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A Comparative Study on SN II Progenitors for the Synthesis of Li^7 and B^{11} with the help of Neutrinos

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Abstract. The synthesis of Li^7 and B^{11} confronts astrophysicists. Type II (SN II) and Type Ic (SN Ic) supernovae are supposed to be the producers of these two elements. In this study we calculate the yields of these two elements for SN II progenitors with 8, 10 and 20 solar masses. The process considered here is the neutral current interaction of heavy flavour neutrinos (ν_μ or ν_τ) with He^4 nuclei of the helium zone. The low mass progenitors are considered because the helium zone lies much closer to the core and hence experiences large neutrino flux. The starting point of the helium zone depends on detail stellar model. However, the shell radius at which it begins is available for these stars. 20 solar mass is considered for comparison of our production ratio Li/B with that of an earlier work. It is contrasted with the shock heating yields in the hydrogen envelope. The Li/B ratio has been found to be about 0.96. In the three model stars, the Li^7 and B^{11} yields are found to be in the range 6.61×10^{-6}–$2.63 \times 10^{-6} M_{\text{Sun}}$ and 6.92×10^{-6}–$2.75 \times 10^{-6} M_{\text{Sun}}$ respectively as we go from 8 to $20 M_{\text{Sun}}$. Some equivalence is found with shock induced nucleosynthesis model for SN II. The SN II yield is found to be compatible with that of hypernovae produced by C–O core collapse but higher than the yields obtained by neutrino processes in SNIc.

Key words. Supernova progenitor—neutrino process—neutral current.

1. Introduction

Certain light elements in the cosmos can not be synthesized by known stellar fusion processes. Li^7 and B^{11} are marked examples. But there is no dearth of process to explain their origin. Interaction of supernova neutrinos with nuclei of the stellar zones before the explosion has been studied (Domogatskii *et al.* 1978; Woosley *et al.* 1990). Lower bound on cross section of neutrino processes (Woosley *et al.* 1990; Haxton 1988, 1998) motivates the study of neutrino nucleosynthesis. Inelastic neutrino scattering excites nuclei to particle unbound states. The result is particle emission. The left over nuclei can undergo further capture events to form new nuclei. It may be one additional mechanism for element synthesis.

Enhancement of light element production by neutrino interaction in Type Ic supernovae (SN Ic henceforth) and spallation of exploded material with ambient matter has also been studied (Nakamura *et al.* 2010). In SN Ic, the production of B^{11} due to interaction of high temperature muon neutrinos ($T = 6-8$ MeV) with the carbon-rich layer of compact progenitor was studied.

In cosmology, the lithium abundance calculated by using the Big Bang model has given rise to lithium discrepancy. The lithium channels in the early universe environment are the following: $H^3(He^4, \gamma)Li^7$; $He^3(He^4, \gamma)Be^7(e^-, \nu_e)Li^7$; $Be^7(n, p)Li^7$. Observations on metal-poor stars (Ryan *et al.* 2000) and Li^7 abundance from globular clusters (Bonifacio *et al.* 2002) show that abundance predicted by Big Bang differs from measurements by a factor of 3–4 (Boyd 2008). Modification of early universe expansion rate either due to cosmological term or due to increased 'gravitational constant' has been studied (Kalita *et al.* 2012) for modification of lithium abundance. Apart from Big Bang nucleosynthesis for Li^7, Li^7 and B^{11} can be synthesized in AGB stars by the chain: $H^1(H^1, e^+\nu_e)D^2(H^1, \gamma)He^3(He^4, \gamma)Be^7(e-, \nu_e)Li^7$; $Be^7(He^4, \gamma)C^{11} \xrightarrow{\beta^+} B^{11}$ (Cameron 1955). Galactic cosmic rays for Li, Be, B (lithium, beryllium and boron) are other investigated processes (Nakamura *et al.* 2010). However, in most cases there appears significant disagreement between observational results and theoretical predictions. For example, B^{11}/B^{10} abundance ratio observed in meteorites cannot be reproduced by galactic cosmic ray spallation (Nakamura *et al*. 2010).

Another interesting mechanism is the shock heating of the hydrogen envelope (Dearborn *et al.* 1989). Here the burning of He^3 due to alpha capture leading to lithium and boron is discussed and the yield has been studied for various progenitor stars. Some of them are less extended blue progenitors whereas the others are extended red giants like Betelgeuse. The Li/B production ratio and the masses of these two elements produced per event were calculated for different models parameterized by shock velocities. In this study the typical shock velocities 4000–6000 km/s were taken for these two types of stars.

