Neutrino-induced nucleosynthesis as a result of mixing between the He and C–O–Ne shells in core-collapse supernovae

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ABSTRACT

The nucleosynthesis in core-collapse supernovae resulting from interaction of the neutrino flux with $^4\text{He}$ can contribute to the light element production (such as Li and B) and under favourable conditions to the origin of heavier nuclides belonging to the weak $r$-process component right up to the mass number $A \approx 130$. Here we investigate possibility of considerable contribution of the neutrino–$^4\text{He}$ interaction to the weak $r$-process component. We assume that a large-scale convective mixing could occur between the He and C–O–Ne shells in core-collapse supernovae. In that case some $^4\text{He}$ would be exposed to the neutrino radiation at a radius smaller than that predicted for He shell by standard pre-supernova models. Our calculations demonstrate that for metal-poor stars the neutrino contribution to creation of the weak $r$-process component becomes noticeable in case $^4\text{He}$ is dragged down at radii $R \lesssim 10^9$ cm.

Key words: neutrinos – nuclear reactions, nucleosynthesis, abundances – methods: miscellaneous – supernovae: general.

1 INTRODUCTION

When the neutrino radiated by the collapsing stellar core penetrates into outer pre-supernova carbon–oxygen–neon and helium shells it interacts with a number of atomic nuclei thereby modifying the composition of finally ejected supernova envelope. Such modifications observed in supernova spectra can provide reliable information about both the properties of the neutrino flux and hydrodynamics of a supernova envelope ejection. Here we continue to investigate consequences of the neutrino interaction with $^4\text{He}$ in matter throwing out by supernovae.

The interaction of neutrino flux with $^4\text{He}$ in supernova He shell was first discussed in Domogatsky, Eramzhyan & Nadyozhin (1978) and used there to estimate the synthesis of light elements such as Li, Be, and B. Then the neutrino-induced disintegration of $^4\text{He}$ was suggested by Epstein, Colgate & Haxton (1988) to be a source of neutrons for driving the $r$-process.

Further studies of this suggestion revealed that the resulting neutrino-induced yields of heavy nuclides were sensitive to a number of parameters describing the physical condition in pre-supernova He shell and depend on not yet finally established details of the supernova mechanism (see Nadyozhin, Panov & Blinnikov 1998; Nadyozhin & Panov 2007, 2008, and references therein).

The most important parameters are (i) the neutrino ‘light curve’ and the neutrino energy and flavour spectra; (ii) the supernova total explosion energy $E$ that determines the strength of the shock wave and time it takes to propagate through the pre-supernova envelope; (iii) the properties of the onion-like pre-supernova chemical structure, especially the radii $R$ of different chemical shells.

It was shown (Nadyozhin & Panov 2007) that neutrons produced by neutrino interaction with $^4\text{He}$ could appreciably contribute to a light (weak) component of a two-component $r$-process model (Wasserburg, Busso & Gallino 1996; Qian & Wasserburg 2000), especially in the case of a low-metallicity pre-supernova. However, this becomes possible if either the number densities of the neutron poisons in He shell, such as $^{12}\text{C}$, $^{14}\text{N}$, $^{16}\text{O}$, $^{20}\text{Ne}$, do not exceed at least that of iron seeds or the radius of He shell is below $(1–2) \times 10^9$ cm. Both the constraints are in conflict with currently available pre-supernova models in which some neutron poison abundances exceed by number that of iron seeds by a factor of 10–100 and the He shell radii are in the interval $4 \times 10^9-4 \times 10^{10}$ cm.

The calculations in Nadyozhin & Panov (2007) demonstrated the possibility of the neutrino-induced creation of the weak $r$-process component ($A \lesssim 130$) for the He shell at a radius of $1.37 \times 10^9$ cm when admixtures of neutron poisons are deactivated. These admixtures can depend on the still poorly studied diffusion and mixing...
of matter at the stars final evolutionary phases (semiconvection, meridional circulation).

