Pair neutrino energy loss for nuclei ^{56}Fe at the late stages of stellar evolution*

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Abstract Based on the Weinberg-Salam theory, the pair neutrino energy loss rates for nuclei ^{56}Fe are canvassed for the wide range of density and temperature. The results of ours ($Q_{\rm LJ}$) are compared with those of Beaudet G, Petrosian V and Salpeter E. E's ($Q_{\rm BPS}$), and it shows that the pair neutrino energy loss rates of $Q_{\rm BPS}$ are always larger than $Q_{\rm LJ}$ .The $Q_{\rm BPS}$ is 12.57%, 12.86%, 14.99%, 19.80% times higher than $Q_{\rm LJ}$ corresponding to the temperature T_9=0.385, 1.0, 5.0, 10, respectively.

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

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1 Introduction

According to the stellar evolution theory, when the temperature goes up to 5×10^9 K or more and the density is no more than 10^7 g/cm^3, the matter will have no degenerate nature in the cores of massive stars ($M>(60—100)M_\odot$). At this time, the average energy of the hot photons has already exceeded the quiescent energy of the electron. It is known that the radiation of pair neutrino would be dominated over other electromagnetic radiations. During this evolution period, a good many neutrinos which can escape unhindered in circumstances where photons are trapped, are produced and carry away a large quantity of messages and energy from stellar. On the other hand, the gravitation of the massive star will exceed greatly the pressure of the electron gas. It may lead to the gravitation collapse of the massive star. Some researches show that the pair neutrino energy loss is large enough to make the core of the massive star cool greatly and the pressure of the electron gas would go down quickly. So the pair neutrino energy loss (PNEL) plays a key role and is the major factor for unstable gravitation collapse.

Some authors investigated extensive results of their calculation of the PNEL, such as Weinberg[1]; Salam[2] and Dicus[3]. Based on the Feynmann-Gell-Mann theory, Pinave[4] and Beaudet, Petrosian, and Salpeter (BPS)[5] remarked the PNEL. The PNEL rates were also investigated by Naoki Itoh et al.[6—8] based on the Weinberg-Salam theory. Ref. [9] investigated the PNEL at wide density-temperature region at the late stages of stellar evolution. Based on the Weinberg-Salam theory, the PNEL for nuclei ^{56}Fe will be investigated at the late stages of stellar evolution. We reconsider the PNEL rates, according to the method of Itoh's, for the wide range of the density and temperature. The results we obtained will be compared with BPS's which was reinvestigated according to the method of BPS's. The present paper is organized as follows. In the next Section, the calculation of the PNEL rates is formulated. In Section 3 some numerical results on the PNEL rates will be presented. Some conclusions are given in Section 4.

2 The PNEL rates

Based on the Weinberg-Salam theory, the PNEL rates per unit volume per unit time due to the pair neutrino process are written as[1, 2, 8]

$$Q_{\rm LJ} = \frac{1}{2}\left[(C_V^2+C_A^2)+n(C_V'^2+C_A'^2)\right]Q^+_{\rm pair}+ \frac{1}{2}\left[(C_V^2-C_A^2)+n(C_V'^2-C_A'^2)\right]Q^-_{\rm pair}\ , \quad (1)$$

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where $C_V = \frac{1}{2} + 2\sin^2\theta_{\rm W}$; $C_A = \frac{1}{2}$; $C'_V = 1 - C_V$; $C'_A = 1 - C_A$ and $\sin^2\theta_{\rm W} = 0.2319 \pm 0.0005$. $\theta_{\rm W}$ is the Weinberg angle and n is the number of neutrino flavors other than the electron neutrino, whose masses can be neglected compared with $K_{\rm B}T$ ($K_{\rm B}$ is the Boltzmann constant, T is the temperature of electron gas). According to Ref. [8], the pair neutrino energy loss rates are expressed in unit of ergs·cm^{-3}· s^{-1} as

$$\begin{aligned} Q_{\rm LJ} = & \frac{1}{2}\left[(C_V^2+C_A^2)+n(C_V'^2+nC_A'^2)\right]\times \\ & \left[1+\frac{(C_V^2-C_A^2)+n(C_V'^2-C_A'^2)}{(C_V^2+C_A^2)+n(C_V'^2+C_A'^2)}q_{\rm pair}\right]\times \\ & g(\lambda){\rm e}^{-2/\lambda}f_{\rm pair}\ , \end{aligned} \tag{2}$$

where

$$\begin{aligned} q_{\rm pair} = & (10.7480\lambda^2+0.3967\lambda^{0.5}+1.0050)^{-1.0}\times \\ & \big[1+(\rho/\mu_{\rm e})(7.692e+0.7\lambda^3+ \\ & 9.715e+0.6\lambda^{0.5})^{-1.0}\big]^{-0.3}, \end{aligned} \tag{3}$$

