Electron capture of strongly screening nuclides $^{56}$Fe, $^{56}$Co, $^{56}$Ni, $^{56}$Mn, $^{56}$Cr and $^{56}$V in pre-supernovae

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ABSTRACT

According to the shell-model Monte Carlo method, based on the random-phase approximation and linear response theory, we carried out an estimation of electron capture (EC) of the strongly screening nuclides $^{56}$Fe, $^{56}$Co, $^{56}$Ni, $^{56}$Mn, $^{56}$Cr and $^{56}$V in pre-supernovae. The EC rates are decreased greatly and may even exceed 21.5 per cent in the case of SES. We also compare our results with those calculated by the method of Aufderheide in the case of SES. Our results agree reasonably well with those of Aufderheide in higher density and temperature surroundings (e.g. $\rho_T > 60$, $T_y = 15.40$) and the maximum error is $\sim 0.5$ per cent. However, the maximum error is $\sim 13.0$ per cent in lower density surroundings (e.g. $^{56}$Cr at $\rho_T = 10$, $T_y = 15.40$, $Y_e = 0.41$). We also compared our results for SES with those of Fuller, Fowler & Newman and Nabi, which apply to a case without SES. The comparisons show that our results are lower than those of Fuller, Fowler & Newman by more than one order of magnitude and about 7.23 per cent lower than those of Nabi.

Key words: methods: data analysis – stars: evolution – stars: interiors.

1 INTRODUCTION

The electron capture (EC) rates of $^{56}$Fe, $^{56}$Co, $^{56}$Ni, $^{56}$Mn, $^{56}$Cr and $^{56}$V play a key role in the final evolution of massive stars, especially pre-supernova evolution. Some pioneering works on EC rates are investigated by Fuller, Fowler & Newman (1982, hereafter FFN), Aufderheide et al. (1994, hereafter AUFD), Langanke & Martinez-Pinedo (1998, 2000) and Nabi & Klapdor-Kleingrothaus (1999) under supernova explosion conditions. Liu & Luo (2007a,b,c, 2008a), Liu & Luo (2008b) and Liu et al. (2011) also discussed weak interaction reactions on these nuclides. However, their discussions did not consider the influence of strong electron screening (SES) on EC rates.

SES has raised strong interest among nuclear astrophysicists; also, it has always been an interesting issue and challenging problem with regard to stellar weak-interaction rates in pre-supernova stellar evolution and nucleosynthesis. It is extremely interesting, important and necessary for us to understand, solve and calculate accurately the SES and screening corrections in dense stars under the conditions of a relativistic degenerate electron liquid.

In the process of EC, what role does the SES on earth play in stars? How does SES affect EC rates? These problems have already been discussed by Gutierrez et al. (1996), Bravo & Garcia-Senz (1999), Luo & Peng (2001), Itoh et al. (2002), Luo et al. (2006), Liu & Luo (2007a) and Liu (2010a,b,c). Juodagalvis et al. (2010) have improved previous rate evaluations by taking screening corrections to the reaction rates properly into account. Their research shows that it is extremely important and necessary to calculate the screening corrections to EC rates in dense stars accurately.

Due to the importance of SES in astrophysical surroundings, in this article we investigate the effect of iron group nuclides on EC rates in SES, based on linear response theory (Itoh et al. 2002) using the shell-model Monte Carlo (SMMC) method, which was discussed amply by Dean et al. (1998). We also discuss the EC cross-section using random-phase approximation (RPA) theory and the rate of change of electron fraction (RCEF) due to EC in SES. Additionally we discuss the error factor $C_1$, which is a comparison of the rates of $\lambda_{\text{SMMC}}$, calculated by the method of SMMC, and $\lambda_{\text{AUFD}}$, calculated by the method of AUFD with SES, and the screening factor $C_2$ with and without SES. We also present a comparison of our results with SES with those of FFN and Nabi, which are for a case without SES. The present article is organized as follows: in the next section we analyse the EC rates in SES in stellar interiors, some numerical results and discussion are given in Section 3 and conclusions are summarized in Section 4.