The present work deals with the possibility of obtaining the weak r-process component by means of decreasing the He shell radius. We suggest that shortly before the beginning of gravitational collapse, large-scale circulation of matter can occur between the carbon–oxygen–neon and helium shells. This way a noticeable amount of helium could be transported down to be exposed to much stronger neutrino flux at smaller radii. Such suggestion assumes the braking of spherical symmetry at final stages of stellar evolution that was already repeatedly discussed in literature, see for example Bazán & Arnett (1998) and references therein.

2 PRE-SUPERNOVA MODEL

To estimate the efficiency of mixing between the He and C–O–Ne shells for production of the weak r-process component we make use of a 1.5 M⊙ low-metallicity (0.0001 Z⊙) evolutionary presupernova model (Heger 2013). Labelled as dd15z-4, the model belongs to materials collected for preparation of the review paper by Woosley, Heger & Weaver (2002). Finally, this model never was included in that review. Fig. 1 shows the mass fraction abundances X of chemical elements in the He and C–O–Ne shells versus mass coordinate m. Dark grey circle in the He shell and light grey one in the C–O–Ne shell enclose the region of mixing in our calculations. The properties of stellar matter for both the circles are listed in Table 1.

We assume that the mixing between He and C–O–Ne shells occurs at the last stage of hydrostatic pre-supernova evolution before onset of a powerful neutrino burst. As a result, a portion of He from the He shell (dark grey circle in Fig. 1) proved to be dragged into C–O–Ne shell (light grey circle) where it undergoes mixing with the C–O–Ne composition. Therefore, the mixed composition reads

\[
X_i = \alpha X_i(\text{He}) + (1 - \alpha) X_i(\text{CONe})
\]

(1)

where \(X_i(\text{He})\) and \(X_i(\text{CONe})\) are the mass fractions from the left- and right-hand columns of Table 1. Efficiency of mixing is controlled in our calculations by a parameter \(\alpha\). When \(\alpha = 0\) there is no intrusion of He shell matter at all. In case \(\alpha = 1\) we have an unsullied matter from He shell inside C–O–Ne one. Helium should penetrate into the C–O–Ne shell not earlier than several seconds before the neutrino burst. Otherwise He would be burnt in thermonuclear reactions (in our case, mostly in the 16O(α, γ)20Ne one) rather than to interact with the neutrino flux.

The mass fraction of the iron group seeds for r-process in the model dd15z-4 turns out to be as small as \(X_{Fe} \approx 1.38 \times 10^{-7}\), \((Y_{Fe} \approx X_{Fe}/56 = 2.46 \times 10^{-9})\).

3 THE NEUTRINO FLUX PROPERTIES AND NEUTRINO–NUCLEUS INTERACTIONS

The rate of the neutrino-induced transformation of a nuclide of mass number \(A\) is given by

\[
\frac{dY_A}{dt} = -q \frac{L_{104}(t) (\sigma_{Al})}{4\pi R^2(t)} Y_A
\]

(2)

where \(Y_A = \frac{n_A m_A}{\rho}\) is the number of nuclides \(n_A\) in unit volume per barion, \(L_{104}(t)\) is the total neutrino and antineutrino luminosity of all the neutrino flavours, \(q\) is the fraction of the total neutrino flux responsible for the interaction in question, \((E_r)\) is the neutrino mean individual energy, \(R(t)\) is the radius of the shell exposed to the neutrino interaction, and \((\sigma_{Al})\) is the cross-section averaged over the neutrino energy spectrum.

Integrating equation (2) by time at constant \(R(t) = R_0\), one can estimate that the magnitude of the neutrino-induced transformations is given by

\[
\xi \equiv \frac{\Delta n_A}{n_A} = N_\nu \frac{\langle \sigma v \rangle}{4\pi R_0^2} \approx \left(10^{-3} \text{ to } 10^{-5}\right)
\]

(3)

where \(N_\nu\) is total number of neutrino radiated whereas the numerical values are for typical case \(N_\nu \approx 10^{38}\), \((\sigma v) \approx 10^{-42} \text{ cm}^2\), \(R_0 = (10^7 \text{ to } 10^{10})\) cm. Therefore, as a rule one can neglect the neutrino interactions with the nuclides already produced by neutrinos. The neutrino-induced yields of such secondary interactions are of the order of \(\xi^2\).

