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The effects of ion screening on neutrino-nucleus interactions in core-collapse supernova explosions

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Abstract The effects of ion screening in stellar core collapses are investigated based on a new progenitor star model. Simulation results show that ion screening slightly affects the leptons and decreases explosion energy, which is a negative factor for energy transfer supernova explosions. We also investigate the effect on type II-supernova explosions of neutrino-nucleus elastic scattering based on the new progenitor star model. It is shown that, compared with the previously calculated results, neutrinos-nucleus elastic scattering in stellar core collapses is more severe, leading to an obvious reduction of the neutrino leakage energy loss and an increase of supernova explosion energy.

Key words: stars: supernovae: general — neutrino-nucleus

1 INTRODUCTION

Neutrinos are vital in matter both for the prompt-explosion model and the delayed-explosion model. Core-collapse supernovae produce huge fluxes of neutrinos, resulting in interactions between neutrinos and other particles in supernovae. Neutrino-matter interactions have been studied by many researchers in recent decades. Freedman (1974), Lamb & Pethick (1976), Burrows & Young (2000) and Langanke (2006) investigated neutrino-nucleus elastic scattering, and found that neutrino-nucleus reactions occur during the core collapse of a supernova's explosion phase, which plays an interesting role for supernova nucleosynthesis. Barnea & Gazit (2008) analyzed inelastic neutrino scattering with $A = 3, 4$ nuclei. Nakamura et al. (2009) calculated the energy loss rate due to neutrino absorptions through the charged-current process as well as neutrino scattering through the neutral-current process. Supernova models depend on details of the associated neutrino interactions.

Neutrino-nucleus elastic scattering, which dominates the neutrino opacity, is substantially reduced for low energy neutrinos (corresponding to neutrino energies $E_\nu \leq 2\hbar c/a_{\rm ion} \approx 20\,{\rm MeV}$) (Epstein & Arnett 1975). This results from interference effects that occur when the neutrino wavelength becomes longer than the interion spacing, and is analogous to a crustal becoming transparent to X-rays when the change in wave number from scattering is smaller than the reciprocal lattice spacing. This reduction in the neutrino-elastic scattering cross section, referred to as "ion screening," has been calculated recently by Horowitz & Wehrberger (1991), Horowitz (1997) and Marek et al. (2005).

In spite of great achievements in neutrino research, neutrino-matter elastic scattering and ion screening effects remain a very complicated problem; there exist a lot of issues regarding detailed interactions and transport equations. More recently, Nakamura et al. (2009) and Marek et al. (2005) have made a useful assessment of the importance of neutrino interaction and ion screening effects on the neutrino-nucleus scattering in supernova explosions. We wish to carry out independent calculations that investigate ion screening effects on stellar core collapse and the effects on type II-supernova explosions of neutrino-nucleus elastic scattering based on a new progenitor star model, to obtain more useful information about ion screening effect theory, neutrino-nucleus elastic scattering and supernova explosion mechanisms.

The paper is organized as follows: in Section 2 prescriptions for neutrino-nucleus elastic scattering and ion screening effects are presented, in Section 3 the inputs of our simulation results and analysis are described, and in Section 4 the conclusions are drawn.

2 NEUTRINO-NUCLEUS ELASTIC SCATTERING AND ION SCREENING EFFECTS

The neutrino-nucleus interaction is an important reaction in the stellar core collapse phase. We apply Freedman (1974), Lamb & Pethick (1976), Burrows & Young (2000), Langanke (2006), and Nakamura et al. (2009) researches to neutrino-nucleus elastic scattering $\nu_{\rm e} + A(N,Z) \rightarrow \nu_{\rm e} + A(N,Z)$. This approach determines the neutrino opacity, which is substantially changed for low energy neutrinos, and this reaction can form ion screening effects.

Freedman (1974) found that the scattering amplitude of the neutrino-nucleus interaction would be changed when the wavelength of the neutrino is much longer than the size of nuclei, and the nuclei do not photodisintegrate if the temperature is low enough. Then the supernova stellar core would produce a neutrino sphere. When the mean free path of neutrinos $\lambda < R_{\rm core}$ (the radius of core), then the neutrinos cannot freely be transported because of collisions, so the opacity of neutrinos would increase. If neutrinos cannot escape from the core of the collapse phase when $\tau_{\rm diff} < \tau_{\rm coll}$ ($\tau_{\rm diff}$: the neutrino diffusion time, $\tau_{\rm coll}$: the core collapse dynamic time), then the neutrinos would be trapped. The trapped neutrinos seem to be dragged into the stellar center when their outward velocity is equal to the collapse velocity. To estimate the mean free path of these neutrinos (λ), Epstein & Arnett first provided an equation in 1975:

$$\lambda = \frac{1.024 \times 10^{20}}{\rho} \cdot \frac{1}{E_\nu^2} \left[\left(X_n + \frac{3}{4} X_p + \frac{1}{4} X_\alpha \right) + \frac{X_A}{4} A \left(1 - \frac{Z}{A} \right)^2 \right]^{-1} , \tag{1}$$

where ρ is the density of the material, E_ν is the neutrino energy, $X_{\rm n}$, $X_{\rm p}$, X_α and X_A are the abundance of free neutrons, free protons, the mean light nuclei and heavy nuclei (A>1), respectively, and A and Z are the nucleon number and proton number of heavy nuclei, respectively. Wang et al. (1989) programmed the complex code "SNII-WLYW89" to simulate the explosion of a type II-supernova, and he applied the above equation and Epstein & Arnett's neutrino-nucleus interaction theory to calculate the energy of resulting neutrinos and the state equation. In addition, Brown et al. (1982) provided another equation (3):

$$\lambda = \frac{1.5 \times 10^{20}}{\rho} \cdot \frac{1}{E_\nu^2} \left[(1 - X_{\rm n}) \frac{C^2}{A} \langle S \rangle R_{\rm e} + X_{\rm n} \left(C_\nu^{n2} + 5 C_a^{n2} \right) \right]^{-1} . \tag{2}$$

$\langle S \rangle$ is the ion correlation factor. The total weak charge of a nucleus of charge Z and neutron number N is: $C = -2Z \sin^2\theta_W + (Z - N)/2$ (Weinberg angle of $\sin^2\theta_W = 0.223$). The constant $C_\nu^n = -1/2$, $C_a^n = -g_A/2 = -0.854$, and $R_{\rm e}$ is an additional correlation factor that describes electron screening. It takes the ion screening effects and the electron screening effects into account. However, because the mechanism of the two screening effects is too difficult to understand in terms of the detailed results, some researchers omit their influence. Recently, Horowitz & Wehrberger (1991), Horowitz (1997) and Marek et al. (2005) conducted some useful studies of the ion screening effect and obtained some useful information about type II-supernova explosions.

In the paper, electron screening is not considered and $R_{\rm e} \approx 1$. Using the strict solution of $\langle S\rangle$ becomes too difficult for attaining an accurate result, and we do the Monte Carlo fitting for the ion screening factor and get a fitting formula $\langle S\rangle_{\rm fit}$:

$$\langle S\rangle_{\rm fit} = X(\gamma,\xi)/\left[1+\frac{3\Gamma}{2\varepsilon^2}\exp\left(-\frac{\varepsilon^2}{\Gamma^{1/16}}\right)\right]; \tag{3}$$

$$\begin{aligned} X(\gamma,\xi) \;=\;& 1-\frac{1}{7.8}(\xi-1)^2(\gamma+2)^2\exp\left[-10\left(\xi-\frac{\gamma}{10}-0.25\right)^2-0.8(\gamma-0.2)\right] \\ &-\;\frac{1}{10}(\gamma+2)^{-0.3}\exp\left[-6\left(\xi-\frac{\gamma}{10}+0.2\right)^2\right] \\ &+\;\frac{1}{74}(\gamma+1.1)^5\exp\left[-130\left(\xi+\frac{\gamma}{10}-0.5\right)^2\right] \\ &-\;\frac{1}{42.2}(\gamma+1)^2\exp\left[-20(\gamma+2)(\xi-0.25)^2-0.8(\gamma-0.2)\right], \end{aligned} \tag{4}$$

where

$$\begin{aligned} \gamma &= (\log_{10}^{\Gamma}-1.10206)/1.10206, \\ \xi &= \log_{10}^{\varepsilon}, \\ \varepsilon &= E_\nu a_I/197.3, \\ a_I &= 7.346\times10^{-9}\times(\rho/A)^{-1/3}, \\ \Gamma &= 2.275\times10^{5}\times(A^{5/3}\times X1^2\times\rho^{1/3})/T, \\ X1 &= Z/A, \end{aligned}$$

where Z, A, ρ, T, and E_ν have the same meanings as in the above equations.