2 EC IN SES IN STELLAR INTERIORS

The stellar EC rate for the $k$th nucleus (Z, A) in thermal equilibrium at temperature $T$ is given by a sum over the initial parent states $i$
and the final daughter states \( f(\text{Fuller et al. 1982; Aufderheide et al. 1994}) \):

\[
\lambda_k = \lambda_{\text{cc}} = \sum_i \frac{2(J_i + 1)e^{-E_i/kT}}{G(Z, A, T)} \sum_f \lambda_{i,f}.
\]  

(1)

The EC rate from one of the initial states to all possible final states is \( \lambda_{i,f} \), \( J_i \) and \( E_i \) are the spin and excitation energies of the parent states, \( G(Z, A, T) \) is the nuclear partition function and given by

\[
G(Z, A, T) = \sum (2J_0 + 1) \exp \left( -\frac{E_0}{kT} \right)
\]  

(2)

using the level density formula, \( \vartheta(E, J, \pi) \); the contribution from the excited states is discussed. Thus the nuclear partition function becomes approximately (Aufderheide et al. 1994)

\[
G(Z, A, T) \approx (2J_0 + 1) + \int_0^\infty dE \int_J dJ d\vartheta(2J_0 + 1)
\times \vartheta(E, J, \pi) \exp \left( -\frac{E_0}{kT} \right).
\]  

(3)

The level density is given by (Holmes et al. 1986; Thielemann, Truran & Arnould 1986)

\[
\vartheta(E, J, \pi) = \frac{1}{\sqrt{2\pi\sigma}} \frac{\sqrt{\pi}}{12a^{1/4}} \exp \left[ \frac{-E_0^2}{2\sigma^2} \right] f(E, J, \pi),
\]  

(4)

where

\[
f(E, J, \pi) = \frac{1}{2} \frac{J(J + 1)}{2\sigma^2} \exp \left[ -\frac{J(J + 1)}{2\sigma^2} \right].
\]  

(5)

where \( a \) is the level density parameter and \( \delta \) is the backshift (pairing correction), \( \sigma \) is defined as

\[
\sigma = \left( \frac{2m_n A R^2}{2\hbar^2} \right)^{1/2} \left[ \frac{(E - \delta)}{a} \right]^{1/4},
\]  

(6)

where \( R \) is the radius and \( m_n = 1/N_\Lambda \) is the atomic mass unit.

Based on RPA theory with a global parametrization of single particle numbers, the EC rate is related to the EC cross-section by (Juodagalvis et al. 2010)

\[
\lambda_{i,f} = \frac{1}{\pi c^2 h^3} \sum_{j,f} \int_{E_f}^\infty \rho_{i,f}^2 \sigma_{nc}(\epsilon_n, \epsilon_i, \epsilon_f) \rho(\epsilon_n, U_f, T) d\epsilon_n,
\]  

(7)

where \( \epsilon_0 = \max(Q_{if}, 1) \). Here, \( p_c = \sqrt{\epsilon_0 - 1} \) is the momentum of an incoming electron with energy \( \epsilon_n \), \( U_f \) is the electron chemical potential and \( T \) is the electron temperature. Note that in this article all energies and moments are in units of \( m_e c^2 \) and \( m_e c^2 \) respectively, where \( m_e \) is the electron mass and \( c \) is the light speed in a vacuum.