We use the temporal behaviour of \(L_{104}\) based on the calculations of gravitational collapse of a 1.82 M⊙ iron core surrounded with a 0.18 M⊙ oxygen envelope from Nadyozhin (1977a,b, 1978; see also fig. 1 in Nadyozhin et al. 1998). Full energy carried away by neutrinos \(\int_0^\infty L_{104}(t) dt\) turned out to be 5.3 \times 10^{53} \text{ erg}. Henceforth we assume that the neutrino flux starts at \(t = 0\).

Table 1. Properties of layers undergoing mixing in presupernova model dd15z-4.

| Mid of He shell (zone 365) | C–O–Ne shell (zone 230) |
|---------------------------|-------------------------|
| \(m = 3.50 M_{\odot}\)   | \(m = 2.15 M_{\odot}\) |
| \(R_0 = 1.58 \times 10^{10} \text{ cm}\) | \(R_0 = 1.3 \times 10^9 \text{ cm}\) |
| \(T = 7.914 \times 10^4 \text{ K}\) | \(T = 7.7 \times 10^4 \text{ K}\) |
| \(\rho = 36.6 \text{ g cm}^{-3}\) | \(\rho = 3.9 \times 10^5 \text{ g cm}^{-3}\) |
| \(X_{He} \approx 1.0000\) | \(X_{He} = 0.0\) |
| \(X_{C12} = 9.743 \times 10^{-8}\) | \(X_{C12} = 5.089 \times 10^{-3}\) |
| \(X_{N14} = 1.331 \times 10^{-6}\) | \(X_{N14} = 0.0\) |
| \(X_{O16} = 3.201 \times 10^{-8}\) | \(X_{O16} = 6.978 \times 10^{-1}\) |
| \(X_{Ne20} = 2.40 \times 10^{-7}\) | \(X_{Ne20} = 2.353 \times 10^{-1}\) |
| \(X_{Mg24} = 4.11 \times 10^{-8}\) | \(X_{Mg24} = 5.539 \times 10^{-2}\) |
| \(X_{Fe} = 1.38 \times 10^{-7}\) | \(X_{Fe} = 1.38 \times 10^{-7}\) |
The neutrino–nuclear interactions and their mean cross-sections per target nucleus.

| Reaction | Mean cross-section $\langle \sigma v \rangle$ (10^{-42} \text{ cm}^2) |
|----------|-----------------------------------------------|
| $^4\text{He}(v, v')^3\text{He}$ | 0.403 |
| $^4\text{He}(v, v'p)^4\text{H}$ | 0.441 |
| $^{12}\text{C}(v, v'n)^{11}\text{C}$ | 0.512 |
| $^{12}\text{C}(v, v'p)^{11}\text{B}$ | 1.86 |
| $^{12}\text{C}(v, v'\alpha)^{10}\text{Be}$ | 0.0024 |
| $^{14}\text{N}(v, v'n)^{13}\text{C}$ | 0.312 |
| $^{16}\text{O}(v, v'n)^{15}\text{O}$ | 0.747 |
| $^{16}\text{O}(v, v'p)^{15}\text{N}$ | 2.68 |
| $^{20}\text{Ne}(v, v'n)^{19}\text{Ne}$ | 1.05 |
| $^{20}\text{Ne}(v, v'p)^{19}\text{F}$ | 7.31 |
| $\rho(x, e^-)/n$ | 9.70 |

In our calculations we also assume that $L_{\text{act}}(t)$ is equidistributed among the neutrino species, i.e., $q_{e\nu} = q_{\nu\mu} = q_{\nu\tau} = q_{\nu_x} = q_{\tau\nu} = 1/6$. During the first ~100 ms of the collapse, $L_{\text{act}}(t)$ is building up mostly by the electron neutrino from neutronization of stellar matter. However, later on the approximate equidistribution over the neutrino flavours sets in.

We took into account the neutrino–nuclear current interactions listed in Table 2 where $v$ stands for $\nu$ and $\bar{\nu}$ neutrino and antineutrino. The charged current electron antineutrino $\bar{\nu}_e$ capture by protons of the order of $1.25 \times 10^{-2} \text{ MeV}$ was included as well. We neglected the reaction $^4\text{He}(\bar{\nu}_e, e^-n)^3\text{He}$ suggested by Banerjee, Haxton & Qian (2011) since its cross-section is about two orders of magnitude less than that for neutral currents. The neutrino cross-sections averaged over the Fermi–Dirac spectra were taken from Heger et al. (2005), Woosley et al. (1990), and Domogatskij & Imshennik (1982).