Study of synthesis of Li, Be and B in hypernova produced by collapse of massive carbon–oxygen (C–O) core is also available in literature (Fields *et al.* 2001). The hypernova ejecta enriched with C and O can undergo spallation reactions with ambient hydrogen and helium to produce these three elements. Such objects have been observed (Iwamoto *et al.* 1998, 2000).

Yoshida & collaborators (2007) have studied the production of Li and B due to interaction of neutrinos with supernovae matter in neutrino oscillation models. The abundances are found to be dependent on the mixing between different neutrino flavours.

In the present work, we study the neutrino process in the He zone leading to production of these two elements and then compare with the models of SN II progenitors parametrized by shock velocities as well as those of SN Ic . We take progenitors with $M = 8$, 10 and 20 solar masses for which the base radii of the helium zone are available in models discussed by Epstein *et al.* (1988) and Woosley *et al.* (1990). For 8 and 10 solar masses, the helium zone lies much closer to the stellar core and hence experiences large neutrino flux. 20 solar mass is taken for comparison of the yield ratio Li/B of the earlier work (Woosley *et al.* 1990) with ours. We assume that the amount of lithium and boron produced are proportional to the amount of helium destroyed by neutral current neutrino interaction. The calculated yield is also compared with that given by certain explosive events that have been reported to be reminiscent of hypernovae (Fields *et al.* 2001).

2. Method of production

Studies of Dearborn *et al*. (1989) and Woosley *et al*. (1990) discussed production of Li^7 and B^{11} by the channels He^3(He^4, γ)Be^7(e^-, ν_e)Li^7 and Be^7(He^4, γ)C^{11}, C$^{11} \xrightarrow{\beta^+}$ B^{11} respectively in the hydrogen zone. But it requires constant supply of alpha particles for significant production. Moreover, He^3 represents the unburned primordial abundance (Woosley *et al.* 1990) which is quite small towards the hydrogen envelope. Therefore, Woosley *et al.* (1990) took the helium zone of a red supergiant progenitor with $M =$ 20 solar mass as the attractive site for production of these two elements. The reaction channels for production of Li^7 and B^{11} are initiated by the charged current as well as neutral current interaction of neutrinos with the helium nuclei. Helium being the gateway for synthesis of other abundant nuclei is considered in our work to see the outcome of the neutrino process in lower mass progenitors.

As neutral current reactions are initiated by high energy muon and taon neutrinos, they play a major role in the nucleosynthetic process. Electron neutrinos having low energy have small cross section and hence they have little (although not negligible) role. For completion, the excitation cross section for neutral current $\nu +$He^4 reaction is about (2.14$-$6.78) $\times$ 10^{-43} cm^2 (Woosley *et al.* 1990) in the energy range 8–10 MeV which is typical for muon or taon neutrinos. The interaction cross section per He-nucleus lies in the range (2.14 $\times$ 10^{-1}$-$1.63) $\times$ 10^{-42} cm^2 (Woosley *et al.* 1990). On the other hand, the electron neutrinos carrying only about 4–5 MeV have charged current interaction cross section with helium of about10^{-45}–10^{-44} cm^2 and the interaction cross section per He-nucleus is about (5.30 $\times$10^{-4}–1.25 $\times$ 10^{-1}) $\times$ 10^{-42} cm^2 (Woosley *et al.* 1990). The reaction rates of neutrinos with the He-nuclei scale just with these numbers.

The spallation reaction considered here is He^4(ν, $n\nu'$)He^3. Here ν represents muon or taon neutrinos. The neutral current processes for synthesis of Li^7 and B^{11} are respectively given as He^4(ν, $n\nu'$)He^3(He^4, γ)Be^7(e^-, ν_e)Li^7 and He^4(ν, $n\nu'$)He^3(He^4, γ)Be^7(He^4, γ)$C^{11} \xrightarrow{\beta^+}$ B^{11}. The interaction is considered here for progenitor of supernova type II (SN II). There is a competition between beta decay of Be and its alpha capture. The competition is dependent on density and temperature as shown below.

