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Bremsstrahlung neutrino energy loss for ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca, ^{56}Fe in strong electron screening*

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Abstract Based on Weinberg-Salam theory the bremsstrahlung neutrino energy loss for nuclei ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca and ^{56}Fe are investigated in strong electron screening. Our results are compared with those of Dicus' and show that the latter are higher by 2 orders of magnitude in the density-temperature region of 10^8 g/cm$^3 \leqslant \rho/\mu_e \leqslant 10^{11}$ g/cm^3 and $2.5 \leqslant T_9 \leqslant 4.5$. On the other hand, the factor C shows that the maximum differences are 99.16%, 99.13%, 99.12%, 99.055%, 99.040% corresponding to the nuclei ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca and ^{56}Fe.

Key words bremsstrahlung, neutrino energy loss, electron screening

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1 Introduction

The theory of weak interaction has been of great interest in astrophysics ever since Fermi introduced his far-sighted original theory of beta decay in 1935. In the following few years astrophysics experienced its greatest impact from modern nuclear physics. As is well known, neutrino and antineutrino emission is possible in some weak interactions processes. Since the work of Gamow & Schonberg [1], it has been recognized that the emission of neutrinos can be an important energy loss mechanism for dense stars and plays a key role in stellar evolution. Energy is cyclically carried away by the escaping neutrinos with seemingly no noticeable change for the nuclei participating in the reactions. This is so because the neutrino interaction with matter is so weak. Some researches show that if nuclear energy sources were absent inside the star, then the energy losses due to neutrinos could lead to collapse even before the nuclei of the iron group disintegrate into helium nuclei and free nucleons, the process which according to current views is a primary cause of type II supernovae explosions.

It is known that the main driving force of stellar evolution is the continuous loss of energy into the surrounding space. The neutrinos are the carriers of the escaping energy during most of the star's lifetime and play therefore a key role in stellar evolution. Due to changes of the various physical conditions inside a presupernova, different neutrino processes are important, such as electron capture process, the pair, photo-, plasma, bremsstrahlung and recombination neutrino processes. During the explosion process in a supernova a large quantity of energy is set free with the escaping of neutrinos. These neutrinos also carry a lot of information on the gravitational collapse. This huge energy loss shortens appreciably the timescale of the later stellar evolution. Therefore researches [2–8] on neutrinos and the neutrino energy loss have been a hotspot on the forefront in astrophysics and particle-physics.

The bremsstrahlung neutrino energy loss (BNEL) is a very important process. Based on the Feynmann-Gell-Mann theory, Beaudet, Petrosian and Salpeter [7] investigated the bremsstrahlung neutrino energy loss at $T \sim 10^8$ K and $\rho \sim 10^5$ g/cm^3, however did not consider the rates for very high density. On the other hand, including the neutral current effects, some authors had done pioneering work on this subject such as Feynman and Gell-Mann; Weinberg; Dicus and Flowers [8–11]. In recent years, considerable progress

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has been made in BNEL such as the researches of P. Haensel et al [12]; Itoh Naoki et al [13, 14].

Based on the Weinberg-Salam theory according to the method of Itoh, [14] we reinvestigate in this paper the BNEL for the nuclides ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca and ^{56}Fe. We also reinvestigate the BNEL rates according to the method of Dicus [15] which includes the neutral current effects for electrons in extreme degenerate states with a strong electron screening (SES). We give a few corrections of Dicus's fitting formulae, using $\sin^2\theta_{\rm W}=0.230$ instead of the value 0.45 used by Dicus and include the production of muon- and antimuon neutrinos. In stead of V-A theory we use the Weinberg-Salam theory which has not been discussed in detail by Dicus. On the other hand the obtained results will be compared with those of Dicus.

The present paper is organized as follows. In the next section, the calculation of BNEL rates is formulated. In section 3 some numerical results on BNEL rates will be presented. Some concluding remarks are given in section 4.

