_{\rm A}'^2\right)Q_{\rm A}\right]. \qquad (8)$$

As BPS pointed out, the present theory is not valid when the condition of $h\omega_0 \geqslant 2mc^2$ and the electron nondegeneracy condition are both satisfied.

3 Some numerical results of the NEL rates and discussions

Figures 1 and 2 show that the ratable factor C varies with the temperature of T_9 for different types of neutrino flavors n = 0, 1, 2 at the density of 10^2 g/cm^3, 10^3 g/cm^3, 10^4 g/cm^3, 10^5 g/cm^3, 10^6 g/cm^3, 5.86×10^7 g/cm^3, 3.30×10^8 g/cm^3 and 10^{13} g/cm^3 respectively. One can find from the two figures that the ratable factor is very sensitive to the temperature. The higher the temperature is, the larger the factor is. For example, the factor C increases to a maximum of 0.95 at temperatures of T_9=20 and T_9=40 in Fig. 1. On the other hand, one can also find from Fig. 1 that the factor C always increases as the temperature of T_9 changes from 0—100. This is because the ratable factor strongly depends on the function of the temperature and the density when the temperature is so high and the density is low enough. The higher the temperature is, the lager the factor is, and it will be close to 1. This is due to the fact that the electron gas has been in nondegenerate states. The axial-vector contributions are the major parts of all the contributions. Therefore the axial-vector contributions cannot be neglected.

The numerical results of the factor C are given in Fig. 2 at the density of 3.30×10^8 g/cm^3, 10^{13} g/cm^3 correspondingly. It has been found that the influence of the factor is on the order of ∼0.1% at different densities. The higher the temperature is, the smaller the factor is. For instance, the factor C will increase to a maximum of 4.0×10^{-4}. The calculations we obtained are in good agreement with Itoh's[12] at the temperature-density region of 10^7 g/cm^3 $\leqslant \rho/\mu_e \leqslant 10^{13}$ g/cm^3 and $T \leqslant 10^{11}$ K.

By analyzing the plasma NEL rates and the influence of the unstable factor, we draw the following conclusion that it is in good agreement with Itoh's at relatively high density (such as $\rho/\mu_e > 10^7$ g/cm^3). However, the ratable factor will reach a maximum of 0.95 or more at relatively higher temperature and lower density (such as $\rho/\mu_e < 10^7$ g/cm^3).

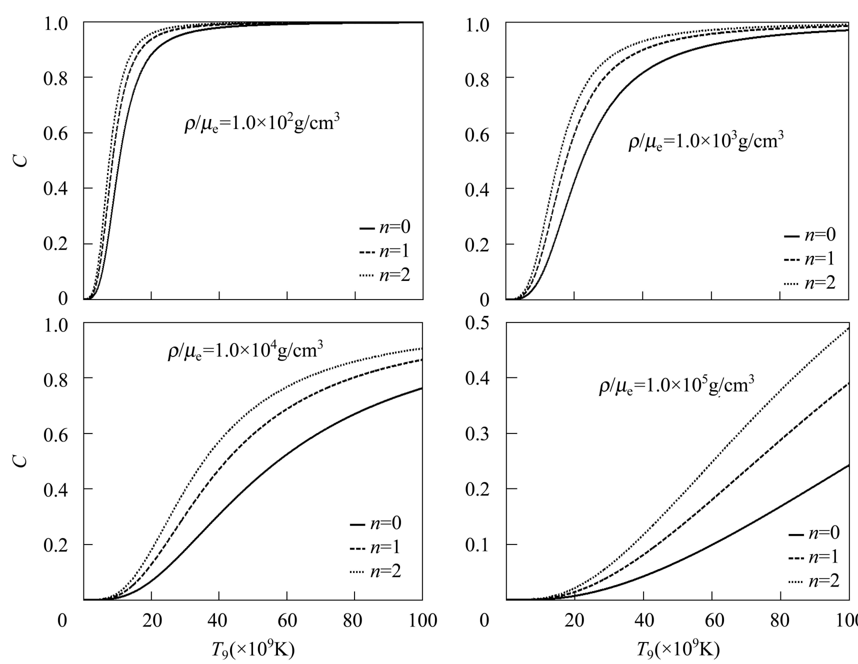

Fig. 1. The ratable factor C versus T_9 at the density of 10^2 g/cm^3, 10^3 g/cm^3, 10^4 g/cm^3, 10^5 g/cm^3 respectively. The curves from bottom to top correspond to n = 0, 1, 2.