For a particle of type 1 interacting with a target of type 0 having mass numbers and atomic numbers as A_1 and $A_0$and Z_1 and Z_0 respectively, the nuclear reaction rate is given by $P = n_1 n_0 \langle\sigma v\rangle$, where n_1 and n_0 are number densities of species 1 and 0 respectively (Burbidge *et al.* 1957). The average of the product of reaction cross section and relative velocity of the particles is expressed as (Boyd 2008)

$$\langle\sigma v\rangle = 7.20 \times 10^{-19}[A Z_1 Z_0]^{-1} S(E_0)\tau^2 \exp[-\tau]\,\mathrm{cm}^3\,\mathrm{s}^{-1} \quad (1)$$

with $A = A_1 A_0/(A_1 + A_0)$ and $\tau = 42.46[Z_1^2 Z_0^2 A/T_6]^{1/3}$. Here T_6 is the temperature expressed in unit of 10^6 K and $S(E_0)$ is the astrophysical S factor evaluated at the effective thermal energy (Burbidge *et al.* 1957), which is fixed for a given environment and for a given reaction. Following Burbidge *et al.* (1957), the mean reaction rate per particle of type 0 is written as

$$p(0) = \frac{\nu_0 P}{n_0} = \nu_0 n_1 7.20 \times 10^{-19} [A Z_1 Z_0]^{-1} S(E_0) \tau^2 \exp[-\tau]\, \mathrm{s}^{-1}. \qquad (2)$$

Here ν_0 is the number of particles of type 0 destroyed per reaction. If ρ is the density of the stellar material and x_1 is the mass fraction of particle 1 present, then $n_1 = \rho x_1 / m_H A_1$, where $m_H \approx 1.6 \times 10^{-24}$ g is the nucleon mass.

In our case, He^4 ($A_1 = 4$, $Z_1 = 2$) and Be^7 ($A_0 = 7$, $Z_0 = 4$) are the particles of types 1 and 0 respectively. Since $\varphi_\alpha = 1 - x_1$ is the mass fraction of helium destroyed due to neutrino interaction and only one particle of Be^7 is destroyed per reaction, the mean reaction rate per Be^7 nucleus is given by

$$p(\mathrm{Be}^7 + \mathrm{He}^4) \approx \frac{\rho(1-\varphi_\alpha)}{4} 4.5 \times 10^5 \frac{11}{224} S(E_0) \frac{53772.97}{T_6^{2/3}} \exp\left[-\frac{231.89}{T_6^{1/3}}\right] \mathrm{s}^{-1}. \quad (3)$$

We consider temperature and density environment of helium burning zone as $T_6 = 100$–300 and $\rho \approx (10^2$–$10^3)$ g/cm^3 respectively. The mass fraction of helium destroyed can be ignored compared to unity. For a given density and up to an astrophysical S factor, this gives the variation of mean reaction rate $p(\mathrm{Be}^7 + \mathrm{He}^4)$ of alpha capture with beryllium as a function of temperature as shown in Figure 1. The beta decay half-life of Be^7 which is about 53 days gives a rate of about $2.18 \times 10^{-7}\ \mathrm{s}^{-1}$. It is seen from Figure 1 that towards the inner zones of the helium shell (the zones with high temperature) the alpha capture rate overwhelms the beta decay rate of Be^7.

The inelastic neutral current neutrino interaction alters the elemental composition by efficiently exciting nuclei to particle unbound states by the process $(Z, A) + \nu \rightarrow (Z, A)^* + \nu'$. Here we consider inelastic neutrino interaction releasing free neutrons. On the basis of certain standard models of supernova progenitors and

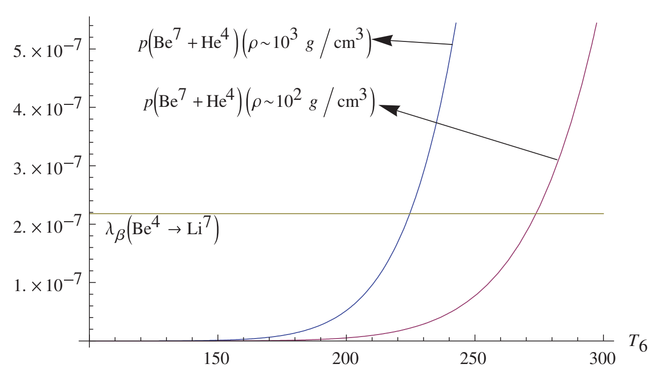

Figure 1. The variation of alpha capture rate on Be^7 with temperature and density. The capture rate overwhelms the beta decay rate towards the inner side (high temperature zone) of the helium zone. The rates are in the unit of s^{-1}.

neutrino properties it is interesting to contrast several mechanisms of production of these two elements. To calculate the amount of lithium and boron produced we have to estimate the neutrino flux at the helium zone, which in turn depends on the base radius of the helium zone. For the progenitor models with $M = 8$ and 10 solar mass, the base radii of the helium zone are taken from Epstein *et al.* (1988) and the base radius for the 20 solar mass progenitor is taken from Woosley *et al.* (1990).