The phase-space factor is defined as

\[
f = f(\epsilon_n, U_f, T) = \left[ 1 + \exp \left( \frac{\epsilon_n - U_f}{kT} \right) \right]^{-1},
\]  

(8)

where an electron with energy \( \epsilon_n \) goes from an initial proton single particle state with energy \( \epsilon_i \) to a neutron single particle state with energy \( \epsilon_f \). Due to energy conservation, the electron, proton and neutron energies are related to the neutrino energy and the \( Q \)-value for the capture reaction (Cooperstein & Wambach 1984) is

\[
Q_{i,f} = \epsilon_n - \epsilon_i = \epsilon_n - \epsilon_f = \epsilon_f - \epsilon_i
\]  

(9)

and we have

\[
\epsilon_n = \epsilon_i + \epsilon_f = \epsilon_f + \mu + \Delta_{np},
\]  

(10)

where \( \mu = \mu_n - \mu_p \), the difference between neutron and proton chemical potentials in the nucleus, and \( \Delta_{np} = M_d c^2 - M_p c^2 = 1.293 \) MeV, the neutron and proton mass difference. \( Q_{i,f} = M_f c^2 - M_i c^2 = \mu + \Delta_{np} \), with \( M_i \) and \( M_f \) being the masses of the parent nucleus and daughter nucleus respectively; \( \epsilon_f^e \) corresponds to the excitation energy in the daughter nucleus at a state of zero temperature.

The electron chemical potential is found by inverting the expression for the lepton number density:

\[
n_e = \rho = \frac{8\pi}{(2\pi)^3} \int_0^\infty \rho_{\pi}^2 (f_{-\pi} - f_{+\pi}) d\rho_e,
\]  

(11)

where \( \rho \) is the density in g cm\(^{-3} \), \( \mu_e \) is the average molecular weight, \( \lambda_c = b/(m_e c) \) is the Compton wavelength, \( f_{-\pi} = [1 + \exp(\epsilon_n - U_{-\pi} - 1)/(kT)]^{-1} \) and \( f_{+\pi} = [1 + \exp(\epsilon_n - U_{+\pi} + 1)/(kT)]^{-1} \) are the electron and positron distribution functions respectively and \( k \) is the Boltzmann constant.

According to the SMMC method, which considers Gamow–Teller strength distributions, the total cross-section for EC is given by (Juodagalvis et al. 2010)

\[
\sigma_{cc} = \sigma_{cc}(\epsilon_n) = \sum_{i,f} \frac{(2J_i + 1)\exp(-\beta E_i)}{Z_A} \sigma_{i,f}(Ee)
\times \sum_{i,f} (2J_i + 1) \exp(-\beta E_i) \sigma_{i,f}(Ee)
\]  

(12)

where \( g_{wk} = 1.1661 \times 10^{-5} \) GeV\(^{-2} \) is the weak coupling constant and \( G_A \) is the axial vector form factor, which is at zero momentum is \( G_A = 1.25 \). Here, \( \epsilon_n \) denotes the total rest mass and kinetic energy; \( F(Z, \epsilon_n) \) is the Coulomb wave correction, which is the ratio of the square of an electron wavefunction distorted by a Coulomb scattering potential to the square of the wavefunction of a free electron.

\( S_{GT^-} \), the total Gamow–Teller (GT) strength available for an initial state, is given by summing over a complete set of final states in Gamow–Teller transition matrix elements \( |M_{GT^-}|^2 \). The SMMC method is also used to calculate the response function \( R_s(\tau) \) of an operator \( \hat{A} \) at an imaginary time \( \tau \). By using a spectral distribution of initial and final states \( |i \rangle \) and \( |f \rangle \) with energies \( E_i \) and \( E_f \), \( R_s(\tau) \) is given by (Langanke & Martinez-Pinedo 1998)

\[
R_s(\tau) = \frac{\sum_{i,f}(2J_i + 1)e^{-\beta E_i}e^{-\tau(\epsilon_f - \epsilon_i)}(|f|\hat{A}|i\rangle|^2)}{\sum_{i,f}(2J_i + 1)e^{-\beta E_i}},
\]  

(13)

Note that the total strength for the operator is given by \( R(\tau = 0) \). The strength distribution is given by

\[
S_{GT^-}(E) = \sum_{l,i}(\delta(E - E_l + E_i)(2J_i + 1)e^{-\beta E_i}(|f|\hat{A}|i\rangle|^2)
\]  

(14)

which is related to \( R_s(\tau) \) by a Laplace transform, \( R_s(\tau) = \int_0^\infty S_{GT^-}(E)e^{-\tau E} dE \). Note that here \( E \) is the energy transfer within the parent nucleus and that the strength distribution \( S_{GT^-}(E) \) has units of MeV\(^{-1} \) and \( \beta = 1/\tau_N \), where \( \tau_N \) is the nuclear temperature.