2 The BNEL rates

For the problems of this study, the condition for strongly degenerate electrons will be satisfied ($T=T_{\rm F}$ and $T=T_{\rm CS}$). $T_{\rm F}=E_{\rm F}/k_{\rm B}$, the Fermi temperature and $T_{\rm CS}$, the coulomb temperature [15], are given by

$$T_{\rm F}=5.9302\times10^9\left\{\left[1+1.018\left(\rho_6/\mu_{\rm e}\right)^{2/3}\right]^{1/2}-1\right\}[K], \tag{1}$$

$$T_{\rm CS}\equiv Z^2e^2/4\pi R_0k_{\rm B}. \tag{2}$$

On the other hand, the parameter which measures the strength of ionic correlations is defined by

$$\varGamma\equiv\frac{Z^2e^2}{aK_{\rm B}T}=2.275\times10^{-2}\frac{Z^2}{T_9}\left(\frac{\rho_6}{A}\right)^{1/3}, \tag{3}$$

here $\mu_{\rm e}=A/Z$, Z and A are the atomic number and mass number of the nucleus considered, R_0 is the screening radius , and $a=\left[3/(4\pi n_i)\right]^{1/3}$ is the ion-sphere radius, ρ_6 is the mass density in units of 10^6 g/cm^3 and T_9 is the temperature in units of 10^9 K.

As is well known, the ionic system will be in the liquid state for $\varGamma<180$ and in the crystalline lattice state for $\varGamma\geqslant180$. In this study we will discuss the neutrino energy loss rates under the conditions of $1\leqslant\varGamma\leqslant160$.

According to the method of Itoh (based on the Weinberg-Salam theory), the bremsstrahlung neutrino energy loss for strongly degenerate electrons will be expressed in units of erg$\cdot$cm$^{-3}\cdot$s^{-1} as (we use natural units $h=c=1$ in this article unless specified explicitly otherwise) [14]

$$\begin{aligned}Q_{\rm LJ}\ =\ &0.5738\times10^6\left(\frac{Z^2}{A}\right)T_9^6\rho\times\\ &\left\{\frac{1}{2}\left[(C_{\rm V}^2+C_{\rm A}^2)+n\left(C_{\rm V}^{\prime2}+C_{\rm A}^{\prime2}\right)\right]F-\right.\\ &\left.\frac{1}{2}\left[(C_{\rm V}^2-C_{\rm A}^2)+n\left(C_{\rm V}^{\prime2}-C_{\rm A}^{\prime2}\right)\right]G\right\},\end{aligned} \tag{4}$$

$$F(u,\varGamma)=vF(u,1)+(1-v)F(u,160), \tag{5}$$

$$G(u,\varGamma)=wG(u,1)+(1-w)G(u,160), \tag{6}$$

$$F(u,1)=\frac{a_0}{2}+\sum_{m=1}^{5}a_m\cos mu+\sum_{m=1}^{4}b_m\sin mu+cu+d, \tag{7}$$

$$F(u,160)=\frac{e_0}{2}+\sum_{m=1}^{5}e_m\cos mu+\sum_{m=1}^{4}f_m\sin mu+gu+h, \tag{8}$$

$$G(u,1)=\frac{i_0}{2}+\sum_{m=1}^{5}i_m\cos mu+\sum_{m=1}^{4}j_m\sin mu+ku+l, \tag{9}$$

$$G(u,160)=\frac{p_0}{2}+\sum_{m=1}^{5}p_m\cos mu+\sum_{m=1}^{4}q_m\sin mu+ru+s, \tag{10}$$

$$\begin{aligned}v\ &=\ \sum_{m=0}^{3}\alpha_m\varGamma^{-m/3},\quad w=\sum_{m=0}^{3}\beta_m\varGamma^{-m/3},\\ u\ &=\ 2\pi(\log_{10}\rho-3)/10,\end{aligned} \tag{11}$$

where

$$C_{\rm V}=\frac{1}{2}+2\sin^2\theta_{\rm W},\quad C_{\rm A}=\frac{1}{2},\quad C_{\rm V}'=1-C_{\rm V},$$

$C_{\rm A}'=1-C_{\rm A}$ and $\sin^2\theta_{\rm W}=0.230$, θ_W is the Weinberg angle and the n is number of the neutrino flavors different from the electron neutrino ($n=2$ in this work), whose masses can be neglected compared with kT. We consider the case in which atoms are completely ionized. Some coefficients can be found in Ref. [14].