3 THE SIMULATION RESULT AND ANALYSIS

In the paper, we apply the new progenitor star model by Woosley et al. (2002) and Hoffman et al. (2008), and make use of neutrino-nucleus elastic scattering with ion screening effects during the core collapse phase. In addition, we apply the Monte Carlo fitting ion screening factor to modify the energy of the neutrinos and the equation of state in the code “SNII-WLYW89.” The code is a software package based on the FORTRAN language. Wang et al. (1989) compiled the type II-supernova explosion simulation code in the 1980s. The modified code is too long to be presented here. We utilize the modified code and calculate the model for thirty new progenitor stars from 11–40 $M_\odot$. Zhang et al. (2009) applied the original code of Wang et al. (1989) to calculate the effect of new progenitor stars on supernova explosions. Comparing the results of Zhang et al. (2009), we get some useful information about the theory of ion screening effects, neutrino-nucleus elastic scattering and type II-supernova explosions.

We optionally list six simulation results: S11, S13, S14, S15, S30 and S40 and display the following tables and figure. Here QS11–QS40 are the simulation results of Zhang et al. (2009) based on Equation (1) and the neutrino-nucleus theory provided by Epstein & Arnett (1975). YS11–YS40 are the results which used Equation (2), Horowitz (1997) and the model provided by Marek et al. (2005) describing the neutrino-nucleus elastic scattering with ion screening effects during the core collapse phase. NS11–NS40 are the results when $\langle S\rangle_{\rm fit} = 1$; it is the case that omits ion screening effects. In the following tables, t_2 is the time when stellar core collapse first reaches $\rho^c \le 10^{12}{\rm g\ cm^{-3}}$, t_4 is the time when ρ^c reaches the maximum value $\rho^c_{\rm max}$ and meets $\rho^c \le 2.7\times10^{14}\,{\rm g\ cm^{-3}}$, t_{11} is the time when the shock propagation reaches the M_{11} shell (units: ms).

Table 1 Results of the Core Collapse

Code	$Y_{\rm e}^c$	Y_ν^c	$Y_{\rm L}^c$	$\rho_{\rm max}^c$	σ	$\tau_{t_4-t_{11}}$	$\rho_{\rm trap}$
QS11	0.3213	0.0810	0.4023	1.2986	4.8096	10.804	1.0114
YS11	0.3192	0.0812	0.4004	1.2917	4.7841	10.707	1.0046
NS11	0.3207	0.0814	0.4021	1.2966	4.8022	10.556	1.0004
QS13	0.3186	0.0791	0.3977	1.2518	4.6363	8.7077	1.0097
YS13	0.3164	0.0786	0.3950	1.2406	4.5948	8.5034	1.0055
NS13	0.3185	0.0788	0.3973	1.2487	4.6248	8.4678	1.0102
QS14	0.3148	0.0759	0.3907	1.1898	4.4067	6.9326	1.0140
YS14	0.3117	0.0751	0.3868	1.1744	4.3496	6.9786	1.0116
NS14	0.3139	0.0765	0.3904	1.1887	4.4026	6.7080	1.0001
QS15	0.3145	0.0782	0.3927	1.2055	4.4648	14.537	1.0010
YS15	0.3128	0.0767	0.3895	1.1900	4.4074	13.764	1.0117
NS15	0.3134	0.0791	0.3925	1.1979	4.4367	13.688	1.0020
QS30	0.3139	0.0755	0.3894	1.1809	4.3737	6.6981	1.0059
YS30	0.3111	0.0743	0.3854	1.1582	4.2896	6.7697	1.0041
NS30	0.3120	0.0771	0.3891	1.1804	4.3719	6.7380	1.0070
QS40	0.3087	0.0743	0.3830	1.1313	4.1900	5.4255	1.0052
YS40	0.3055	0.0721	0.3776	1.1116	4.1170	5.5012	1.0051
NS40	0.3102	0.0726	0.3828	1.1274	4.1756	5.3898	1.0062

$Y_{\rm e}^c$ is the electron abundance, $Y_\nu^c$is the neutrino abundance. $Y_{\rm L}^c = Y_{\rm e}^c + Y_\nu^c$ is the lepton abundance when ρ^c reaches $\rho_{\rm max}^c$, $\rho_{\rm max}^c(\times 10^{15}$ g cm$^{-3})$ is the density when the core density ρ^c reaches the maximum value, $\sigma = \rho_{\rm max}^c/\rho_0$ ($\rho_0 = 2.7 \times 10^{14}$ g cm^{-3}), $\tau_{t_4-t_{11}}$ is shock propagation time from t_4 to t_{11} (units: ms), $\rho_{\rm trap}(\times 10^{12}$g cm$^{-3})$ is the neutrino trapped density at time t_2.