The reaction chains $\mathrm{He}^4(\nu, n\nu')\mathrm{He}^3(\mathrm{He}^4, \gamma)\mathrm{Be}^7(e^-, \mathrm{Li}^7)\nu_e$; $\mathrm{He}^4(\nu, n\nu')\mathrm{He}^3(\mathrm{He}^4, \gamma)\mathrm{Be}^7(\mathrm{He}^4, \gamma)\mathrm{C}^{11} \xrightarrow{\beta+} \mathrm{B}^{11}$ for synthesis of these two elements can proceed to the last stage during the peak temperature raised by the supernova shock. After the passage of the shock the alpha capture by beryllium nuclei stops and formation of C^{11} is also blocked. Therefore, the destruction channel of beryllium is also blocked. The left over nuclei decay to produce Li^7 and B^{11} by the processes $\mathrm{Be}^7 \xrightarrow{\text{electron-capture(EC)}} \mathrm{Li}^7$, $\mathrm{C}^{11} \xrightarrow{\beta^+} \mathrm{B}^{11}$. Here it is important to note that the charged current neutrino interaction cross section is smaller than the neutral current cross section by a factor of 100 (Woosley *et al.* 1990). Thus the destruction of helium due to charged current processes can be ignored. Moreover, He^4 may be destroyed due to capture by N^{14} to produce F^{19} by the sequence $\mathrm{N}^{14}(\mathrm{He}^4, \gamma)\mathrm{F}^{18}(e^+, \bar{\nu}_e)\mathrm{O}^{18}(p, \gamma)\mathrm{F}^{19}$ or to produce N^{15}, O^{18} and Ne^{21} as $\mathrm{N}^{14}(\mathrm{He}^4, \gamma)\mathrm{F}^{18}(e^+, \bar{\nu}_e)\mathrm{O}^{18}$; $\mathrm{F}^{18}(\mathrm{He}^4, p)\mathrm{Ne}^{21}$; $\mathrm{F}^{18}(p, \mathrm{He})\mathrm{O}^{15}(e^+, \bar{\nu}_e)\mathrm{N}^{15}$ (Woosley *et al.* 1990). The amount of N^{14} present in the helium shell is quite less compared to helium. The typical hydrogen burning product in massive population I stars are 99% He^4, 1% N^{14} and feeble amount of C^{13}. This makes us to consider predominantly the effect of helium destruction due to neutral current neutrino process only.

The production of the two elements is associated with the release of free neutrons. These free neutrons are liberated due to neutral current interaction of neutrinos with helium nuclei. The rate of change of neutron fraction is given by (Epstein *et al.* 1988)

$$\dot{Y}_\mathrm{n} = \frac{\varphi_\alpha}{2t_\nu} \exp\left(-t/t_\nu\right), \tag{4}$$

where Y_n is the neutron fraction defined as the number of neutrons per baryons, φ_α is the fraction of helium destroyed and t_ν is the time constant for exponential decay of the neutrino flux which is nearly 3 s (Epstein *et al.* 1988). In calculating the rate of change of neutron fraction they assumed the temperature and density of the inner edge of the helium zone as $T \sim 3 \times 10^8$ K and $\rho \sim 3 \times 10^3$ g/cm^3. It was also assumed that neutrino flux decreases exponentially with a time scale of $t_\nu \approx 3$ s. Calculation of φ_α gives the yield of Li^7 and B^{11}. φ_α is given by Epstein *et al.* (1988) in the following form:

$$\phi_\alpha \approx 3.7 \times 10^{-4} \left(\frac{E_\mathrm{tot}}{2 \times 10^{53}\,\mathrm{erg}}\right) \left(\frac{T}{9\,\mathrm{MeV}}\right)^{4.3} \left(\frac{R_\alpha}{10^9\,\mathrm{cm}}\right)^{-2}, \tag{5}$$

