Effect of Electron Screening on the Collapsing Process of Core-Collapse Supernovae

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ABSTRACT

By using an average heavy nuclei model, the effects of the electron screening on electron capture (EC) in core-collapse supernovae are investigated. A one-dimension code based on the Ws15M\textsubscript{\odot} progenitor model is utilized to test the effects of electron screening during the collapsing process. The results show that, at high densities, the effects of EC on electron capture becomes significant. During the collapsing stage, the EC rate is decreased, the collapse timescale is prolonged and the leakage of the neutrino energy is increased. These effects lead to an appreciable decrease in the initial energy of the bounce shock wave. The effects of electron screening in the other progenitor models are also discussed.

Key words: nuclear reactions, nucleosynthesis, abundances - stars: evolution - supernovae: general.

1 INTRODUCTION

Supernovae explosion is one of the most violent events in our universe. Their explosion mechanism is an old problem, but has not been understood completely (see e.g. Woosley & Heger 2007; Martínez-Pinedo 2008 for reference). Generally, a massive star (\(M \geq 10\text{M}_\odot\)) proceeds through all burning stage from Hydrogen to Silicon, finally leading to an iron core in its center (Blanc & Greggio 2008). Electron capture (EC) causes the number density and the degenerate pressure of electron to decrease with a lot of neutrino energy loss, which lead to the accelerating collapse of the star till the central density reaches the maximum (two-three times the nuclear density). Later on, the infalling outer core collides with the stiff inner core, and then the bounce shock is produced in the vicinity of the boundary between the inner core and outer core. The initial temperature of shock wave is even higher than \(10^{11}\text{K}\). At such a high temperature, photon energy is much larger than the binding energy of nucleus, and the iron nuclei are photodisintegrated into protons, neutrons and electrons behind the shock wave (Janka 2007). Unfortunately with the current numerical simulations, a self-consistent treatment of one-dimension supernova model does not yet lead to successful explosion due to the energy insufficiency, while two-dimension models show some promise (Hix et al. 2003; Burrows et al. 2006).

It is well known that the weak interactions, especially the EC and beta decay, are essential to the evolution of supernovae. Many basic investigations at this aspect have been done by Bahcall (1962,1964), Fuller, Flower, Newman (1982a;1982b), Aufderheide et al. (1994), Langanke, Martínez-Pinedo (1999; 2000) and so on in the last decades. Fuller et al. (1982b) have ever mentioned the screening correction but they did not make a detailed calculation. Later, Hix & Thielemann (1996) and Bravo & García-Senz (1999) considered the screening correction on the silicon burning and nuclear statistical equilibrium (NSE), and they found that screening effect is significant. Luo & Peng (1996) investigated the effect of screening on EC in the supernovae environment by using Fuller et al. (1982a,b) method (i.e. so called shell model brink hypothesis). Their results show screening can reduce the EC rate by 10 – 20 per cent at high density. More recently improved EC rate and screening potential were adopted in Liu, Zhang & Luo (2007). The screening affects the EC mainly in three aspects. (1) The screening changes the Coulomb in-wave function of the electron; however, it can be neglected because the screening potential is much less than the average energy of the electrons. (2) The screening reduces the energy of the electrons in the capture reaction. (3) The screening decreases the number of the high-energy electrons with energy greater than the threshold energy of EC. As a result, the reaction threshold...
energy increases. Compared with screening on EC, there are at least two differences for beta decay. (1) The electron energy of beta decay is decided by the energy difference between parent nucleus and daughter nucleus (including rest mass), but the electron energy in EC can be much larger than that of the capture threshold. (2) In the inner core, beta decay is prohibited due to the Pauli exclusion principle (inhibition degree has been given by Peterson & Bahcall 1963); at the outer core, beta decay gets permission, but the evolution of inner core is quicker than that of outer core at core collapsing stage (which is less than 0.5s). So we here neglect the screening effect on the beta decay. Langanke et al. have suggested the screening should be considered in the simulations (Langanke & Martínez-Pinedo 2003), but up to now the screening effect on the total explosion process has not been done. Early numerical simulations show that the onset of the SN explosion depends on the pre-supernovae model and the evolution mode that is especially sensitive to the physical parameters input, which is closely related to the electron fraction and the weak interaction rates (Heger, Woosley & Martínez-Pinedo 2001). Therefore, it is imperative to obtain the EC rates with high precision. As an actual physical input, screening should not be ignored since a series of important parameters, such as neutrino energy loss, collapsing timescale etc., is changed. In this paper, we investigate the detailed effects of electron screening on EC in core-collapse supernovae.