The neutrino spectra are assumed to be the Fermi–Dirac distributions with zero chemical potentials and the neutrinosphere temperature $T_{\nu\mu\tau}$ which correspond to the neutrino mean energies $E_{\nu} = 25$ and 12 MeV, respectively. These values of $E_{\nu}$ are based on the results obtained by Woosley et al. (1994). However, recent calculations (Fischer et al. 2010; Hidepohl et al. 2010) predict surprisingly low mean energies for $\mu$- and $\tau$- neutrino, as small as $E_{\nu} = 15$–16 MeV.

The cross-section of excitation of $^4\text{He}$ by $\mu$- and $\tau$-neutrinos and the corresponding branching ratios for proton and neutron emission were calculated by Epstein et al. (1988) and Woosley et al. (1990) for the neutrino temperatures $T_{\nu\mu\tau} = 4$–12 MeV. According to Nadyozhin et al. (1998) this cross-section can be approximated by a simple equation

$$\langle \sigma v \rangle_{^4\text{He}} = 5.28 \times 10^{-43} T_{\nu\mu\tau}^2 \exp(-29.4/T_{\nu\mu\tau}) \text{ cm}^2, \quad (4)$$

where $T_{\nu\mu\tau}$ is in MeV. Equation (4) reflects the threshold nature of the process and has an accuracy better than 10 percent within all the temperature range involved (4–12 MeV).

For $E_{\nu} = 16$ MeV, we have $T_{\nu\mu\tau} = 5.15$ MeV, and according to equation (4), the cross-section in question would be by a factor of 7 lower than for $(E_{\nu} = 25 \text{ MeV})$ suggested in our calculations.

### 4 SHOCK WAVE

The main parameters determining the temporal behaviour of shocked matter are the total energy of the explosion $E$ which comes from the supernova mechanism, the initial (pre-shock) density $\rho_0$, and the radius $R_0$ of the shell under consideration (the Si–S, C–O–Ne, or He one). The initial temperature $T_0$ of the shell is virtually unimportant since the shock wave (SW) is always very strong.

The study of the SW propagation through the pre-supernova structure allowed to construct simple formulae that approximate the temporal behaviour of the shocked matter properties resulting from detailed hydrodynamical calculations (Nadyozhin & Deputovich 2002). For the C–O–Ne shell the formulae read as follows:

$$T(t) = \frac{T_p}{1 + \xi_t (t - t_{SW})/t_a}, \quad T_p = \xi_t T_{\text{SW}}, \quad (5)$$
$$\rho(t) = \rho_p \left( \frac{T}{T_p} \right)^3, \quad \rho_p = 7 \rho_0, \quad (6)$$
$$R(t) = R_0 [1 + \xi_t (t - t_{SW})/t_a], \quad (7)$$

where $T_p$ and $\rho_p$ are the peak temperature and density of shocked matter while $\xi_t$, $\xi_T$, and $\xi_{\rho}$ are the dimensionless structural coefficients chosen to fit the hydrodynamic calculations as close as possible.

Equations (5)–(7) imply that the SW takes time $t = t_{SW}$ to reach the layer after the beginning of the neutrino flux. Therefore, equations (5)–(7) are only valid for $t \geq t_{SW}$ whereas within time interval $0 \leq t < t_{SW}$ the temperature, density, and radius remain equal their initial values $T_0$, $\rho_0$, and $R_0$.