where E_tot is the total energy carried by all neutrino flavours, which is close to the binding energy of a typical neutron star, T is the neutrino temperature and R_α is the radius at which the helium zone begins. φ_α was obtained by the relation $\varphi_\alpha = \sum_i E_i \sigma_i / 4\pi R_\alpha^2 \langle \varepsilon_i \rangle$, where E_i is the total energy carried by the neutrino flavour i, σ_i is the total neutrino interaction cross section of the flavour i with helium (including both charged and neutral current) and $\langle \varepsilon_i \rangle$ is the average energy carried by the neutrino flavour i. Since 2/3rd of the total gravitational energy is carried by the heavy flavour neutrinos with 8–10 MeV, the charged current cross section contribution can be neglected so as to retain only the effect of the neutral current interaction (Epstein *et al.* 1988) of these neutrinos with the helium nuclei. Now, R_α depends on the mass of the star. Smaller the mass, smaller is the value of R_α and therefore greater is the neutrino flux leading to greater helium destruction. Consequently, the production of these light elements is reduced in a high mass progenitor compared to the low mass one. For example, in three model stars for SN II with $M/M_{\rm Sun} = 8$, 10 and 20, the helium zone begins at $R_\alpha = 7 \times 10^8$ cm, 4×10^9 cm and 1.51×10^{10} cm respectively (Epstein *et al.* 1988; Woosley *et al.* 1990). By definition $E_{\rm tot}$ is the binding energy of a typical neutron star having mass around 1.4 times the solar mass. Therefore, the variation from star to star is not considered here. On the other hand, Wilson (1986) and Wilson *et al.* (1986) calculated the collapse of massive stars with $M = 10$, 15 and 25 solar mass and reported that time averaged neutrino signal does not have profound variation from star to star (Bahcall *et al.* 1987). Therefore, the average temperature for a particular neutrino flavour can be taken as fixed for the three progenitors of our study. The expected values for temperature of heavy flavour neutrinos are in the range 8–10 MeV (Woosley *et al.* 1990). Thus we take the average of 9 MeV. Considering $E_{\rm tot} \approx 10^{53}$ erg, $T = 9$ MeV and by assuming that there is no neutron production before the arrival of the neutrino burst, the evolution of the neutron fraction is shown in Figure 2.

It is seen that neutron fraction steeply rises within the time constant of the neutrino flux and then levels off. Therefore, the elements Li^7 and B^{11} are produced almost explosively within this time scale.

3. Results and discussion

For the neutral current interactions considered above, the amount of Li^7 and B^{11} are calculated from the knowledge of amount of helium destroyed. It depends on the shell masses ($M_{\rm He\text{-}shell}$) of the progenitors. For 8 solar mass star the helium shell mass is about 0.01 solar mass whereas it is 0.1 solar mass for 10 solar mass star

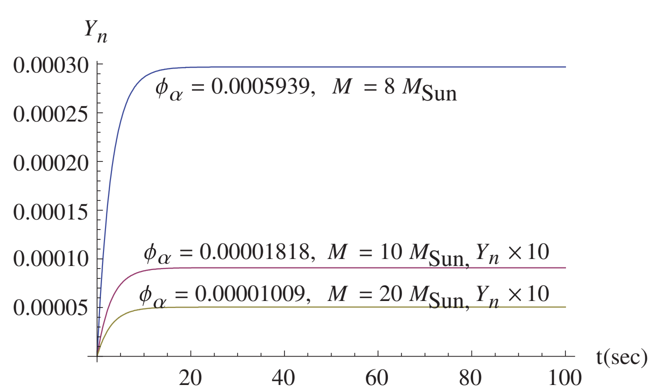

Figure 2. Free neutron mass fraction as a function of time. The helium fraction destroyed and masses of the stars are displayed near the curves.

(Epstein *et al.* 1988). For 20 solar mass star the shell mass is about 1.85 solar mass (Woosley *et al.* 1990). By taking changing shell masses into account, the amounts of Li^7 and B^{11} are obtained as follows.