2 PRE-SUPERNOVAE MODEL AND COMPUTATIONAL APPROACH

We perform numerical simulations by using a modified version of the one-dimension code developed by Y.R. Wang, S.C. Zhang, W.Z. Wang, Z.H. Xie (WZWX 2003) in 1996. In this code the general relativistic hydrodynamic equations are adopted (May & White 1966); the hydrodynamics method is smoothed particle hydrodynamics (SPH) referring to Benz (1991); equations of state are similar to Lattimer & Swesty (1991) and Cooperstein & Wambach (1984); the method of neutrino transport is provided by Suzuki (1994). The pre-supernovae model we choose is the Ws15M⊙ model with an iron core of 1.38M⊙ (Woosley & Weaver 1995). The grid domain includes 1.6M⊙, which is divided into 96 mass layers. Since most of nuclei involved in supernovae environment are on the unstable and excited states, it is difficult to get a precise description of each energy level, especially for heavy nucleus whose excited states are almost continuous. For a simple consideration, we assumed that the matter consists of four typical particles including free protons, free neutrons, α-particles, and heavy nuclei, i.e. the so-called ‘four-particle model’. Such four types of particles can well represent the whole property of pre-supernovae (Lattimer & Swesty 1991; Arcones Janaka & Scheck 2008). Similar to the other authors, detailed numerical model indicates the shock is unable to rush out of the iron core because of too much energy loss in the iron photodisintegration. So here we mainly investigate the screening effect in the collapsing process of supernovae explosion.

Usually, the capture rates for the nucleus (Z, A) in thermal equilibrium at temperature T is given by a sum over the initial parent states and the final daughter states (Pruet & Fuller 2003),

\[ \lambda = \sum_i \frac{(2J_i + 1)e^{-E_i/k_BT}}{G(Z,A,T)} \sum_f \ln \frac{2}{f_{i,f}} f_{i,f}, \]  

(1)

where \( J_i \) and \( E_i \) are the spin and excitation energy of the parent states, respectively, \( k_B \) is the Boltzmann constant and \( G(Z,A,T) \) the nuclear partition function. The \( f_{i,f} \)-values are related to \( GT \) and Fermi transition matrix elements. \( f_{i,f} \) is the phase space integral of electron. But for the ‘four-particle model’ we adopt, matter is composed of protons, free neutrons, α-particles, and heavy nuclei under NE. Only proton and heavy nuclei can capture electrons, so the total EC rate \( \lambda = \lambda_p + \lambda_H \), where \( \lambda_p \) and \( \lambda_H \) are the EC rates for proton and heavy nuclei, respectively. Considering the core of the pre-supernovae is composed of iron element, the dominant influence of electron screening is decided by the heavy nuclei. Precise calculation of the EC rate is usually based on the nuclear shell model, i.e formula (1), but the shortage of energy level quality at high temperature and diverse electron rates for so many different nuclei will bring complication and some uncertainty. Therefore, here the Fermi gas model is adopted to describe the average property of the heavy nuclei. The EC rate is defined by \( \lambda = -(dn_e/dt) \), when the number density of electron decreases \( \lambda > 0 \); otherwise \( \lambda \leq 0 \). According to Bethe et al. (1979), the EC rate for average heavy nuclei is expressed

\[ \lambda_H = 1.18 \times 10^{-44} \frac{3n_e}{\mu_e} \frac{3n_p}{\mu_p} \frac{c}{(p_F^p)^2 (m_e c^2)^2} m_p \int \int \int \frac{d\varepsilon}{\varepsilon} f_e d\varepsilon f_p d\varepsilon, \]