In this study the special case of including the neutral current effects for electrons in extreme degenerate states with SES has been considered. A detailed discussion is given by Dicus D.A, et al [15]. According to the method of Dicus the strong Coulomb interaction between the nuclei for distance $r\leqslant R_0$ (R_0 is the screening radius) is expressed as

$$R_0=\left[\frac{3Z}{4\pi N_{\rm A}\rho Y_{\rm e}}\right]^{1/3}=\frac{(9Z\pi/4)^{1/3}}{P_{\rm F}}\approx\frac{1.92Z^{1/3}}{P_{\rm F}}, \tag{12}$$

where $N_{\rm A}$ is Avogadero's constant, $Y_{\rm e}$ is the average number of protons per atomic mass unit. The nuclear field is completely screened and the number density of the nuclei acquires its free-field value. The Coulomb potential of simple, pure matter can be expressed as

$$A_0(r) = \frac{Ze}{4\pi R_0}\left(\frac{R_0}{r} + \frac{r^2}{2R_0^2} + \frac{3}{2}\right)\theta(R_0 - r), \quad (13)$$

Based on Weinberg-Salam theory we give in the following the expression for the total BNEL rates (in units of ergs$\cdot$cm$^{-3}\cdot$s^{-1}) for the case of SES using the approximations of Festa and Ruderman [8] including the production of electron and muon neutrinos [15]

$$Q_{\rm Dicus} \approx 20 \times \frac{Z^2}{A} \times T_9^6 \times \left[\frac{1}{2}\left[(C_{\rm V}^2 + C_{\rm A}^2) + n(C_{\rm V}'^2 + C_{\rm A}'^2)\right]F_{\rm s}(\beta, Z) - \frac{1}{2}\left[(C_{\rm V}^2 - C_{\rm A}^2) + n(C_{\rm V}'^2 - C_{\rm A}'^2)\right]G_{\rm s}(\beta, Z)\right], \quad (14)$$

$$F_{\rm s}(\beta, Z) = 0.28\left[B_1(4W_2 - W_1) + (\beta^2 - 1)W_2W_3\right], \quad (15)$$

$$G_{\rm s}(\beta, Z) = 0.28(\beta^2 - 1)(W_3 - 4B_1)W_2, \quad (16)$$

$$B_1 = -\frac{2}{3} + \beta^2 + \frac{1}{2}\beta^2(1 - \beta^2)\ln\left|\frac{\beta + 1}{\beta - 1}\right|, \quad (17)$$

$$W_1 = 2 + \frac{6}{\varDelta^2}\left(\frac{\sin 2\varDelta}{2\varDelta} - 1\right) + \frac{9}{4\varDelta^2}\left(1 + \frac{\cos 4\varDelta}{32\varDelta^4} - \frac{1}{32\varDelta^4} + \frac{\sin 4\varDelta}{8\varDelta^3} - \frac{1}{8\varDelta^2}\right), \quad (18)$$

$$W_2 = \ln 2\varDelta + \gamma - C_i(2\varDelta) + \frac{\sin 2\varDelta}{4\varDelta^3} - \frac{\cos 2\varDelta}{2\varDelta^2} + \frac{\sin 2\varDelta}{2\varDelta} - \frac{3}{256\varDelta^6}(1 - \cos 4\varDelta) + \frac{3}{64\varDelta^5}\sin 4\varDelta - \frac{3}{128\varDelta^4}(3 + \cos 4\varDelta) + \frac{\sin 4\varDelta}{32\varDelta^3} + \frac{\cos 4\varDelta}{16\varDelta^2} - \frac{\sin 4\varDelta}{4\varDelta} - \frac{11}{12}, \quad (19)$$

