Neutrino Energy Loss by Electron Capture on Nucleus ^{56}Mn, ^{56}Fe, ^{56}Co and ^{56}Ni in Strong Electron Screening *

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Based on the p–f shell model, the neutrino energy loss rates for nucleus ^{56}Mn, ^{56}Fe, ^{56}Co and ^{56}Ni in the electron capture process are canvassed in and not in a strong electron screening. The results show that the neutrino energy loss rates for ^{56}Mn, ^{56}Fe, ^{56}Co and ^{56}Ni decrease about 15%, 10%, 60% and 1 order of magnitude correspondingly at the temperature $T_9 = 15$ and even debase 2 orders of magnitude at the temperature $T_9 = 1$.

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Neutrino astrophysics has entered a new important stage of development with the discovery of the neutrino burst from SN1987A by the Kamiokande II group (Hirata *et al.* in 1987) and IMB group (Bionta *et al.* in 1987).[1] According to the stellar evolution theory and the observation data, the burst of neutrino is the first signal from the supernova explosion. As is well known, there are different neutrino production mechanisms inside the presupernova due to the changes of the different physical conditions, such as the electron capture process, the pair, photo-, plasma, bremsstrahlung and recombination neutrino processes. During the explosion process, a large quantity of energy from the gravitation collapse would be set free with the escaping of the neutrino. At the same time, lots of messages and the energy are taken away from the star by the neutrinos due to these weak interactions. It will abbreviate the time at the later stages of stellar evolution. Therefore the research on the neutrino and the neutrino energy loss (hereafter NEL) rates has been the hotspot and former-border issue in the astrophysics and particle-physics.

Because of the low-energy ($E_\gamma \leq 1\,\mathrm{MeV}$) of neutrinos from the star, it is very difficult to be detected in the near future, however the accurate neutrino energy loss rates are urgently needed for the study of the stellar evolution. In the last decades, some authors investigated extensive results of calculation of the neutrino energy loss rates. Fuller *et al.*,[2−5] based on the simple shell model, accomplished many pioneering works, in which they made detailed calculation of the NEL rates which come from the electron capture on a lot of nucleus. Their works showed that the main source of the neutrinos is the electron captures by free proton and hyperons during the presupernova explosion process. Itoh *et al.*[6,7] analysed the NEL rates from the pair, photo-, plasma, bremsstrahlung and recombination neutrino processes based on the Weinberg–Salam theory. Esposito *et al.*[8] reviewed the purely leptonic neutrino emission processes and the contributing to the energy loss rate of the stellar plasma. In their works the wide density and temperature region were considered, whereas they paid no attention to the NEL rates which come from the electron capture (hereafter EC) process in a strong electron screening (hereafter SES). This issue has been already studied by some authors, e.g. Gutierrez *et al.*,[9] Bravo and Garcia-Senz,[10] Luo and Peng.[11−14] Some research[15] has shown that at some temperature and density points, the screening still reduces the electron capture rate about 10–20% and protract the collapsing time scale. This may induce the total energy of neutrino leakage increases, correspondingly the energy of shock wave decreases appreciably. Hence electron capture is the major factor in the core collapse supernova (including SNII,SNIb and SNIc) and the NEL rates due to electron capture process are very important to the numerical simulation of the evolutionary mode of pre-supernova objects, especially when the electron screening is considered.

A new screening potential which comes from the linear response theory was calculated and discussed by Iton *et al.*[16] According to this new screening potential theory, based on the *p–f* shell model, the NEL rates for nucleus ^{56}Mn, ^{56}Fe, ^{56}Co and ^{56}Ni in the course of electron capture are investigated in SES. It is very magnificent to research the effect on NEL rates of these nucleuses which are the very typical nucleus in the electron capture reaction during the explosion and the gravitation collapse process.[4,11,14−22]

The NEL rates (in units of $m_e c^2 \mathrm{s}^{-1}$) due to the electron capture for the kth 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