For $E_{tot} \approx 10^{53}$ erg and $T \sim 9$ MeV, the fraction of helium destroyed is $\phi_\alpha \approx 3.7 \times 10^{-4} (R_\alpha/10^9 \text{ cm})^{-2}$. The base radii of the helium zone for 8, 10 and 20 solar mass stars are respectively 7×10^8 cm, 4×10^9 cm and 1.51×10^{10} cm. These give the values of φ_α. The total mass of helium destroyed is $M_\alpha = \phi_\alpha M_{\text{He-shell}}$. For the shell masses of the progenitors, it has been calculated. In the lithium channel $He^4(\nu, \nu' n)He^3(He^4, \gamma)Be^7(e^-, \nu_e)Li^7$, 2 He-nuclei are destroyed in each reaction. Similarly, in the boron channel $He^4(\nu, \nu' n)He^3(He^4, \gamma)Be^7(He^4, \gamma)C^{11} \xrightarrow{\beta^+} B^{11}$, 3 He-nuclei are destroyed in each reaction. Thus the amount of Li^7 and B^{11} produced are given by $M_{Li} = [m(\text{Li})/2m(\text{He})] \times M_\alpha$ and $M_B = [m(\text{B})/3m(\text{He})] \times M_\alpha$ respectively, where $m(\text{Li}) \approx 7.0160$ amu, $m(\text{B}) \approx 11.0093$ amu and $m(\text{He}) \approx 4.0026$ amu. The masses of lithium and boron produced are displayed in Table 1. For 20 solar mass progenitor the mass fractions Li/He and B/He are $2.63 \times 10^{-6}/1.85 \approx 1.42 \times 10^{-6}$ and $2.75 \times 10^{-6}/1.85 \approx 1.48 \times 10^{-6}$ respectively. Similarly, for 8 solar mass, the Li/He and B/He ratios are $6.61 \times 10^{-6}/0.01 \approx 6.61 \times 10^{-4}$ and $6.92 \times 10^{-6}/0.01 \approx 6.92 \times 10^{-4}$ respectively. For 10 solar mass, these ratios are $2.01 \times 10^{-6}/0.1 \approx 2.01 \times 10^{-5}$ and $2.11 \times 10^{-6}/0.1 \approx 2.11 \times 10^{-5}$ respectively.

Results of the calculations show that masses of Li^7 and B^{11} produced in high mass progenitors are small compared to those in low mass progenitors. In the context of neutrino interaction this is interpreted as due to decrease of neutrino flux for a massive star whose helium zone lies far outside compared to that of a compact progenitor.

Dearborn *et al.* (1989) studied production of Li^7 and B^{11} in less extended blue giant and extended red giant models due to shock traversing the base of the hydrogen envelop. They considered shock velocity range 4000–6000 km/s to calculate the yields for these two models. The amount of Li^7 and B^{11} produced in the extended models in all shock velocities lies in the range 10^{-9}–$10^{-7} M_{Sun}$. However, for less extended blue models the amounts are $M(\text{Li}) \approx 1.6 \times 10^{-6} M_{Sun}$; $M(\text{B}) \approx 4.2 \times 10^{-6} M_{Sun}$ for shock velocity of 6000 km/s whereas $M(\text{Li}) \approx 1.5 \times 10^{-6}$–$6.6 \times 10^{-6} M_{Sun}$ for shock velocity of 4000–5000 km/s (Dearborn *et al.* 1989). Therefore, our yields are quite near to the less extended (compact) blue giant progenitors. The Li/B ratio is about 0.96. This is quite small in comparison to the observed one which lies in the range 2.6–8 (Dearborn *et al.* 1989). The solar ratio was observed to lie in the rangeLi/B ≈ 4.9 (Cameron 1982). Therefore, there may be some scope either to elevate Li production or to suppress B production in early solar system events. The ratio found by us satisfies certain constraint ($\text{Li/B} > 0.8$) imposed by neutrino mass

Table 1. The yields of lithium and boron produced by neutrino process in different progenitors.

Progenitor mass (solar unit)	$M(\text{Li})/M_{Sun}$	$M(\text{B})/M_{Sun}$	Li/B
8	6.61×10^{-6}	6.92×10^{-6}	0.955
10	2.01×10^{-6}	2.11×10^{-6}	0.952
20	2.63×10^{-6}	2.75×10^{-6}	0.956

model (Yoshida & collaborators 2007). The amount of Li^7 and B^{11} for a 20 solar mass progenitor is reminiscent of the yield for SN 1987A. In the context of shock models, the yield is generated by less extended progenitor with lower shock velocity.