$$W_3 = -\frac{4}{3} - \beta^2 + \frac{1}{2}\beta^2(\beta^2 + 1)\ln\left|\frac{\beta + 1}{\beta - 1}\right|, \quad (20)$$

$$C_i(x) = \ln x + \gamma + \sum_{n=1}^{\infty}(-1)^n\frac{x^{2n}}{2n(2n)!}, \quad (21)$$

$$\varDelta = R_0/P_{\rm F} \approx 1.92Z^{1/3}, \quad \gamma = 0.577215\cdots, \quad \beta = E_{\rm F}/P_{\rm F}, \quad (22)$$

where $\varDelta$ is a dimensionless function of Z only, γ and $C_i(x)$ are Euler's constant and the cosine integral respectively. $E_{\rm F}$ and $P_{\rm F}$ are the Fermi energy and the momentum of the electron gas.

In order to compare the results of $Q_{\rm LJ}$ with those of $Q_{\rm Dicus}$ for the nuclei ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca and ^{56}Fe at different temperatures, a factor C is defined as

$$C = \frac{(Q_{\rm Dicus} - Q_{\rm LJ})}{Q_{\rm Dicus}}. \quad (23)$$

3 Some numerical results on BNEL rates

Figures 1–5 show that the factors C calculated at different temperatures for ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca and ^{56}Fe vary with density. One finds that with SES included, factor C is sensitive to the temperature. The higher the temperature, the lower is the factor C. This reason is that to a higher temperature corresponds higher average electron energy, making the screening potential slightly less effective. The bremsstrahlung neutrino process would be dominated due to SES. On the other hand, one also observes that with increasing atomic charge Z the C decreases. It is for that reason that the conditions for the validity of the model of strong screening will be more strongly satisfied for the heavier elements ($R_0 \propto Z^{1/3}$). Therefore we conclude that due to the strong Z-dependence the bremsstrahlung neutrino process will be important for the heavy elements.

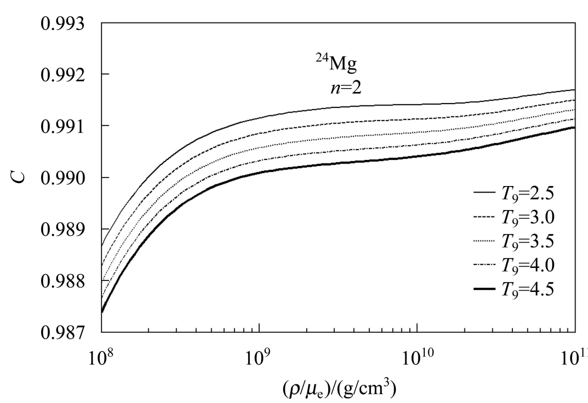

Fig. 1. Factor C for pure ^{24}Mg matter as a function of the density for different temperatures.

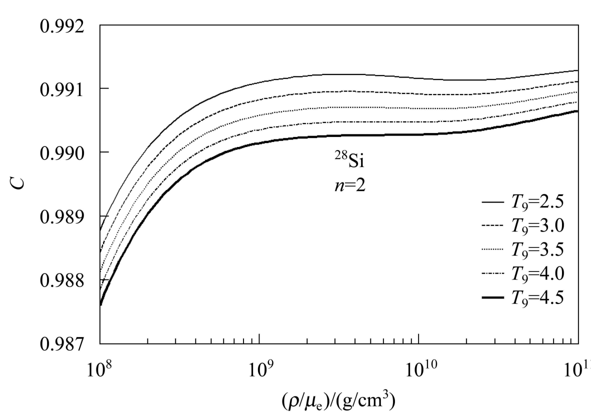

Fig. 2. Factor C for pure ^{28}Si matter as a function of the density for different temperatures.