Table 1 summarizes the result of the core collapse. Comparison with the simulation results of Zhang et al. (2009) shows that the corresponding changes of the seven measured parameters are not obvious. On one hand, the results sufficiently prove that application of neutrino-nucleus elastic scattering with ion screening effects in the core collapse phase is very reasonable. On the other hand, from these bold data in the table, we can also see some interesting and regular physical phenomena. Taking into account the ion screening effect, the electron abundance $Y_{\rm e}^{\,c}$ and the neutrino abundance Y_ν^c yield slight reductions; eventually the lepton abundance $Y_{\rm L}^c$ decreases by about $0.4\% \sim 1.4\%$ compared to omitting the ion screening (see Table 1). In addition, in Horowitz's (1997) calculations of ion screening, his results imply a larger increase in the neutrino mean-free path by ion screening. According to his research results, the amount of neutrino energy and the mean velocity of shock propagation would decrease because of ion screening effects, and lead to the propagation time $\tau_{t_4-t_{11}}$ being prolonged. Table 1 shows that $\tau_{t_4-t_{11}}$ is prolonged under the influence of ion screening effects. It fully shows that our analysis is reasonable. In addition, an important factor is that changes in the trapped density $\rho_{\rm trap}$ are irregular. It is also shown that ion screening effects are very complex for the neutrino trapped density. The reasons for these phenomena need to be further studied.

Tables 2 and 3 display the transferred energy in the shock propagation and the loss of energy due to photodisintegration in the outer core, respectively. Comparing with the simulation result of Zhang et al. (2009), the corresponding changes of the parameters are obvious. Table 2 shows that the energy of neutrino leakage (ΔE_ν) has evidently decreased based on a new progenitor star model that has neutrino-nucleus elastic scattering with ion screening during the stellar core collapse phase. Comparing the results of Zhang et al. (2009), the reduced amount of ΔE_ν is from 10×10^{43} J to 7×10^{43} J. Although the transferred energy ΔE_b^H also has some reduction, the neutrino energy loss is comparatively smaller than ΔE_b^H, leading to an obvious increase of $E_{\rm xp}^{11}$; the increment is from 1×10^{43} J to 4×10^{43} J. Table 3 shows the evident increase of explosive energy $E_{\rm xp}$ at the last minute compared with results of Zhang et al. (2009). How to raise the explosion energy is an important topic to better understand type II-supernova explosion mechanisms. Among the relevant parameters, the

Table 2 Transferred Energy in the Shock Propagation

Code	$E_\nu(t_4)$	$E_\nu(t_{11})$	ΔE_ν	$E_b^H(t_4)$	$E_b^H(t_{11})$	ΔE_b^H	$E_{\rm xp}^{11}$
QS11	–17.3583	–31.9194	14.5611	–75.7593	–152.1426	76.3883	9.79470
YS11	–18.0447	–24.9402	6.89550	–79.3956	–153.0587	73.6631	11.0122
NS11	–17.3812	–23.9641	6.58290	–76.1798	–151.8399	75.6601	12.2243
QS13	–17.6875	–32.4134	14.7259	–67.3962	–144.5495	77.1533	9.4016
YS13	–18.5047	–25.7600	7.2553	–71.8473	–144.4831	72.6358	10.0190
NS13	–17.7105	–24.1004	6.3899	–66.5388	–145.5993	79.0605	11.9018
QS14	–18.9832	–35.3931	16.4099	–78.9562	–147.2931	68.3369	5.9914
YS14	–19.9651	–27.0810	7.1159	–82.4123	–147.4377	65.0254	6.8542
NS14	–18.9891	–25.5343	6.5452	–79.0168	–147.0549	68.0381	10.0879
QS15	–18.7912	–34.9616	16.1704	–90.0314	–155.1008	65.0694	6.4571
YS15	–19.6561	–26.3709	6.7148	–81.7717	–146.5900	64.8183	10.5189
NS15	–18.7336	–25.2721	6.5385	–78.0129	–147.4025	69.3896	10.7275
QS30	–19.3357	–36.0979	16.7622	–79.9289	–147.7804	67.8515	5.8297
YS30	–20.3017	–27.4248	7.1231	–83.6652	–146.9963	62.8613	9.4888
NS30	–19.3310	–25.8552	6.5242	–80.2365	–146.9963	66.7598	9.7894
QS40	–21.0541	–21.0541	17.5819	–69.0011	–138.7248	62.7237	5.1026
YS40	–22.1178	–22.1178	7.1322	–77.6125	–140.1496	62.5371	6.2911
NS40	–21.0299	–21.0299	6.6904	–69.0793	–140.2580	71.1787	6.8211