Parameters $t_{SW}$, $T_{SW}$ (a Weaver & Woosley 1980 estimate of the peak temperature), and characteristic time $t_a$ are given by

$$t_{SW} = \delta t + \xi_{SW} E_{51}^{-0.38} (R_{90})^{1.4} \text{ s}, \quad (8)$$
$$T_{SW} = \left( \frac{3E}{4\pi a R_0^2} \right)^{1/4} = 2.37 \times 10^9 E_{51}^{0.25} (R_{90})^{-0.75} \text{ K}, \quad (9)$$
$$t_a = 3.83 \times 10^{-3} \rho_0^{0.5} E_{51}^{-0.5} (R_{90})^{2.5} \text{ s}, \quad (10)$$

where $E_{51} = E/10^{51} \text{ erg}$, $R_{90} = R/10^9 \text{ cm}$, and $\xi_{SW}$ is another dimensionless structural coefficient. All such coefficients listed above slightly depend on the composition of the shell under consideration and pre-supernova mass. They are tabulated in Nadyozhin & Deputovich (2002).

For the C–O–Ne shell of a 15$M_\odot$ pre-supernova we use here $\xi_t = 0.95$, $\xi_T = 1.4$, $\xi_\rho = 1.25$, $\xi_{SW} = 1.1$. The term $\delta t$ in the right-hand side of equation (8) is the delay time necessary for converting of standing accretion shock into outgoing blast wave. A standard value $\delta t = 100 \text{ ms}$ was assumed in our calculations. In the calculations we used in equations (5)–(10) standard value for the explosion energy $E_{51} = 1$ and the values of $R_0$ and $\rho_0$ from Table 1 for the C–O–Ne shell. Finally, we have

$$T_p = 1.85 \times 10^9 \text{ K}, \quad \rho_p = 2.75 \times 10^5 \text{ g cm}^{-3}, \quad t_{SW} = 1.688 \text{ s}, \quad t_a = 1.457 \text{ s}. \quad (11)$$

As a result, the radius $R(t)$ of the Lagrangian layer increases by a factor of 2 in 1.17 s after the SW arrival whereas the temperature $T(t)$ becomes two times less than $T_p$ in 0.83 s.

### 5 METHOD OF CALCULATION

We have used two nuclear kinetics codes. The first one controls the nuclear kinetics for the light nuclides from D, $^3\text{H}$, $^3\text{He}$, . . . through $^{24}\text{Mg}$ (the L code). The L code calculates the kinetics of about 160 thermonuclear reactions and $\beta$-processes (including neutrino–nuclear interactions listed in Table 2) connecting 40 most important
light nuclides. The second code (H) controls the nuclear kinetic for the heavier nuclides up to \( Z = 82 \) (Pb). In our calculations the H code deals with about 1300 isotopes. It uses effective method of Gear (1971) for solving stiff systems of differential nuclear–kinetic equations and involves a special algorithm of converting the sparse Jacobian matrix (see detailed description in Blinnikov & Panov 1996).

The rates of thermonuclear reactions, neutron capture reactions, and \( \beta \)-decays used by the L and H codes are described in Nadyozhin et al. (1998) and Nadyozhin & Panov (2007). Both the codes work consistently by iterative exchange with free neutrons and protons. The method was first proposed in Nadyozhin et al. (1998) and then was developed in Nadyozhin & Panov (2001a, b) where one can find further details.

6 RESULTS AND DISCUSSION

We have fulfilled the calculations for different values of the mixing parameter \( \alpha = 0, 0.3, 0.4, 0.5, \) and 1. Fig. 2 shows the densities of free neutrons \( N_n \) and protons \( N_p \) as functions of time for the case \( \alpha = 1 \). Before the SW arrival (\( 0 < t < 1.688 \) s), the species \( n, p, {^3}\text{He}, {^3}\text{H} \) produced in the first two reactions of Table 2 interact with themselves, \( {^4}\text{He}, \) admixtures of the C, N, O, Ne isotopes listed in Table 1, and with ‘Fe’ peak nuclides. As a result, considerable part of neutrons released in the reaction \( {^4}\text{He}(\nu, \nu'n) {^3}\text{He} \) is absorbed in the reaction \( {^3}\text{He}(n,p) {^3}\text{H} \) followed by a chain of thermonuclear reactions creating light nuclides with excess of neutrons, such as \( {^{13}}\text{C}, {^{14}}\text{C}, {^{15}}\text{N}, {^{16}}\text{O}, {^{17}}\text{O}, {^{19}}\text{F}, {^{21}}\text{Ne} \) in amounts comparable with that of Fe seeds and \( N_n(t) \) begins to decrease after attaining its maximum at \( t \approx 0.01 \) s.