(2)

where \( n_e = \rho N_A Y_e, n_p = x \chi \mu \rho N_A, p_F = (2m_p \mu_p)^{1/2} \), \( \rho \) is the density, \( N_A \) is the Avogadro constant, \( \mu_p \) is the chemical potential for proton, \( Y_e \) is the electron fraction, \( m_p \) the mass of proton, \( z = Z/A, Z, A \) are the mass number and charge of average heavy nuclei, respectively. \( \chi_H \) is the fraction of the average heavy nucleus. \( \varepsilon_e \) and \( \varepsilon_p \) is the energy of electron and proton, respectively. \( f_e = \{1 + \exp[(\varepsilon_e - \mu_e - m_e c^2)/(k_B T)]\}^{-1} \) is the Fermi-Dirac distribution function for electrons. Because of the conservation of energy, \( \varepsilon_e + \varepsilon_p = \varepsilon_n + \varepsilon_v \), equation (2) becomes

\[ \lambda_H = 1.18 \times 10^{-44} \frac{3n_e}{\mu_e} \frac{3n_p}{\mu_p} \frac{c}{(p_F^p)^2 (m_e c^2)^2} \int \int \int \int \frac{d\varepsilon}{\varepsilon} f_e (\varepsilon_e + \varepsilon_p - \varepsilon_n)^2 f_e d\varepsilon f_p d\varepsilon, \]

(3)

where \( Q \) is the reaction threshold energy. \( Q = |Q_{i,f}| \) if \( Q_{i,f} < -0.511 MeV \), otherwise \( Q = 0.511 MeV \). \( Q_{i,f} = (m_p c^2 - m_d c^2 + E_i - E_f) \), \( m_p \) and \( m_d \) are the mass of parent and daughter nucleus, respectively, \( E_i \) and \( E_f \) is the excited energy for parent and daughter nuclei, respectively. Note that here parent and daughter nuclei are proton and neutron in bound state of nucleus, so \( Q_{i,f} = \mu_n + \Delta_n - \varepsilon_p \), which can also assure the energy of neutrino is not less than zero. Proton energy \( \varepsilon_p = \mu_p - \Delta_p \), therefore

\[ \Delta_p = \mu_p - \varepsilon_p = \mu_p - (\varepsilon_n + \varepsilon_v - \varepsilon_e) \approx \mu_p - (\mu_n + \Delta_n + \varepsilon_v - \mu_e) = \mu_e - \mu_n + \mu_p - \Delta_n = \mu_e - \mu_n + \mu_p - \Delta_n, \]

(4)

where \( \mu \approx \mu_n - \mu_p, \Delta = \mu_e - \mu_n - \Delta_n = 1.15 \rho_{10}^{-1/8} \mu_e/Y_e (d\mu_p/d\mu_e)^{1/4} \) is the maximum energy of
emitting neutrino, average energy of neutrino \( \varepsilon_\nu \approx (3/5)\Delta \), so \( \Delta_\rho \approx (2/5)\Delta \). \( \Delta_n = \min(3, \max(0, \Delta/2)) \), where 3MeV is a refereed value given by Bethe et al. (1979). Some values at initial moment are listed in Table 1.