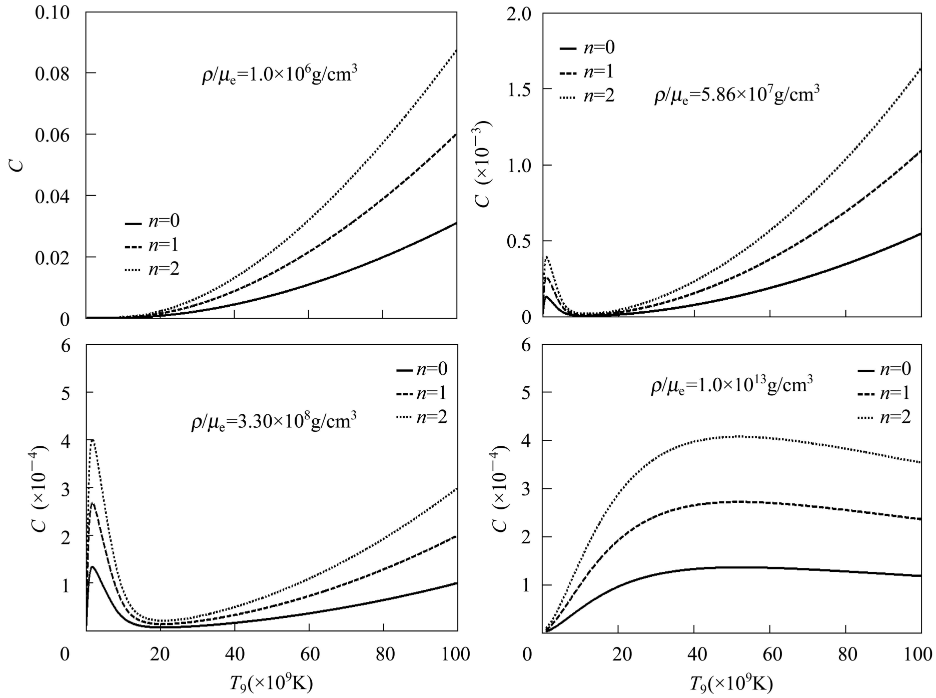

Fig. 2. The ratable factor C versus T_9 at the density of 1.0×10^6 g/cm^3, 5.86×10^7 g/cm^3, 3.30×10^8 g/cm^3, 1.0×10^{13} g/cm^3. The curves from bottom to top correspond to $n = 0, 1, 2$.

4 Concluding remarks

In summary, we calculated the neutrino energy loss rates due to the plasma neutrino process of the vector and axial-vector contributions using the Weibberg-Salam theory. We also discussed the influence of the ratable factor C versus T_9 at different density regions of 10^2 g/cm^3 $\leqslant \rho/\mu_e \leqslant 10^{13}$ g/cm^3. The results we obtained show that we cannot neglect casually the neutrino energy loss rates of the axial-vector contribution at the density-temperature region 10^2 g/cm$^3 \leqslant \rho/\mu_e \leqslant 10^7$ g/cm^3 and $T \leqslant 10^{11}$ K. However, the plasma NEL rates of the axial-vector contribution are on the order of ~0.01% relative to that of the total contribution. This is in good agreement with the results of Itoh, at relatively high density (such as $\rho/\mu_e > 10^7$ g/cm^3) and the temperature of $T < 10^{11}$ K.

As is well known, one of the crucial parameters which strongly affect the stellar evolution is the cooling rate. The energy loss during stellar life always plays a key role. It is in the form of electromagnetic or gravitational waves, and as a flux of neutrinos. Some research shows that the NEL is the main cooling mechanism during the late stages of stellar evolution, in particular for Dwarfs and supernovae. Thus the conclusion we have drawn may have a significant influence on further research on nuclear astrophysics and neutrino astrophysics; in particular, it might be extremely useful for numerical computation of the stellar evolution.

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