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f,[23]

$$\lambda_k^\nu = \sum_i \frac{(2J_i+1)e^{-E_i/kT}}{G(Z,A,T)} \sum_f \lambda_{if}^\nu, \quad (1)$$

where J_i and E_i are the spin and the excitation energy of the parent states, $G(Z,A,T)$ is the nuclear partition function. The NEL rates associated with the EC from one of the initial states to all possible final states is λ_{if}^ν, $\lambda_{if}^\nu = \frac{\ln 2}{(ft)_{if}} f_{if}$ with the relation $\frac{1}{(ft)_{if}} = \frac{1}{(ft)_{if}^F} + \frac{1}{(ft)_{if}^{GT}}$. The *ft*-values and the corresponding Gamow–Teller or Fermi transition matrix elements are related by

$$\frac{1}{(ft)_{if}^{GT}} = \frac{10^{3.596}}{|M_{GT}|_{if}^2}, \quad \frac{1}{(ft)_{if}^{F}} = \frac{10^{3.79}}{|M_{F}|_{if}^2}, \quad (2)$$

the phase space factor with no SES is defined as[2]

$$f(Q_{if}) = \int_{\varepsilon_0}^{\infty} \varepsilon p (Q_{if}+\varepsilon)^3 \frac{F(z,\varepsilon)}{1+\exp\left(\frac{\varepsilon - U_F - 1}{kT}\right)} d\varepsilon, \quad (3)$$

where k is Boltzmann's constant, T is the electron temperature in units of K, U_F is the electron chemical potential. $Q_{if} = Q_{00} + E_i - E_f$ is the EC threshold energy. $Q_{00} = M_p c^2 - M_d c^2$, M_p and M_d are the masses of the parent nucleus and the daughter nucleus, respectively; E_i and E_f are the excitation energies of the nuclear ith and fth states respectively, ε is the total rest mass and kinetic energy. Note that in this study all of the energies and momentum are in units of $m_e c^2$ and $m_e c$, with m_e being the electron mass and c the velocity of light in vacuum. $F(Z,\varepsilon)$ is the coulomb correction function.[1] Without considering the screening, the threshold energy ε_0 is defined by

$$\varepsilon_0 = \begin{cases} Q_{if}, & \text{for } Q_{if} < -1, \\ 1, & \text{otherwise.} \end{cases} \quad (4)$$

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

$$n_e = \rho/\mu_e = \frac{1}{\pi^2 N_A \lambda_e^3} \int_0^\infty (f_{-e} - f_{+e}) dp, \quad (5)$$

where ρ is the density in g/cm^3, μ_e is the average molecular weight, λ_e is Compton wavelength, $f_{-e} = \left[1+\exp\left(\frac{\varepsilon_n - U_F - 1}{kT}\right)\right]^{-1}$ and $f_{+e} = \left[1+\exp\left(\frac{\varepsilon_n + U_F + 1}{kT}\right)\right]^{-1}$ are the electron and positron distribution functions, respectively; N_A is Avogadro's constant.

In high density plasma the electron is strongly screened and the screening energy D of electron is high enough so that it is not negligible. Due to the screening, the energy of electron decreases from ε to $\varepsilon' = \varepsilon - D$ in the capture reaction. At the same time, the screening relatively decreases the numbers of electron whose energy is more than the threshold energy of electron capture. Thus, the threshold energy increases from ε_0 to $\varepsilon_s = \varepsilon_0 + D$. The phase space integral with screening is written as[11]

$$f^s(Q_{if}) = \int_{\varepsilon_s}^{\infty} \varepsilon'(\varepsilon'^2-1)^{1/2}(Q_{if}+\varepsilon')^3 F(z,\varepsilon') f_e(\varepsilon) d\varepsilon'. \quad (6)$$