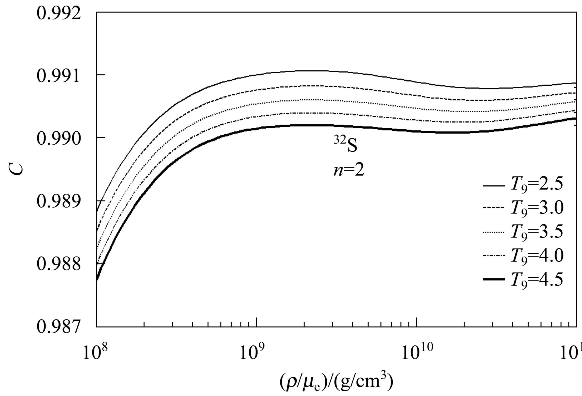

Fig. 3. Factor C for pure ^{32}S matter as a function of the density for different temperatures.

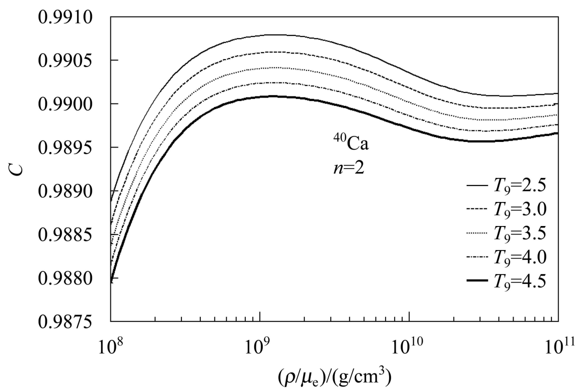

Fig. 4. Factor C for pure ^{40}Ca matter as a function of the density for different temperatures.

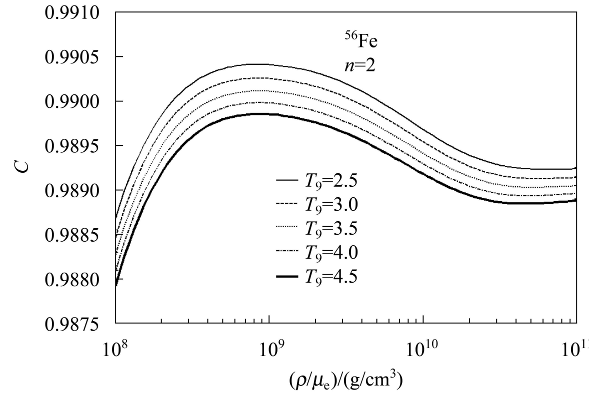

Fig. 5. Factor C for pure ^{56}Fe matter as a function of the density for different temperatures.

From the comparison of the results of $Q_{\rm LJ}$ with those of $Q_{\rm Dicus}$ shown in Figs. 1–5 we see that C has maxima of 99.16%, 99.13%, 99.12%, 99.055%, 99.040% corresponding to ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca and ^{56}Fe.

The numerical results of $Q_{\rm LJ}$ and $Q_{\rm Dicus}$ are given in Tables 1–5. It can be seen that due to SES the BNEL rates of Dicus are constantly higher than ours by two orders of magnitude. This is due to the fact that the special case of including the neutral current effects for the electrons in extreme degenerate states

Table 1. The bremsstrahlung NEL rates $Q_{\rm LJ}$ and $Q_{\rm Dicus}$ (erg·cm^{-3}·s^{-1}) for pure ^{24}Mg matter.