$$f_{\rm pair} = \frac{(a_0+a_1\xi+a_2\xi^2){\rm e}^{-c\xi}}{\xi^3+b_1\lambda^{-1}+b_2\lambda^{-2}+b_3\lambda^{-3}}, \tag{4}$$

$$g(\lambda) = 1-13.04\lambda^2+133.5\lambda^4+1534\lambda^6+918.6\lambda^8\ , \tag{5}$$

$$\xi = \left(\frac{(\rho/\mu_{\rm e})}{10^9{\rm gcm}^{-3}}\right)\lambda^{-1}\ , \tag{6}$$

$$\lambda = \left(\frac{T}{5.9302\times10^9{\rm K}}\right), \tag{7}$$

where $\rho/\mu_{\rm e}$ is the density in unit of g/cm^3 and T is the temperature in unit of K. We use the natural unit in which $\hbar = c = 1$ in this article unless specified explicitly. The constant a_0, a_1, a_2, b_1, b_2, b_3, c will be found in Ref. [7].

Based on the Feynmann-Gell-Mann theory, BPS calculated the NEL rates for the pair neutrino process. They fitted their results to[5]

$$\begin{aligned} Q_{\rm BPS} = & \frac{g^2}{18\pi^5}(mc^2)\left(\frac{mc}{\hbar}\right)^3\left(\frac{mc^2}{\hbar}\right)\times \\ & \big[G_0^-(7G_{1/2}^++5G_{-1/2}^+)+G_0^+(7G_{1/2}^-+5G_{-1/2}^-)+ \\ & G_1^-(8G_{1/2}^+-2G_{-1/2}^+)+G_1^+(8G_{1/2}^--2G_{-1/2}^-)\big], \end{aligned} \tag{8}$$

$$G_n^{\pm}(\lambda,\nu) = \lambda^{3+2n}\int_{\lambda^{-1}}^{\infty}\frac{x^{2n+1}(x^2-\lambda^{-2})^{1/2}}{1+{\rm e}^{x\pm\nu}}{\rm d}x, \tag{9}$$

$$g = Gm^2 = (3.002\pm0.006)\times10^{-12}\ . \tag{10}$$

In order to compare the results of $Q_{\rm LJ}$ with those of $Q_{\rm BPS}$ for the nuclei ^{56}Fe at different temperatures, the factors C are defined as follows

$$C = (Q_{\rm BPS}-Q_{\rm LJ})/Q_{\rm LJ}\ . \tag{11}$$

3 Some numerical results on PNEL rates

Figure 1(a—d) show that the NEL rates for nuclide ^{56}Fe vary with density $\rho/\mu_{\rm e}$ at the temperature T_9 = 0.385, 1.0, 5.0, 10 respectively (T_9 is the temperature in unit of 10^9 K). One can find that the PNEL rates are sensitive to the temperature. The higher the temperature (such as T_9=15), the smaller the affection on the NEL. For example, the PNEL rate $Q_{\rm LJ}$ of ^{56}Fe is 1.5×10^4 ergs·cm^{-3}·s^{-1} at the density of 10^4 g/cm^3 and T_9=0.385 in Fig. 1(a), but it will increase to 6.2×10^{21} ergs·cm^{-3}·s^{-1} at T_9=5 in Fig. 3(c). The reason is that the Boltzmann factor ${\rm e}^{-(2/\lambda)}$ is very small at lower temperature (such as T_9=0.385) but it is very important at medium and high temperature (such as T_9=5), especially at lower density (such as density of 10^4 g/cm^3).

On the other hand, the comparison of the results of $Q_{\rm LJ}$ with those of $Q_{\rm BPS}$ for the nuclei ^{56}Fe at different temperatures will be shown in the four figures. One can also find that the PNEL rates of $Q_{\rm BPS}$ are always larger than $Q_{\rm LJ}$. The higher the temperature (such as T_9=10) is the larger the difference of the PNEL rates is between $Q_{\rm BPS}$ and $Q_{\rm LJ}$. It may be the reason that the pair neutrino process will be dominated over the other neutrino energy loss processes at relativity high temperature (such as $T > 10^9$ K) due to the strong dependence of the number density of the electron and positrons. It is readily seen that the NEL rates of BPS are higher than ours because no consideration is given to the plasma affection on the electron-positron pairs by BPS. As they thought the plasma affection is important only for large $\gamma(\gamma = \frac{\hbar\omega_0}{kT}$, where ω_0 is the plasma frequency).