The pre-supernova EC rate is given by folding the total cross-section with the flux of a degenerate relativistic electron gas in the
\[ \lambda_{ec}^0 = \frac{\ln 2}{6163} \int_0^\infty d\xi S_{GT} c^3 \left( \frac{m_e e^2}{\xi} \right)^{\frac{1}{3}} \times \int_{p_0}^{\infty} dp_e p^2_e (-\xi + \epsilon_a) F(Z, \epsilon_a) f. \]  

(15)

Here, \( p_0 \) is defined as

\[ p_0 = \begin{cases} \sqrt{Q^2_f - 1} & \text{when } Q_f < -1, \\ 0 & \text{otherwise}. \end{cases} \]  

(16)

Using linear response theory, Itoh et al. (2002) calculated the screening potential for relativistic degenerate electrons. A more precise screening potential is given by

\[ D = 7.525 \times 10^{-3} \cdot 10^2 \frac{Q^2}{A} \frac{1}{3} \cdot 10^{-3} J(r, R) \text{ (MeV)}, \]  

(17)

where \( \rho_f \) is the density in units of \( 10^9 \text{ g cm}^{-3} \) and \( J(r, R) \), \( r \), and \( R \) can be found in Itoh et al. (2002). Formula (12) is valid for \( 10^{-5} < r_i < 10^{-1}, 0 < R \leq 50 \); these conditions are usually fulfilled in pre-supernova environments.

If an electron is strongly screened and the screening energy is high enough not to be neglected in a high-density plasma, its energy will decrease from \( \epsilon \) to \( \epsilon' = \epsilon - D \) in the decay reaction due to electron screening. At the same time, relatively speaking the screening decreases the number of high-energy electrons with energies higher than the threshold energy for EC. The threshold energy increases from \( \epsilon_0 \) to \( \epsilon_1 = \epsilon_0 + D \). Thus the EC rate for SES becomes

\[ \lambda_{ec} = \frac{\ln 2}{6163} \int_0^\infty d\xi S_{GT} c^3 \left( \frac{m_e e^2}{\xi} \right)^{\frac{1}{3}} \times \int_{p_0}^{\infty} dp_e p^2_e (-\xi + \epsilon_a) F(Z, \epsilon_a) f. \]  

(18)

Next, we define the error factor \( C_1 \), which compares our \( \lambda_{SMMC} \), obtained through the method of SMMC, with \( \lambda_{AFUD} \), calculated by the method of AFUD. We also define the screening factor \( C_2 \) with and without SES:

\[ C_1 = \frac{(\lambda_{SMMC} - \lambda_{AFUD})}{\lambda_{SMMC}}, \]  

(19)

\[ C_2 = \frac{\lambda_{SMMC} \lambda_{AFUD}}{\lambda_{SMMC}^2}. \]  

(20)

The RCEF also plays a key role in stellar evolution and presupernova outbursts. In order to understand how SES affects the RCEF, the RCEF due to the EC reaction on the \( k \)th nucleus in SES is defined as

\[ Y_{ec}^{(k)}(k) = -\frac{X_k}{A_k} \lambda^k, \]  