In the high density gas, screening electron cloudy is formed. Screening reduces the energy of the electron and enhances the threshold energy, so the EC rate will decrease. We adopt the method similar to Liu et al. (2007), i.e., we ignore the effect on the electron energy and threshold energy. So the capture rate in the strong screening is rewritten as

\[
\lambda'_H = C \int_{\mu_p-\Delta_\rho}^{\mu_p} \int_{Q+D}^{\infty} (\varepsilon_e - \varepsilon_s)^2 
\]

\[
(\varepsilon_e - \varepsilon_s + \varepsilon_p - \mu_n - \Delta_n)^2 f_e d\varepsilon_e d\varepsilon_p 
\]

\[
C = 1.18 \times 10^{-44} \frac{3n_e}{\mu^2} \frac{3n_p}{k_f^2} \frac{c}{(m_e c^2)^2} m_p, 
\]

where \( \mu \) is the modification to the threshold energy, \( \varepsilon_s \) is the screening potential (Fuller et al. 1982b, Itoh et al. 2002):

\[
D = 2.94 \times 10^{-5} Z^{2/3} (pY_s)^{1/3} (\text{MeV}) 
\]

\[
v_s = 7.525 \times 10^{-5} Z^{3/2} \left( \frac{Z}{p_0} \right)^{1/3} J(\text{MeV}) 
\]

where \( p_0 \) is the density in the unit of \( 10^6 \) g cm\(^{-3} \), \( J = \sum_{i,j=0}^{10} a_{ij} s^i u^j \), \( s = 0.5(\log r_s + 3) \), \( u = 1/25(R - 25) \), \( r_s = 1.388 \times 10^{-2}(A/Z\rho_0)^{1/3} \), \( a_{ij} \) can be found in Itoh et al. (2002), equation (5) is valid for \( 10^{-5} \leq r_s \leq 10^{-1} \) (i.e. \( \rho \leq 10^{15} \text{g cm}^{-3} \)), which is usually fulfilled in the supernovae environment.

For the EC on proton, the most probable energy of interaction \( E_0 \simeq E_\nu \). Because of \( E_0 \gg E_p \) and \( kT > E_p \), where \( E_p \) is the Coulomb energy for proton, strong screening is invalid and weak screening is valid (Salpeter & von Horn 1969). According the method of Kippenhahn & Weigert (1990), Bahcall, Chen, & Kaminowski (1998) and Kippenhahn & Weigert (1990), weak screening factor is \( \exp(2\pi m \eta) \) for \( x_0 < < 1 \), where \( x_0 = r_c/r_D \equiv (Z/Z_{200}E_0)/(\zeta_g/T)^{1/2} \) (note that here \( E_0 \) is in KeV); \( r_c, r_D \) are the classical turning-point radius and Debye radius, respectively; \( \zeta = \sqrt{\sum_{i}(X_i Z_i^2/A_i + X_i Z_i/A_i)} \), \( X_i, Z_i, \) and \( A_i \) are the mass fraction, charge, and mass number, respectively; \( T_f \) is temperature in unit of \( 10^7 K \), \( \eta = (m/2)^{1/2}[(Z_i Z_{200}^2)/(\hbar E_0^{1/2})] \), where \( m \) is the reduced mass. With rough estimate for the core region of supernova, \( T \sim 10^9K, \zeta \sim 10, \) and \( \rho \sim 10^5 \sim 10^{12} \text{g cm}^{-3} \), weak screening correction is not more than 0.001. On the other hand, proton fraction is much smaller than heavy nuclei, so screening correction for free proton capture is not important comparing with that on heavy nuclei.

### 3 SIMULATION RESULTS

Because there are many output parameters in the simulation, in Table 1 we only tabulate some important parameters (only 10 layers are listed) at the initial moment of simulation (about 0.27s before bounce). One can see that the mass number and charge of average heavy nuclei, density, electron fraction, temperature in the pre-supernovae model and screening potentials at the different layers. Here, \( \lambda \) and \( \lambda' \) represent the EC rate without/with screening, respectively. It is shown in Table 1 that the mass number and charge of heavy nuclei decrease from the center to the outer layer. The screening potential is mainly dependent on the density, so both \( \lambda \) and \( \lambda' \) decrease monotonically with densities. \( \lambda \) is not only a function of \( Z, A, Y, \) and \( T \), but also a function of \( \lambda_p, \lambda_H, \lambda_{\nu_e} \), and \( \mu_e \), so it is not monotonic to the mass layers. With screening effect into consideration, it is easy to find that \( \lambda' \) is always smaller than \( \lambda \).