The numerical results of the factor C versus the density of nuclei ^{56}Fe at different temperatures are given in Fig. 2. One can see that the maximum differences between BPS's and ours are 12.57%, 12.86%, 14.99%, 19.80% corresponding to the temperature of T_9=0.385, 1.0, 5.0, 10, respectively.

In summary, one can conclude that the influence of the temperature on PNEL is very obvious. The higher the temperature (such as T_9=10), the larger the affection on the PNEL. From the above five figures, we can also find that the density has different effects on PNEL rates for nuclei ^{56}Fe at different temperatures. According to the condition of degenerate electron $\rho/\mu_{\rm e} > 2.4\times10^4\ T_8^{3/2}$ g/cm^3 (T_8 is the temperature in unit of 10^8 K), with increasing the electron number density, the electron Fermi energy is so high at high density that the electron is very easy to be degenerate and the pair neutrino process will be

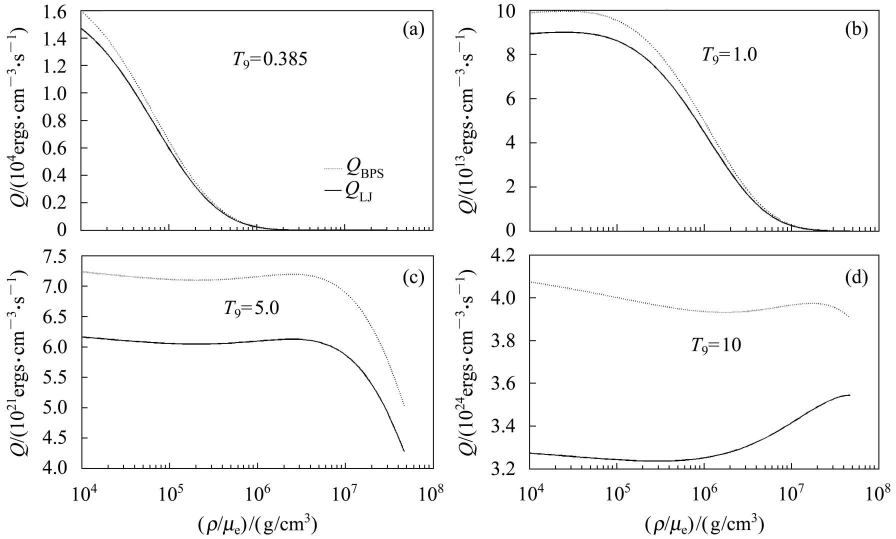

Fig. 1. The PNEL rates of $Q_{\rm BPS}$ and $Q_{\rm LJ}$ versus the density of nuclei ^{56}Fe at the temperature of T_9=0.385(a), 1.0(b), 5.0(c), 10(d).

bated, thus the PNEL rates will decrease. On the contrary, with the augment of the electron gas temperature, at low density and high temperature the electron Fermi energy is so small and the electron average energy is high enough, the energy of γ photons will also increase greatly. It will lead to annihilation of double γ photons and produce a good many electrons and protons, therefore the PNEL process will be dominated.

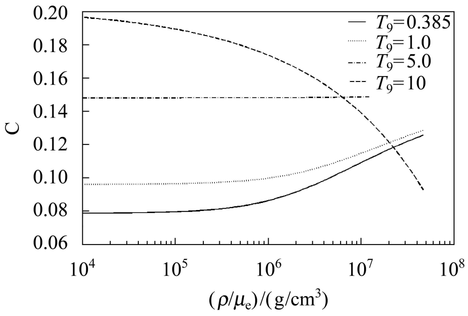

Fig. 2. The factor C versus the density of nuclei ^{56}Fe at different temperatures of T_9=0.385, 1.0, 5.0, 10.

4 Concluding remarks

We calculate the neutrino energy loss rates due to the pair neutrino process using the Weibberg-Salam theory. By analyzing the PNEL rates of the nuclei ^{56}Fe at different temperature-density region, we draw the following results that the PNEL rates are sensitive to the temperature. The PNEL rates of $Q_{\rm BPS}$ are always larger than $Q_{\rm LJ}$. The $Q_{\rm BPS}$ of the nuclei ^{56}Fe is 12.57%, 12.86%, 14.99%, 19.80% times higher than $Q_{\rm LJ}$ corresponding to the temperature T_9=0.385, 1.0, 5.0, 10 respectively.

As is well known, with the escape of a great number of neutrinos by pair neutrino process, the neutrino energy loss gives one of the main contributions to the cooling of stellar interior in the late stages of star evolution. It is helpful to the collapse and the explosion of the supernova[10]. Therefore the investigations on the neutrino energy loss have been the important questions and the conclusion we derived in this study may have significant help for further research of particle astrophysics and neutrino astrophysics.

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