$E_\nu(t_4)$ and $E_\nu(t_{11})$ are the energy of the neutrino at time t_4 and t_{11}, $\Delta E_\nu = E_\nu(t_4) - E_\nu(t_{11})$: the neutrino carries off energy when the shock propagates through the M_{11} shell. $\Delta E_b^H = E_b^H(t_4) - E_b^H(t_{11})$: Transferring energy from the inner core to the outer core when time is from t_4 to t_{11}. $E_{\rm xp}^{11}$: the explosion energy when the shock arrives at the M_{11} shell (units: 10^{43} J).

Table 3 Loss of Energy of Photodisintegration in the Outer Core

Code	$E_{\rm dis}$	$E_\nu^{\rm oc}$	$E_{\rm xp}$	Code	$E_{\rm dis}$	$E_\nu^{\rm oc}$	$E_{\rm xp}$
QS11	5.0851	14.5895	9.7420	QS15	16.940	6.8775	1.0010
YS11	5.0851	6.8955	11.011	YS15	6.6803	6.7148	11.131
NS11	5.0851	6.5829	12.206	NS15	6.6803	6.5386	11.442
QS13	14.849	8.3550	1.0097	QS30	17.405	2.9001	1.0059
YS13	5.6302	7.2554	9.8026	YS30	6.1721	7.1234	2.9001
NS13	5.6302	6.3900	10.7130	NS30	6.1721	6.5246	2.9001
QS14	16.908	3.5799	1.0140	QS40	19.107	0.7189	1.0052
YS14	6.5393	7.0534	4.2422	YS40	5.7226	7.1348	1.0412
NS14	6.5393	6.5455	7.3224	NS40	5.7226	6.6927	1.2810

$E_{\rm xp}$ is the explosion energy in the last minute, $E_{\rm dis} = 16.961 \times (M_{\rm Fe} - M_s) \times 0.577$ is the equivalent photodisintegration energy in the outer core, $E_\nu^{\rm oc} = E_\nu(t_4) - E_\nu(t)$ is the neutrino energy in the outer core shell (units: 10^{43} J).

explosion energy is the key factor that controls the supernova explosion. On one hand, in this sense, our simulation results are more reasonable than the previous calculation results. This also clearly shows that neutrino-nucleus interactions during the core collapse phase is stronger, leading to the neutrino leakage energy loss per unit time having an obvious reduction and resulting in increased supernova explosion energy per unit time, so this way is more beneficial to supernova explosion research. On the other hand, taking into account ion screening effects shows that transferring energy (ΔE_b^H) from the inner core to the outer core leads to shock energy having some reductions. In addition, the escape neutrino energies ΔE_ν and $E_\nu^{\rm oc}$ have some increase, and it implies an increase in the loss of neutrino energy. Because of the shock energy that is formed, the explosion energy needs to overcome the lost neutrino energy and the lost energy of photodisintegration. So their changes would lead to a result that the explosion energy must decrease. Tables 2 and 3 show that $E_{\rm xp}^{11}$ and $E_{\rm xp}$ indeed decrease. In this sense, the influence of ion screening effects already becomes a negative factor in energy transfer in type II-supernova explosions.

In order to research how explosion energy varies with time, we draw six figures of the variation of explosive energy with time by applying ORIGIN software (Fig. 1). From Figure 1, comparison with the results of Zhang et al. (2009), six new progenitor star models all clearly show that the magnitude of explosive energy with time has obvious elevation, moreover, each curve has a similar trend of changes in the six images. In addition, ion screening effects slightly decrease the resulting explosion energy.