(21)

where \( \lambda^k \) is the EC rate in SES, \( X_k \) is the mass fraction of the \( k \)th nucleus and \( A_k \) is the mass number of the \( k \)th nucleus.
made up of lower energy transition rates between the ground states and higher energy transition rates between GT resonance states. Some research shows that the work of AUFD is an oversimplification and therefore its accuracy is limited. The charge exchange reactions (p, n) and (n, p) make it possible to observe, in principle, the total GT strength distribution in nuclei. Experimental information is particularly rich for some iron nuclides and the availability of both GT$^+$ and GT$^-$ makes it possible to study in detail the problem of renormalization of $\sigma\tau$ operators. We have calculated the total GT strength in a full $p$–$f$ shell calculation, resulting in $B(GT) = g_A[(\sigma\tau_\lambda)]^2$, where $g_A$ is the axial-vector coupling constant. For example, under pre-supernova conditions EC on $^{56}\text{Ni}$ is dominated by the wavefunctions of the parent and daughter states and affected greatly by SES due to the fact that the electron screening potential can change the Coulomb wavefunction of electrons and the total GT strength for $^{56}\text{Ni}$ in a full $p$–$f$ shell calculation, resulting in $B(GT) = 10.1g_A^2$. The total GT strength of the other important nuclide, $^{56}\text{Fe}$, in a full $p$–$f$ shell calculation can be found in Caurier et al. (1995). An average of the GT strength distribution is in fact obtained by the SMMC method. A reliable replication of the GT distribution in the nucleus is carried out and detailed analysis performed using an amplification of the electronic shell model. Thus, the method is relatively accurate.

The screening factor $C_2$ is plotted as a function of $\rho\tau$ in Figs 4 and 5. We find that the effect on EC rates is very obvious for SES. The EC rates are reduced greatly, by an amount exceeding ~21.5 per cent and ~8 per cent in Figs 4 and 5 respectively. One can see that the lower the temperature, the larger the effect on EC rates in SES. SES mainly decreases the number of higher energy electrons joining the EC reaction. In contrast, one can also see from Figs 4 and 5 that the screening factor is nearly the same at higher densities and is independent of temperature and density. The reason is that in higher density surroundings the electron energy is mainly determined by its Fermi energy, which is strongly dependent on density. On the other hand, the lower the temperature, the larger the effect on $C_2$. This is because the higher the temperature, the higher the average electron energy but the lower the SES potential. In addition, because of the smaller electron screening potential at low densities, the lower the density, the smaller the effect. As the density increases, $C_2$ increases gradually due to increases of the shielding potential in the EC reaction. As the density increases further, the factor $C_2$ decreases and will reach unanimity at relatively higher densities. This is because the electron energy is mainly determined by the Fermi energy at higher densities and the effect of temperature is relatively weaker. As the density increases, the electronic Fermi and shielding potentials increase. The ratio between shielding potential and Fermi energy has nothing to do with density, at least to a first approximation.

From the oxygen-shell-burning phase up to the end of the convective core silicon-burning phase of massive stars, the EC rates of these nuclides play an important role. FFN performed some pioneering work on EC rates. In order to understand how much EC is affected by SES, the comparisons of our results ($\lambda_{LJ}^0$) for SES with those of FFN ($\lambda_{LJ}^0$) and Nabi ($\lambda_{ec}^0$) are based on Proton-neutron quasi-particle random phase approximation (pn-QRPA) theory without SES. The two tables also show comparisons of our results for SES with those of FFN and Nabi at $\rho_Y = 10^7$ g cm$^{-3}$, $T_0 = 3$ and $\rho_Y = 10^{11}$ g cm$^{-3}$, $T_0 = 3$ respectively.