However, at high temperature after the SW arrival, above nuclides undergo a quick destruction through the reactions \( {^{13}}\text{C}(\text{He}, n) {^{16}}\text{O}, {^{14}}\text{C}(p, n) {^{14}}\text{N}, {^{15}}\text{O}(\text{He}, n) {^{18}}\text{Ne}, {^{17}}\text{O}(\text{He}, n) {^{19}}\text{Ne}, {^{19}}\text{F}(p, n) {^{19}}\text{Ne}, {^{21}}\text{Ne}(\text{He}, n) {^{22}}\text{Mg} \) which emit neutrons forming a large maximum of \( N_n(t) \) in Fig. 2.

Fig. 3 shows the \( r \)-process abundances of heavy nuclides \( Y_A = m_u N_A/\rho \) versus mass number \( A \) for several times. Since the neutron and proton captures do not change the total number of heavy nuclides, at any time the \( Y_A \) distribution meets an equation

\[
\sum_A Y_A = Y_{\text{Fe}},
\]

where \( Y_{\text{Fe}} = m_u N_{\text{Fe}}/\rho = X_{\text{Fe}}/56 = 2.46 \times 10^{-9} \) is the initial (at \( t = 0 \)) value.

The \( Y_A \) distribution for \( t = 4.2 \) s is virtually indistinguishable from that for \( t = 15 \) s. One can observe only tiny differences marked by arrows with letters ‘a’ and ‘b’. This means that the \( r \)-process comes to its end at \( t \sim 4 \) s when temperature and density fall below \( 5.7 \times 10^8 \) K and \( 8.2 \times 10^3 \) g cm\(^{-3} \), respectively. The radius of the expanding shell increases by a factor of 3 and the neutrino flux decreases by an order of magnitude. In total only \( 1.6 \times 10^{53} \) erg or \( \sim 30 \) per cent of available neutrino energy was actually used in our calculations.

The final yields are shown in Fig. 4 for different degree of mixing \( \alpha \). One can observe that \( \alpha \) should exceed a critical value 0.3 for the \( r \)-process to be launched beyond \( A \approx 80 \).

Figure 2. The free neutron \( N_n \) and proton \( N_p \) densities (in cm\(^{-3} \)) versus the time (in logarithmic scale) measured from the beginning of the collapse at \( t = 0 \).

Figure 3. The temporal development of the \( r \)-process for \( \alpha = 1 \).

Figure 4. The final yields at \( t = 15 \) s for different degree of mixing \( \alpha \).
The number of neutrons and protons captured per ‘Fe’ seed.

| $\alpha$ | Before SW ($t = t_{sw}$) | Final ($t = 15$ s) |
|---------|----------------|------------------|
|         | n/Fe$^{\alpha}$ | p/Fe$^{\alpha}$  | n/Fe$^{\alpha}$ | p/Fe$^{\alpha}$ |
| 0.0     | 0.240          | $1.7 \times 10^{-8}$ | 0.234          | 0.067          | 0.301          |
| 0.3     | 6.0            | $6.7 \times 10^{-5}$ | 20.4           | 0.7            | 21.1           |
| 0.4     | 7.0            | $1.1 \times 10^{-4}$ | 31.0           | 1.8            | 32.8           |
| 0.5     | 11.8           | $2.0 \times 10^{-3}$ | 32.9           | 2.72           | 35.6           |
| 1.0     | 21.0           | $4.4 \times 10^{-2}$ | 46.8           | 2.73           | 49.5           |
| 1.0$^a$ | 21.0           | 0.0               | 27.3           | 0.0            | 27.3           |
| 1.0$^b$ | 21.8           | $5.6 \times 10^{-1}$ | 62.3           | 3.5            | 65.8           |

*aProton-capture reactions are neglected.

*bShort-time neutrino flux curve with e-folding time 3 s is adopted.