The neutrino leakage and diffusion process are the key factors on the explosion energy, and the energy loss of neutrino exceeds 90 per cent of the total in the whole evolution process of the star. Neutrino energy loss rate is an important and complicated parameter to affect the explosion energy and evolution, which is related with the weak interaction rate, neutrino energy, and transport equation and so on. The change of EC rate must influence the neutrino energy loss rate. Fig. 1 shows the comparison of neutrino loss rate with/without screening at 0.27s before bounce. Solid curve is neutrino energy loss rate without screening, while dashed curve is that with screening in the different layers.
denotes loss rate without screening, dotted curve denotes that with screening. We find neutrino energy loss rate decreases generally, at some region the modification is more than 5 per cent (It closely depends on EC rate), but for outer part of iron core, it has hardly changed.

Fig. 2 shows the evolution of EC rate with/without screening at different moment during the collapsing stage. One can find (i) the EC rate with screening is always smaller than that without screening, which is caused by the decrease of the EC rate and the delay of collapse time-scale. At the initial stage (such as symbol 1), the difference is mainly caused by the different EC rates, and at the later stage (such as symbols 5,6,7), the difference comes from a different collapse history, while at bounce moment, for the case without screening(symbol 8), the EC rates are similar to that at moment 6ms later for the case with screening. (ii) In the inner part of the core, both the EC rates and the difference between the case with screening and the case without screening increase rapidly with time. The reason is that the densities increase quickly with the collapsing process. The higher the density, the larger the screening potential. However the screening effect is decided not only by the potential, but also by the Fermi energy of electrons. When the density is large enough, the Fermi energy becomes much larger than the potential energy. Correspondingly the screening effect will decrease.(iii) In the outer part of the core, the EC rates change comparatively slow. At the edge of iron core (1.38M⊙), there is an inflexion because both the fraction of heavy nuclei and the densities break obviously. At the outer envelop, EC rate is almost stable since the time is just 0.3s. (iv) Note the squares symbols in Fig. 2, from left to right, they denote neutrino trapping critical position at -5.0, -1.5 and 0.0ms before bounce, respectively. We can find the high density region extents rapidly with time. Because of the inverse process of EC rate \[\nu_e + (A,Z) \rightarrow e^- + (A,Z + 1)\] enhances with density, above critical density (\[\mu_{\text{trapping}}\] is about \(3 \times 10^{12} \text{gcm}^{-3}\)), an equilibrium of neutrino will be reached and the lepton fraction (including electron fraction and neutrino fraction) will keep as a constant. Surely, at such situation our method for screening modification is invalid to change of lepton fraction, but screening is still exist and keep effect in the reversible reaction.

We also compare the collapsing time and the radius of protoneutron star (PNS) with screening/without screening(as shown in Fig. 3 and 4). We find (i) the collapsing time is prolonged; t=0.267s without screening while t=0.272s with screening. The reason is that screening decreases the capture rate. This makes the electron number density and degenerate pressure to drop a little more slowly than the fiducial case. During the collapsing stage, the total pressure is dominated by the electron degenerate pressure, so that the decrease of total pressure also become more