The calculated rates for most nuclides in SES are decreased, by an amount exceeding one order of magnitude, compared with FFN’s results in the case without SES. The two tables also show comparisons of our results for SES with those of Nabi, which are presented in tabular form. Tables 1 and 2 show a comparison of our results for SES with those of FFN and Nabi at $\rho_Y = 10^7$ g cm$^{-3}$, $T_0 = 3$ (e. g. $^{56}\text{Co}$, $^{56}\text{Ni}$ and $^{56}\text{V}$). However, the

Table 1. Comparisons of our calculations in SES for nuclides $^{56}\text{Fe}$, $^{56}\text{Co}$, $^{56}\text{Ni}$, $^{56}\text{Mn}$, $^{56}\text{Cr}$ and $^{56}\text{V}$ with those of FFN and Nabi for the case without SES at $\rho_Y = 10^7$ g cm$^{-3}$, $T_0 = 3$. The ratios are computed as $k_1 = \lambda_{LJ}^0/\lambda_{ec}^0$(FFN)) and $k_2 = \lambda_{LJ}^0/\lambda_{ec}^0$(Nabi)).

| Nuclide | $\lambda_{ec}^0$(FFN) | $\lambda_{ec}^0$(Nabi) | $\lambda_{LJ}^0$ | $k_1$ | $k_2$ |
|---------|----------------------|-----------------------|-----------------|------|------|
| $^{56}\text{Fe}$ | 5.236e-8 | 1.028e-9 | 1.013e-9 | 1.9347e-2 | 0.98541 |
| $^{56}\text{Co}$ | 0.0115 | 0.0032 | 0.00307 | 0.26696 | 0.95397 |
| $^{56}\text{Ni}$ | 0.0019 | 0.0013 | 0.00124 | 0.65262 | 0.95380 |
| $^{56}\text{Mn}$ | 4.140e-7 | 3.0903e-6 | 3.0368e-6 | 7.33530 | 0.98270 |
| $^{56}\text{Cr}$ | 2.460e-19 | 1.002e-16 | 9.872e-17 | 401.301 | 0.98521 |
| $^{56}\text{V}$ | 1.247e-14 | 7.178e-13 | 6.827e-13 | 54.7474 | 0.95110 |
Table 2. Comparisons of our calculations in SES for nuclides $^{56}$Fe, $^{56}$Co, $^{56}$Ni, $^{56}$Mn, $^{56}$Cr and $^{56}$V with those of FFN and Nabi for the case without SES at $\rho Y_e = 10^{11}$ g cm$^{-3}$, $T_0 = 3$. The ratios are computed as $k_1 = \lambda_{1J}/\langle \lambda^0_{1J} \rangle_{\text{FFN}})$ and $k_2 = \lambda_{1J}/\langle \lambda^0_{1J} \rangle_{\text{Nabi}}$.

| Nuclide | $\lambda^0_{1J}$ (FFN) | $\lambda^0_{1J}$ (Nabi) | $\lambda^0_{1J}$ | $k_1$   | $k_2$   |
|---------|------------------------|------------------------|----------------|--------|--------|
| $^{56}$Fe | 5.408e4 | 1.683e4 | 1.591e4 | 0.29430 | 0.94570 |
| $^{56}$Co | 1.596e5 | 4.730e3 | 4.451e4 | 0.27890 | 0.94100 |
| $^{56}$Ni | 1.718e5 | 6.210e4 | 5.761e4 | 0.33533 | 0.92770 |
| $^{56}$Mn | 1.574e4 | 1.089e5 | 1.0367e5 | 0.65840 | 0.95200 |
| $^{56}$Cr | 1.189e4 | 5.960e3 | 5.6220e3 | 0.47280 | 0.94330 |
| $^{56}$V | 1.862e4 | 4.860e3 | 4.6251e3 | 0.24840 | 0.95170 |


decrease is about 7.23 per cent at $\rho Y_e = 10^{11}$ g cm$^{-3}$, $T_0 = 3$ for $^{56}$Ni.