Table 3 sums up the results of our calculations for different $\alpha$ in terms of the numbers of neutrons and protons captured by all heavy nuclides per ‘Fe’ seed. The second and third columns give the results at the moment of the shock arrival whereas the final values are in next two columns. The last column shows the total number of nucleons (n+p) captured per ‘Fe’ seed. Note that in case $\alpha = 0$ the final value of n/Fe$^{\alpha}$ at $t = 15$ s is slightly below than that at $t = t_{sw}$. This occurs due to the (p,n) reactions activated on heavy nuclides after the SW arrival.

The last line of Table 3 is for the case when the neutrino luminosity curve is described by the law $L_\nu \sim \exp(-t/\tau)$ with the e-folding time $\tau = 3$ s used, for example, in Banerjee et al. (2011). Such a fast decay of $L_\nu$ contradicts the observations of supernova 1987A in the Large Magellanic Cloud. However, it increases the fraction of the total radiated neutrino energy that could be useful for the nucleosynthesis we deal with. At obtained above quenching time 4.2 s about 75 per cent of all neutrino energy is radiated rather than only 30 per cent for the neutrino light curve adopted in our calculations.

Fig. 5 demonstrates the role of the proton capture reactions (p,$\gamma$) and (p,n) by heavy nuclei created from ‘Fe’ seeds. These reactions, activated by high temperature of shocked matter, increase atomic number $Z$ and thereby accelerate the $r$-process. The dash–dotted and solid lines are from Fig. 3. The dashed line comes from the calculation neglecting above proton capture reactions. A comparison of the solid and dashed lines shows that the abundance peaks at $A \approx 110$ and 130 become about an order of magnitude higher due to the proton capture reactions. This result is in accordance with the conclusion of our previous work Panov & Nadyozhin (1999). The total number of nucleons captured per ‘Fe’ seed turns out to be by a factor of 1.8(!) lower than in case when the proton capture reactions are taken into account (the last but one line in Table 3).

The final abundances $Y_A$ are shown in Fig. 4 for $t = 15$ s when virtually all $\beta$-unstable nuclides have been decayed. One can observe four peaks at $A \approx 80–84, 94–102, 110–114$, and 127–132 which are mainly formed by nuclides of atomic numbers $Z = 35$ (Br), 36 (Kr), $Z = 42$ (Mo), 44 (Ru), 46 (Pd), 48 (Cd), and $Z = 52$ (Te), I(53), 54 (Xe), respectively. The peak $A = 80–84$ appears when the mixing parameter $\alpha$ is as large as $\alpha \gtrsim 0.3$ whereas other peaks rise with increasing $\alpha$ and become clearly distinguishable for $\alpha \gtrsim 0.5$. Such a pattern can be regarded as finger prints of the neutrino mechanism considered here.

The main goal of our paper is to reveal the conditions favourable for a contribution of the neutrino interactions to the weak $r$-process. So, it would be premature to compare in detail our results with observations of metal poor stars, such as for example being discussed in recent review by Roederer et al. (2012). We can only mention that peaks for $A \approx 80–84$ and 94–102 are there (see fig. 16 in Roederer et al. 2012) whereas there are no abundance measurements for atomic numbers $46 < Z \leq 54$ responsible for the peaks $A \approx 110–114$ and 127–132.

The abundance pattern obtained in our calculations deserves further careful study including extensive grid of calculations that covers variations of basic input parameters such as a pre-supernova mass and metallicity, its He and C–O–Ne shells radii, properties of the neutrino spectra, and supernova explosion energy.

7 CONCLUSION

To guarantee a noticeable contribution of the neutrino radiation into the weak $r$-process component the following conditions have to be satisfied.

(1) The breaking of spherical symmetry is necessary in presupernova models to take into account possible large-scale circulating currents transporting some He from $R = 4 \times 10^9$ to $4 \times 10^{10}$ cm in deeper layers.

(2) Helium has to be at radius $R \lesssim 10^9$ cm with the mass fraction $X_{He} \gtrsim 0.3$. If the mean neutrino energy ($E_\nu$) is actually as low as 16 MeV then for $R_0 = 10^8$ cm the minimum $X_{He}$ should be close to 1.

(3) Shock wave must be described accurately since it activates evaporation of neutrons absorbed by light elements before its arrival as well as stimulates the proton (p,n), (p,$\gamma$) captures by heavy elements produced from ‘Fe’ seeds, thereby considerably speeding up the $r$-process.

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