	T_9									
$\lg\rho$	2.5		3.0		3.5		4.0		4.5	
	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$
8.0	2.8637e16	2.5272e18	8.8355e16	7.5463e18	2.2916e17	1.9029e19	5.2329e17	4.2400e19	1.0841e18	8.5957e19
8.4	7.0494e16	7.2708e18	2.1750e17	2.1710e19	5.6430e17	5.4746e19	1.2894e18	1.2198e20	2.6732e18	2.4730e20
8.8	1.7702e17	1.9639e19	5.4635e17	5.8640e19	1.4182e18	1.4787e20	3.2426e18	3.2948e20	6.7280e18	6.6795e20
9.2	4.4601e17	5.1043e19	1.3784e18	1.5241e20	3.5830e18	3.8433e20	8.2031e18	8.5636e20	1.7043e19	1.7361e21
9.6	1.1178e18	1.2961e20	3.4553e18	3.8702e20	8.9845e18	9.7592e20	2.0579e19	2.1745e21	4.2777e19	4.4084e21
10.0	2.7892e18	3.2466e20	8.6009e18	9.6943e20	2.2320e19	2.4445e21	5.1039e19	5.4469e21	1.0595e20	1.1042e22
10.4	6.8840e18	8.0724e20	2.1152e19	2.4104e21	5.4722e19	6.0781e21	1.2481e20	1.3543e22	2.5849e20	2.7456e22
10.8	1.6749e19	2.0002e21	5.1305e19	5.9726e21	1.3239e20	1.5061e22	3.0127e20	3.3558e22	6.2274e20	6.8031e22
11.0	2.6103e19	3.1470e21	7.9850e19	9.3970e21	2.0580e20	2.3696e22	4.6782e20	5.2799e22	9.6611e20	1.0704e23

Table 2. The bremsstrahlung NEL rates $Q_{\rm LJ}$ and $Q_{\rm Dicus}$ (erg·cm^{-3}·s^{-1}) for pure ^{28}Si matter.

	T_9									
$\lg\rho$	2.5		3.0		3.5		4.0		4.5	
	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$
8.0	3.2950e16	2.9360e18	1.0139e17	8.7668e18	2.6245e17	2.2106e19	5.9842e17	4.9257e19	1.2384e18	9.9859e19
8.4	8.1575e16	8.4466e18	2.5088e17	2.5222e19	6.4923e17	6.3599e19	1.4804e18	1.4171e20	3.0641e18	2.8729e20
8.8	2.0632e17	2.2814e19	6.3440e17	6.8124e19	1.6417e18	1.7178e20	3.7440e18	3.8276e20	7.7515e18	7.7597e20
9.2	5.2331e17	5.9297e19	1.6104e18	1.7706e20	4.1713e18	4.4648e20	9.5214e18	9.9485e20	1.9731e19	2.0168e21
9.6	1.3221e18	1.5057e20	4.0680e18	4.4960e20	1.0537e19	1.1337e21	2.4054e19	2.5262e21	4.9855e19	5.1213e21
10.0	3.3344e18	3.7716e20	1.0234e19	1.1262e21	2.6450e19	2.8399e21	6.0271e19	6.3277e21	1.2473e20	1.2828e22
10.4	8.3150e18	9.3777e20	2.5431e19	2.8002e21	6.5534e19	7.0610e21	1.4894e20	1.5733e22	3.0753e20	3.1896e22
10.8	2.0379e19	2.3237e21	6.2158e19	6.9384e21	1.5979e20	1.7496e22	3.6241e20	3.8984e22	7.4687e20	7.9033e22
11.0	3.1850e19	3.6559e21	9.7026e19	1.0917e22	2.4916e20	2.7528e22	5.6456e20	6.1337e22	1.1625e21	1.2435e23

Table 3. The bremsstrahlung NEL rates $Q_{\rm LJ}$ and $Q_{\rm Dicus}$ (erg·cm^{-3}·s^{-1}) for pure ^{32}S matter.