According to the method of SMMC, based on RPA and linear response theory, we have discussed the EC rates in SES. From the above calculations, we find that the effect of SES on EC is obvious. Comparisons show that the difference is larger between our results and those of FFN; however, our results in SES are generally lower than those of Nabi. The cause may be as follows: the electron screening potential can change the Coulomb wavefunction of electrons. The electron screening potential also decreases the energy of an electron joining the EC reaction and generally decreases EC rates, due to screening increasing the energy of the atomic nucleus in reaction. Moreover, SES evidently decreases the number of higher energy electrons having an energy greater than the threshold in the EC reaction. Thus, SES causes a relative increase in the threshold of reactions and also obviously decreases EC rates.

The EC of these neutron-rich nuclides does not have measured mass, so that the EC $Q$-value has to be estimated with the mass from FFN. FFN used the Seeger & Howard (1975) semi-empirical atomic mass formula. Therefore, the calculation method is a little different. Moreover, FFN did not take into effect the process of particle emission from excited states. FFN adopt the so-called Brink’s hypothesis in their calculations. This hypothesis assumes that the GT strength distribution for excited states is the same as for the ground state, only shifted by the excitation energy of the state. Their work simplifies the nuclear excited energy-level transition calculation method. Therefore, the calculation method is a little approximate and a larger difference appears in comparisons.

Using pn-QRPA theory, Nabi expanded FFN’s works and analysed the nuclear excitation energy distribution. They had taken into consideration particle emission processes, which constrain the parent excitation energies. However, in the GT transitions considered in their works only low angular momentum states are considered. The method of SMMC actually draws an average of the GT intensity distribution of EC: the calculated results are in good agreement with experiments, but the results become generally small, especially for some odd-$A$ nuclides.

In summary, by analysing the effect on EC rates due to SES, one can see that SES has an evident effect on EC rates for different nuclides, particularly for heavier nuclides, the threshold for which is negative at higher densities. According to the above calculations and discussion, one can conclude that EC rates are decreased greatly, by even exceeding 21.5 per cent.

4 CONCLUSIONS

According to the method of SMMC, based on RPA and linear response theory, we have discussed the EC rates of $^{56}$Fe, $^{56}$Co, $^{58}$Ni, $^{58}$Mn, $^{56}$Cr and $^{56}$V in SES in pre-supernovae. We find that the EC rates are decreased greatly by SES, by even exceeding ~21.5 per cent (e.g. $T_0 = 1.33$, $Y_e = 0.49$ for $^{56}$Cr). The lower the temperature, the larger the effect on EC. $F^e_\text{ec}(k)$ is very sensitive to SES and reduces greatly, by an amount exceeding 7 orders of magnitude. We also compare our results with those of AFUD. The error factor $C_1$ shows that our results agree reasonably well with those of AFUD under lower temperature (e.g. $T_0 = 3.40$, $Y_e = 0.47$) and higher density–temperature surroundings (e.g. the maximum error is ~0.5 per cent for $\rho_1 > 60$, $T_0 = 15.40$, $Y_e = 0.41$). However, the error is ~5.50, ~2.90, ~2.70, ~4.10, ~13.0 and ~4.80 per cent for $^{56}$Fe, $^{56}$Co, $^{56}$Ni, $^{56}$Mn, $^{56}$Cr and $^{56}$V at $\rho_1 = 10.0$, $T_0 = 15.40$, $Y_e = 0.41$ respectively. On the other hand, we compared our results for SES with those of FFN and Nabi, which are for the case without SES. The comparisons show that the difference is larger between our results and FFN’s, but our results with SES are generally lower than Nabi’s.

As is well-known, EC rates from SES are quite relevant for simulations of the process of collapse and explosion in massive stars. Additionally, the neutrino energy loss due to EC plays an important role in the process of supernova explosions. In order to understand the mechanisms of supernova explosion and in order to clarify the effects of SES from cooling systems of stars, more and more astronomers and physicists are interested in these problems and are trying their best to seek a key to the problem.

How does SES affect neutrino energy loss in stars? How does SES affect other weak interactions in the stellar evolution process? How does SES affect cooling systems in massive stars? These challenging issues will be our next objectives.

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