| \(j\) | \(A\) | \(Z\) | \(\rho \text{ gcm}^{-3}\) | \(Y_e\) | \(T \text{ K}\) | \(v_e \text{ MeV}\) | \(\mu_p \text{ MeV}\) | \(\mu_n \text{ MeV}\) | \(\Delta_p \text{ MeV}\) | \(\Delta_n \text{ MeV}\) | \(\lambda \text{ s}^{-1} \text{cm}^{-3}\) | \(\lambda' \text{ s}^{-1} \text{cm}^{-3}\) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 61.6 | 26.1 | 8.3E+09 | 0.42 | 8.1E+09 | 0.39 | 0.14 | -12.54 | -6.72 | 0.37 | 0.92 | 6.2E+30 | 5.1E+30 |
| 10 | 60.1 | 25.8 | 5.3E+09 | 0.43 | 7.9E+09 | 0.33 | 0.12 | -12.04 | -7.06 | 0.32 | 0.79 | 1.8E+30 | 1.6E+30 |
| 20 | 58.6 | 25.4 | 3.4E+09 | 0.43 | 7.7E+09 | 0.29 | 0.10 | -11.47 | -7.46 | 0.33 | 0.82 | 1.3E+30 | 1.0E+30 |
| 30 | 57.1 | 25.1 | 2.2E+09 | 0.44 | 7.5E+09 | 0.25 | 0.08 | -10.83 | -7.93 | 0.39 | 0.98 | 1.1E+30 | 1.0E+30 |
| 40 | 55.0 | 24.6 | 1.3E+09 | 0.45 | 7.3E+09 | 0.21 | 0.07 | -9.95 | -8.60 | 0.54 | 1.35 | 1.7E+30 | 1.5E+30 |
| 50 | 52.9 | 24.1 | 7.5E+08 | 0.46 | 6.8E+09 | 0.17 | 0.06 | -9.18 | -9.18 | 0.66 | 1.65 | 1.5E+30 | 1.4E+30 |
| 60 | 52.1 | 23.9 | 3.4E+08 | 0.46 | 7.1E+09 | 0.13 | 0.04 | -9.19 | -9.19 | 0.47 | 1.17 | 1.8E+29 | 1.7E+29 |
| 70 | 49.6 | 23.2 | 1.2E+08 | 0.47 | 6.1E+09 | 0.09 | 0.03 | -9.13 | -9.13 | 0.31 | 0.77 | 7.2E+27 | 6.9E+27 |
| 80 | 43.8 | 21.8 | 2.7E+07 | 0.50 | 4.7E+09 | 0.06 | 0.02 | -8.89 | -8.89 | 0.17 | 0.41 | 9.0E+25 | 8.7E+25 |
| 90 | 43.3 | 21.3 | 2.0E+06 | 0.50 | 2.9E+09 | 0.02 | 0.01 | -8.80 | -8.80 | 0.04 | 0.11 | 3.5E+22 | 3.4E+22 |

note. \(j\) denotes the layer number.
slowly and the collapsing velocity decreases comparatively. 
(ii) The initial energy of shock wave decreases. The initial energy of shock wave at about 0.8ms after bounce is 1.06 foe (1foe=1×10^{51} \text{erg}) without screening and 1.01foe with screening. Their difference is 0.05 foe, which is 5 per cent of the total. On the one hand, it could be that the calculation with screening results in a different radial profile of the star at bounce when compared with a calculation without screening. The different profile could result in differences in the propagation of the shock wave. Figure 4 shows that the total neutrino energy loss rate and the neutrino energy loss rate, the total energy loss is also related to the collapsing time.(iii) Radius of PNS is also related to the collapsing time.

4 CONCLUSION

In this paper, we have considered screening effect on EC, the corresponding effects on the collapsing process, and on the initial shock wave energy of core-collapse supernovae. Our results show that the screening effect is appreciable. Since there are both advantages and disadvantages to the final explosion, more detailed simulation is needed by using more concrete equation of state and progenitor model (Hix et al. 2003). In order to investigate the exact effect of screening, the concrete nuclide and the other methods are needed. In recent years, many methods such as the large-scale shell model and the pn-random phase approach are widely investigated (Nabi & Sajjad 2008). Improved results are universally one order of magnitude smaller than Fuller et al. (1982a,b) results. If the improved EC rates are considered, the screening effect should increase comparatively. Furthermore, for two or three dimension numerical simulations of core-collapse supernovae, our method for electron screening is also valid. The explosion mechanism of the core-collapse supernovae has been investigated extensively in the last four decades and significant progress has been obtained, but some of the most fundamental questions are still unanswered. It is necessary to include the effect of screening in later detailed simulations.

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