$\lg\rho$	T_9									
	2.5		3.0		3.5		4.0		4.5	
	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$
8.0	3.7307e16	3.3409e18	1.1453e17	9.9757e18	2.9590e17	2.5155e19	6.7372e17	5.6050e19	1.3926e18	1.1363e20
8.4	9.2860e16	9.6113e18	2.8480e17	2.8699e19	7.3537e17	7.2369e19	1.6737e18	1.6125e20	3.4589e18	3.2690e20
8.8	2.3649e17	2.5960e19	7.2488e17	7.7517e19	1.8710e18	1.9547e20	4.2573e18	4.3554e20	8.7977e18	8.8296e20
9.2	6.0363e17	6.7473e19	1.8511e18	2.0147e20	4.7805e18	5.0804e20	1.0884e19	1.1320e21	2.2506e19	2.2949e21
9.6	1.5362e18	1.7133e20	4.7092e18	5.1159e20	1.2158e19	1.2900e21	2.7678e19	2.8745e21	5.7227e19	5.8274e21
10.0	3.9104e18	4.2916e20	1.1956e19	1.2815e21	3.0800e19	3.2314e21	6.9982e19	7.2002e21	1.4445e20	1.4597e22
10.4	9.8345e18	1.0671e21	2.9971e19	3.1863e21	7.6988e19	8.0345e21	1.7449e20	1.7902e22	3.5937e20	3.6293e22
10.8	2.4242e19	2.6440e21	7.3695e19	7.8951e21	1.8889e20	1.9908e22	4.2728e20	4.4360e22	8.7845e20	8.9930e22
11.0	3.7964e19	4.1600e21	1.1528e20	1.2422e22	2.9521e20	3.1323e22	6.6720e20	6.9794e22	1.3707e21	1.4149e23

Table 4. The bremsstrahlung NEL rates $Q_{\rm LJ}$ and $Q_{\rm Dicus}$ (erg·cm^{-3}·s^{-1}) for pure ^{40}Ca matter.

$\lg\rho$	T_9									
	2.5		3.0		3.5		4.0		4.5	
	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$
8.0	4.6193e16	4.1564e18	1.4123e17	1.2411e19	3.6367e17	1.2411e19	8.2576e17	6.9733e19	1.7030e18	1.4137e20
8.4	1.1612e17	1.1957e19	3.5454e17	3.5705e19	9.1198e17	3.5705e19	2.0690e18	2.0061e20	4.2641e18	4.0670e20
8.8	2.9946e17	3.2297e19	9.1334e17	9.6438e19	2.3474e18	9.6438e19	5.3219e18	5.4185e20	1.0962e19	1.0985e21
9.2	7.7315e17	8.3942e19	2.3582e18	2.5065e20	6.0615e18	2.5065e20	1.3745e19	1.4083e21	2.8318e19	2.8551e21
9.6	1.9925e18	2.1315e20	6.0734e18	6.3646e20	1.5603e19	6.3646e20	3.5366e19	3.5761e21	7.2839e19	7.2497e21
10.0	5.1457e18	5.3391e20	1.5647e19	1.5943e21	4.0113e19	1.5943e21	9.0749e19	8.9576e21	1.8659e20	1.8160e22
10.4	1.3105e19	1.3275e21	3.9736e19	3.9639e21	1.0162e20	3.9639e21	2.2938e20	2.2272e22	4.7068e20	4.5152e22
10.8	3.2564e19	3.2894e21	9.8544e19	9.8220e21	2.5156e20	9.8220e21	5.6692e20	5.5187e22	1.1616e21	1.1188e23
11.0	5.1130e19	5.1754e21	1.5460e20	1.5454e22	3.9435e20	1.5454e22	8.8812e20	8.6829e22	1.8186e21	1.7603e23

Table 5. The bremsstrahlung NEL rates $Q_{\rm LJ}$ and $Q_{\rm Dicus}$ (erg·cm^{-3}·s^{-1}) for pure ^{56}Fe matter.