Itoh *et al.*[16] have calculated the screening potential caused by relativistic degenerate electron with the linear response theory, which is widely used in the field of solid-state physics and liquid physics. This condition, under which the electrons are strongly degenerate, is expressed as $kT \ll E_c \ll E_0$ where E_0 is no-resonant reaction effective energy, E_c is the coulomb potential energy per nucleon. The screening energy per electron by the relativistic degenerate electron liquid is expressed as[16]

$$D = 7.525 \times 10^{-3} Z \left(\frac{10 Z \rho_7}{A}\right)^{1/3} J(r_s, R)\,\text{MeV}, \quad (7)$$

where $J(r_s,R) = \sum_{i,j=0}^{10} a_{ij} s^i u^j$, $s = 1/2(\log_{10} r_s + 3)$, $\mu = (R-25)/25$, $R = 2K_F r_{nuc} = 6.3 \times 10^{-3} Z^{-1/3} (10\rho_7)^{1/3}$, $r_s = 1.388 \times 10^{-2} (A/10Z\rho_7)^{1/3}$, a_{ij} can be found in the literature (Itoh 2002),[16] r_{nuc} is the nuclear radius and $K_F = 2.613 \times 10^{10} (A/10Z\rho_7)^{1/3}$ is the electron Fermi wave number, Eq. (7) is valid for $10^{-5} \le r_s \le 10^{-1}$, $0 \le R \le 50$, which are usually fulfilled in the presupernova environment.

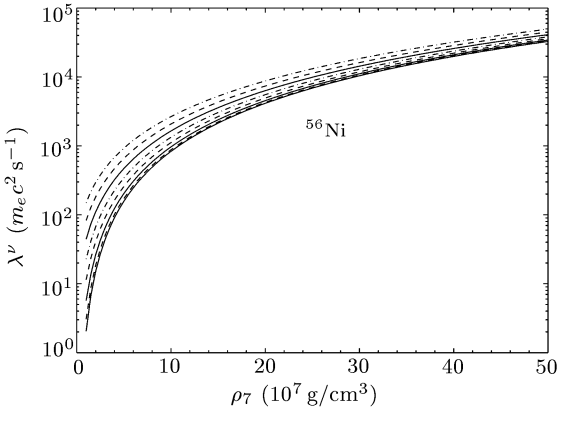


Fig. 1. NEL rates of nuclide ^{56}Ni in no electron screening versus ρ_7 at the different temperatures. The curves from bottom to top correspond to T_9 = 1, 3, 5, 7, 9, 11, 13, 15.

Figures 1–4 show that the NEL rates for nuclide ^{56}Mn, ^{56}Fe, ^{56}Co and ^{56}Ni vary with density ρ_7 at the different temperature in no electron screening. In SES the NEL rates for ^{56}Mn, ^{56}Fe, ^{56}Co and ^{56}Ni are shown in Figs. 5–8. One can find that the NEL rates are sensitive to the temperature. For example, the

NEL rates of ^{56}Ni and ^{56}Co decreased overrun 4 orders of magnitude at $T_9 = 1$ (T_9 is the temperature in units of 10^9K) and the density range $1 \leq \rho_7 \leq 50$ but it is less than about 3 orders of magnitude at $T_9 = 15$.

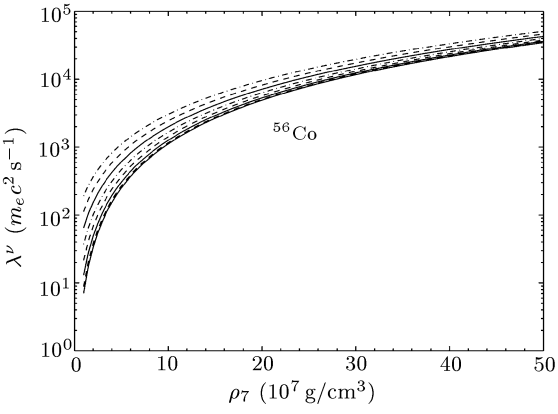


Fig. 2. NEL rates of nuclide ^{56}Co in no electron screening versus ρ_7 at the different temperatures. The curves from bottom to top correspond to $T_9 = 1, 3, 5, 7, 9, 11, 13, 15$.