Nakamura *et al.* (2010) studied production of Li, Be and B in SNIc supernova. The progenitor was taken as a 15 solar mass C–O star whose ideal equation of state of gas and radiation was taken for hydrodynamic calculations of the abundances. In their work, 6 MeV and 8 MeV were taken as two different temperature models for neutrinos. The 6 MeV neutrinos were considered as 'standard' whereas the 8 MeV neutrinos were treated as 'high temperature' neutrinos and the yields were reported. The element production was achieved by decay channels of $C^{12} - \nu$ interactions. As discussed by Woosley *et al.* (1990) the possible paths are: $C^{12}(\nu, \nu' n)C^{11}$; $C^{12}(\nu, \nu' p)B^{11}$; $C^{12}(\nu, \nu' p He^4)Li^7$; $C^{12}(\nu, \nu' n He^4)Be^7$. Even with the highest temperature case the yields of Li^7 and B^{11} lie within 10^{-9}–$10^{-8} M_{Sun}$ and they had to consider spallation reaction of expelled material (C/O) with ambient hydrogen and helium to generate $10^{-6} M_{Sun}$ for B^{11} (Nakamura *et al.* 2010). However, in the present case we have been able to generate about $10^{-6} M_{Sun}$ for Li^7 and B^{11} by taking $T = 9$ MeV neutrinos in the helium shell.

Fields *et al.* (2001) reported production of Li, Be and B in hypernovae. A hypernova is defined as a core collapse explosion of an extremely massive C–O star. According to the study, these elements can be produced due to impact of C/O enriched ejecta from exploding massive C–O core. In their work, the yields in some C–O core explosions (SN 1994I, SN1994I(X10), SN1994(X30), SN 1997ef, SN 1998bw(a), SN1998 bw(b) and SNIa) which are possibly hypernovae candidates were reported. Out of these explosions, three of them have yields near to ours. The events are SN1994I ($Li \sim 3.2 \times 10^{-7} M_{Sun}$, $B \sim 1.2 \times 10^{-6} M_{Sun}$), SN1997ef ($Li \sim 2.2 \times 10^{-6} M_{Sun}$, $B \sim 8.1 \times 10^{-6} M_{Sun}$) and SNIa ($Li \sim 1.0 \times 10^{-7} M_{Sun}$, $B \sim 3.7 \times 10^{-7} M_{Sun}$) (Fields *et al.* 2001). Although SNIa supernovae have low mass progenitors ($M \sim 1.4$ solar mass) their yields are comparable to those of high mass C–O stars like SN1994I ($M \sim 2.1$ solar mass) or SN1997ef ($M \sim 10$ solar mass) (Fields *et al.* 2001). It may be due to high frequency of occurrence of SNIa. The other candidates have much higher yields, the range being 10^{-5}–$10^{-2} M_{Sun}$. In addition to this, in all the seven cases the Li/B ratio of hypernovae lies in the range 0.26–0.28 which is quite small compared to our value, $Li/B \sim 0.96$. Therefore, the SN II neutrino process can compete here too.

Survival of the synthesized Li^7 and B^{11} is an interesting issue. High flux of neutrons and protons during the shock heating may destroy the newly synthesized nuclei. However, this process gets suppressed. Let us take a typical example of a 20 solar mass progenitor. About 0.007% of the total mass of the He-shell is contributed by C^{13}. When the shock passes through the shell, burning may occur releasing free neutrons via $C^{13}(He^4, n)O^{16}$ (Woosley *et al.* 1990). The production and sustenance of Li^7 and B^{11} may be blocked due to the capture events $Be^7(n, p)$; $Li^7(p, 2He^4)$. However, as C^{13} gets consumed the neutron flux is switched off and the destruction of Be^7 is also blocked. This helps in the survival of Li^7 and B^{11}. The consistency of the yield of Li^7 and B^{11} with that of SN II shock induced synthesis and a few hypernovae signifies that the processes $He^4(\nu, n\nu')He^3(He^4, \gamma)Be^7(e^-, \nu_e)Li^7$; $He^4(\nu, n\nu')He^3(He^4, \gamma)Be^7(He^4, \gamma)C^{11} \xrightarrow{\beta+} B^{11}$ are quite important even if the neutrino interaction is considered on the helium zone with appreciably low density

$10^2 - 10^3$g/cc. It may be important for further study of neutrino interaction with supernovae matter.

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