$\lg\rho$	T_9									
	2.5		3.0		3.5		4.0		4.5	
	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$	$Q_{\rm LJ}$	$Q_{\rm Dicus}$
8.0	5.6009e16	4.9520e18	1.7043e17	1.4787e19	4.3710e17	3.7286e19	9.8906e17	8.3081e19	2.0336e18	1.6843e20
8.4	1.4258e17	1.4340e19	4.3323e17	4.2820e19	1.1097e18	1.0798e20	2.5084e18	2.4059e20	5.1530e18	4.8775e20
8.8	3.7324e17	3.8887e19	1.1327e18	1.1612e20	2.8985e18	2.9280e20	6.5461e18	6.5242e20	1.3437e19	1.3226e21
9.2	9.7611e17	1.0132e20	2.9618e18	3.0253e20	7.5783e18	7.6288e20	1.7114e19	1.6998e21	3.5129e19	3.4460e21
9.6	2.5472e18	2.5765e20	7.7237e18	7.6933e20	1.9751e19	1.9400e21	4.4581e19	4.3226e21	9.1471e19	8.7631e21
10.0	6.6635e18	6.4590e20	2.0164e19	1.9287e21	5.1471e19	4.8634e21	1.1599e20	1.0836e22	2.3763e20	2.1969e22
10.4	1.7145e19	1.6067e21	5.1769e19	4.7974e21	1.3188e20	1.2097e22	2.9666e20	2.6955e22	6.0677e20	5.4646e22
10.8	4.2864e19	3.9817e21	1.2923e20	1.1889e22	3.2878e20	2.9981e22	7.3865e20	6.6802e22	1.5091e21	1.3543e23
11.0	6.7417e19	6.2648e21	2.0314e20	1.8707e22	5.1653e20	4.7171e22	1.1599e21	1.0511e23	2.3687e21	2.1308e23

with a type of strong screening has been considered. On the other hand, the ion-ion correlations are neglected in the method of Dicus. Actually the strong inter-ion force will condense the nuclei into a liquid or solid state, and interference effects can alter the bremsstrahlung rate, thereby overestimating the neutrino energy loss rates by Dicus.

4 Concluding remarks

In summary, we calculated the bremsstrahlung neutrino energy loss rates using the Weinberg-Salam theory with SES. We also discussed the comparison of the results of $Q_{\rm LJ}$ with those of $Q_{\rm Dicus}$ for the nuclei ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca and ^{56}Fe at different temperatures. It has been found that the BNEL rates are sensitive to temperature and that due to SES the BNEL rates of Dicus will be highly overestimated by 2 orders of magnitude as compared to our results. On the other hand, the bremsstrahlung neutrino process may be an important and a dominant process for some heavy elements due to the strong dependence on atomic charge (Z^2-dependence) in SES in the considered density-temperature region of 10^8 g/cm$^3 \leqslant \rho/\mu_e \leqslant 10^{11}$ g/cm^3 and $2.5 \leqslant T_9 \leqslant 4.5$.

As is well known, for stars such as white dwarfs and neutron stars, the problem of cooling has always been a very challenging subject. Stellar theory tells us that the emission of neutrinos can be an important energy loss mechanism for dense stars in their late stages of evolution. Because neutrinos interact so weakly with matter they escape with a lot of energy and carry information on the processes in the interior of the stars. Some researches haven shown that the bremsstrahlung neutrino process on nuclei is mostly important and dominant for extremely large core densities such as $\rho/\mu_e \geqslant 10^8$ g/cm^3 and temperatures of $10^8K \leqslant T \leqslant 10^{10}K$. Such conditions are typically realized in white dwarfs and neutron stars. With the escaping of a huge amount of neutrinos due to the bremsstrahlung process, the neutrino energy loss may give one of the main contributions at the late stages of stellar evolution. Thus the conclusion obtained in this study may give significant help to further research in nuclear astrophysics and neutrino astrophysics, especially the research on energy-loss and the cooling mechanism.

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