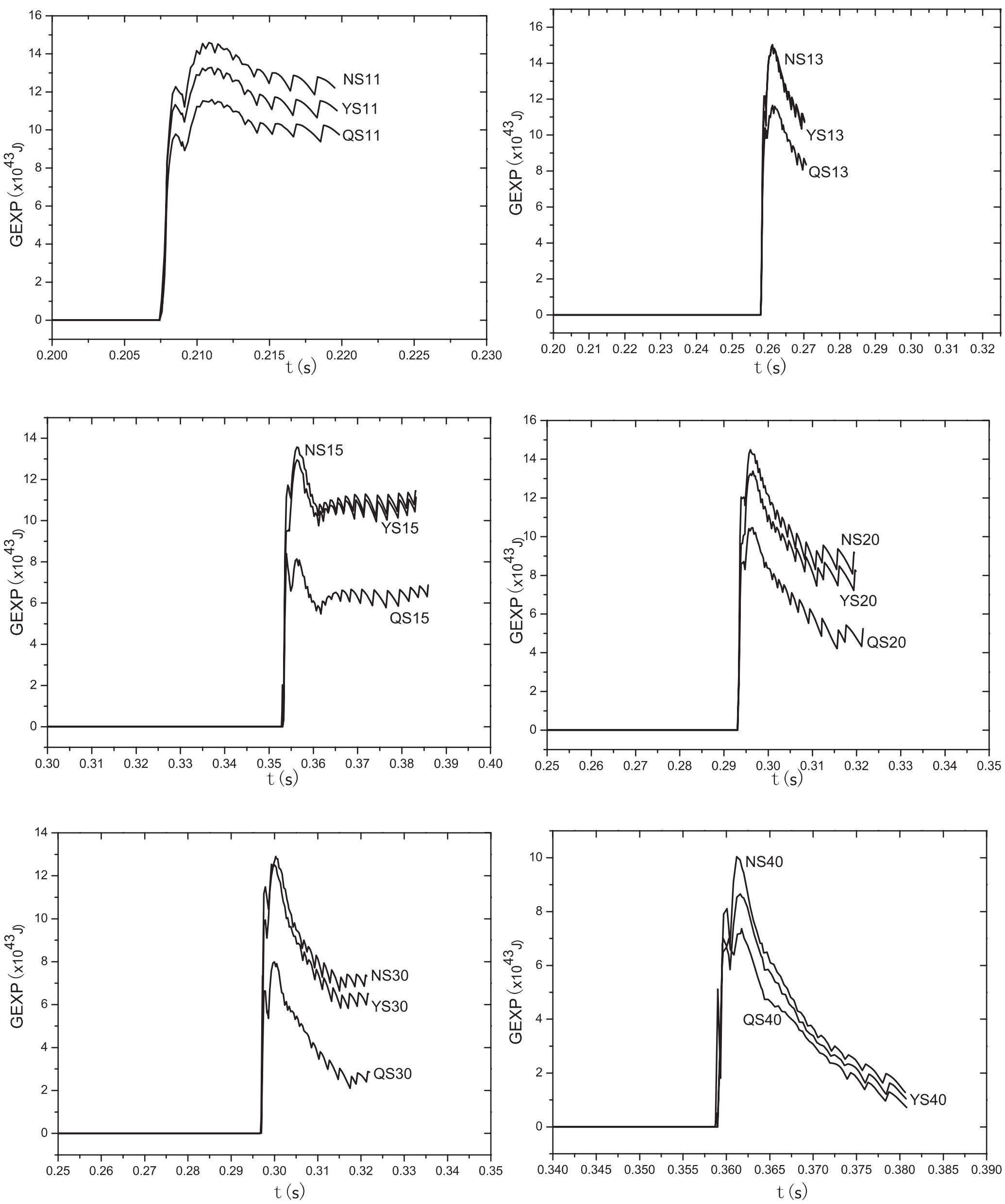

Fig. 1 Variation of explosive energy with time.

4 CONCLUSIONS

Even after 40 years of progress and development, we are far from a systematic and detailed understanding of the core-collapse supernova mechanism. In this paper, with application of a new progenitor star model as a prerequisite, we investigate how neutrino-nucleus elastic scattering with ion screening affects type II-supernova explosions. On the basis of detailed numerical simulations, we draw the following conclusions:

(1) Ion screening effects have slight perturbations on leptons and the shock propagation time is prolonged due to the influence of ion screening effects. In addition, ion screening effects slightly decrease explosive energy and become a negative factor regarding energy transfer in a type II-supernova explosion.

(2) Compared with the results of Zhang et al. (2009), neutrino-nucleus elastic scattering in a stellar core collapse is more severe, leading to an obvious reduction of the neutrino leakage energy loss and an increase of supernova explosion energy. It is more beneficial to energy transfer in a type II-supernova explosion. Hence, application of neutrino-nucleus elastic scattering with ion screening based on a new progenitor star model is more reasonable in the stellar core collapse phase.

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