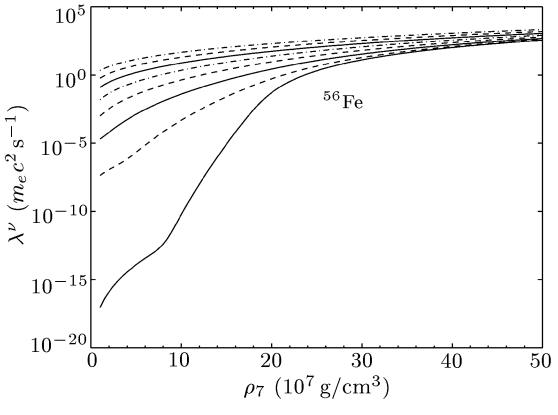


Fig. 3. NEL rates of nuclide ^{56}Fe in no electron screening versus ρ_7 at the different temperatures. The curves from bottom to top correspond to $T_9 = 1, 3, 5, 7, 9, 11, 13, 15$.

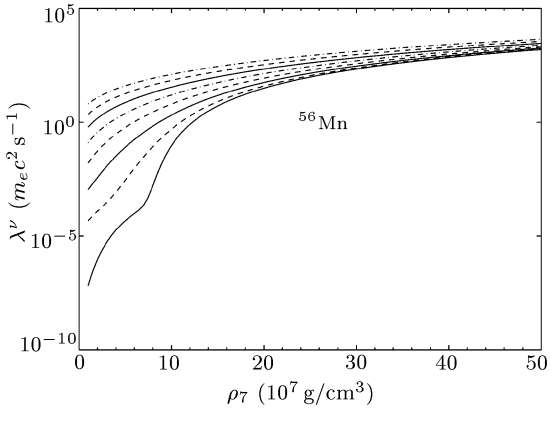


Fig. 4. NEL rates of nuclide ^{56}Mn in no electron screening versus ρ_7 at the different temperatures. The curves from bottom to top correspond to $T_9 = 1, 3, 5, 7, 9, 11, 13, 15$.

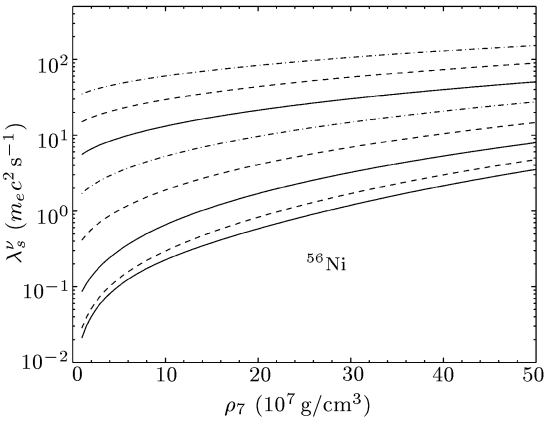


Fig. 5. NEL rates of nuclide ^{56}Ni in SES versus ρ_7 at the different temperatures. The curves from bottom to top correspond to $T_9 = 1, 3, 5, 7, 9, 11, 13, 15$.

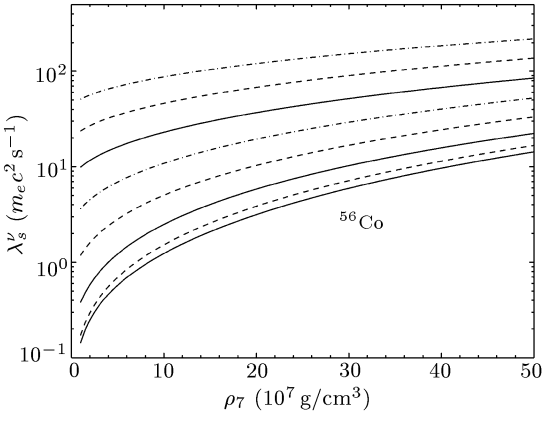


Fig. 6. NEL rates of nuclide ^{56}Co in SES versus ρ_7 at the different temperatures. The curves from bottom to top correspond to $T_9 = 1, 3, 5, 7, 9, 11, 13, 15$.

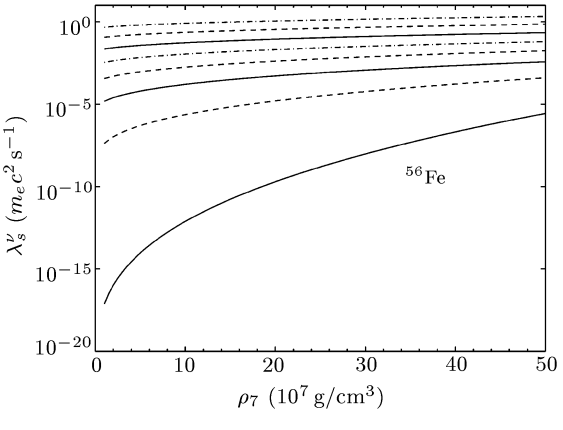


Fig. 7. NEL rates of nuclide ^{56}Fe in SES versus ρ_7 at the different temperatures. The curves from bottom to top correspond to $T_9 = 1, 3, 5, 7, 9, 11, 13, 15$.

Due to the SES, one can see that the NEL rates for ^{56}Ni decrease about 1 order of magnitude at $T_9 = 15$ and decrease about 2 orders of magnitude at $T_9 = 1$

from Figs. 1 and 5. One can also find due to the SES that the NEL rates for ^{56}Co decrease about 60% at $T_9 = 15$ and decrease closely to 2 orders of magnitude at $T_9 = 1$ from Figs. 2 and 5. According to Figs. 3 and 7, 4 and 8, the NEL rates for nuclei ^{56}Fe decreases about 10% at $T_9 = 15$ and for nuclide ^{56}Mn decreases about 15% because of the screening. The NEL rates decrease closely to 2 orders of magnitude for the two nuclides at $T_9 = 1$ due to SES.

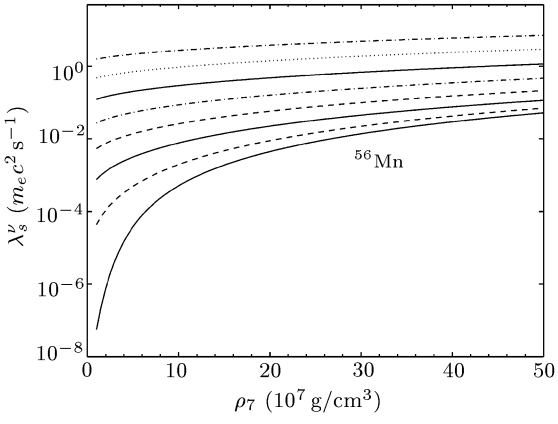


Fig. 8. NEL rates of nuclide ^{56}Mn in SES as versus ρ_7 at different temperatures. The curves from bottom to top correspond to $T_9 = 1$, 3, 5, 7, 9, 11, 13, 15.

By analysis for ^{56}Mn, ^{56}Fe, ^{56}Co and ^{56}Ni due to SES we draw the following results that the NEL rates decrease about 10%, 15%, 60% and 1 order of magnitude at temperature of $T_9 = 15$ correspondingly and decrease about 2 orders of magnitude at $T_9 = 1$.

In summary, one can conclude that the influence of the electron screening on NEL is very obvious. The higher the temperature is (such as $T_9 = 15$), the smaller the affection on the NEL is. Because the higher the temperature is, the higher the electron average energy is. The screening potential will be weaken relatively. On the contrary, the lower the temperature is, the larger the influence is. It is because the screening potential of electron is comparably high to the Fermi energy at the lower temperature (such as $T_9 = 1$). On the other hand, the affection on the higher energy Gammon–Teller transition is much larger than the lower energy ground transition by T_9. Meanwhile the screening potential made a large numbers of higher energy electrons not to join in the electron capture reactions.

As is well known, with escaping of a great many of neutrinos by electron capture, the neutrino energy loss gives one of the main contributions to the cooling of stellar interior in the late stages of stellar evolution. It is helpful to the collapse and the explosion of the supernova. Therefore the investigations on the neutrino energy loss have been the important questions and the conclusion obtained in this study has significant help on further research of nuclear astrophysics and neutrino astrophysics.

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