Sylvia Ekström & Cyril Georgy

Ruth Peterson

https://doi.org/10.1017/S1743921310004631 Published online by Cambridge University Press

Light Elements in the Universe
Proceedings IAU Symposium No. 268, 2009
C. Charbonnel, M. Tosi, F. Primas & C. Chiappini, eds.

doi:10.1017/S1743921310004631

Lithium, beryllium, and boron production in core-collapse supernovae

Ko Nakamura[1], **Takashi Yoshida**[2], **Toshikazu Shigeyama**[2,3] **and Toshitaka Kajino**[1,2]

[1]National Astronomical Observatory of Japan,
Osawa 2-21-1, Mitaka, Tokyo, 181-8588 Japan
email: nakamura.ko@nao.ac.jp

[2]Department of Astronomy, Graduate School of Science, University of Tokyo,
Hongo 7-3-1, Bunkyo-ku, Tokyo, 113-0033 Japan

[3]Research Center for the Early Universe, Graduate School of Science, University of Tokyo

Abstract. Type Ic supernova (SN Ic) is the gravitational collapse of a massive star without H and He layers. It propels several solar masses of material to the typical velocity of 10,000 km/s, a very small fraction of the ejecta nearly to the speed of light. We investigate SNe Ic as production sites for the light elements Li, Be, and B, via the neutrino-process and spallations. As massive stars collapse, neutrinos are emitted in large numbers from the central remnants. Some of the neutrinos interact with nuclei in the exploding materials and mainly ^{7}Li and ^{11}B are produced. Subsequently, the ejected materials with very high energy impinge on the interstellar/circumstellar matter and spall into light elements. We find that the ν-process in the current SN Ic model produces a significant amount of ^{11}B, consistent with observations if combined with B isotopes from the following spallation production.

Keywords. Neutrinos, nuclear reactions, nucleosynthesis, abundances – Supernovae: general

1. Introduction

Most of metals up to iron are synthesized inside main sequence stars via nuclear reactions called nuclear burning. Newly-synthesized elements are ejected into interstellar space and pollute the interstellar gas primitively consisted of hydrogen and helium. However, light elements such as Li, Be, B and their isotopes (LiBeB) are hardly produced by nuclear burning partly because of Li fragile property and absence of stable nuclei with atomic mass number of eight. Some processes considered to mainly produce these elements are briefly summarized below.

Shortly after the Big Bang, protons and neutrons combine and produce hydrogen and helium isotopes. Subsequently, tritium and ^{3}He combine with α-particle to form ^{7}Li (and ^{7}Be eventually decaying to ^{7}Li), which make an almost constant Li abundance observed on the surfaces of metal-poor halo stars, the so-called Spite Plateau (Spite & Spite 1982).

After star formation and its gravitational contraction, hydrogen burning reaction is ignited at the center. Although light elements synthesized at the hot regions of stars are fated to be broken by surrounding hot protons, an escape route for them are known. Cameron proposed a mechanism (Cameron 1955) available for AGB stars, called Be-transport mechanism, where ^{7}Be in hydrogen burning shell are brought to cool envelopes by the circulation currents during a thermal pulse phase. A fraction of survived ^{7}Be (^{7}Li) capture α-particle and form ^{11}B, both of them are ejected into the interstellar space through stellar winds. This mechanism is effective for stars with masses in the range $4 \leqslant M/M_\odot \leqslant 6$. Some computational works, however, have revealed that lithium from AGB stars are not important for the Galactic chemical evolution (Romano *et al.* 2001; Ventura *et al.* 2002). Note that in some cases AGB stars show low, not high, lithium abundances caused by dilution during the previous evolutionary phases (Maceroni *et al.* 2002). For more massive stars, they are known to collapse and explode as supernovae at the end of their lives. Most of the gravitational energy released at the explosion of a massive star is carried away by neutrinos emitted from the central remnant. Their number is achieved to more than 10^{58}. Although cross sections of neutrino-nucleus reactions are very small, such a huge number of neutrinos enable to contribute the increase in the yields of some species of nuclei. This is called the ν-process (Woosley *et al.* 1990). The ν-process mainly contributes to the production of ^{7}Li and ^{11}B among light elements (e.g. Woosley *et al.* 1990; Heger *et al.* 2005; Yoshida *et al.* 2005, 2008).

The processes described above predominantly produce ^{7}Li and ^{11}B, while cosmic-ray (CR) nucleosynthesis produces all stable isotopes of LiBeB (e.g. Meneguzzi *et al.* 1971; Suzuki & Inoue 2002; Rollinde *et al.* 2008). In CR nucleosynthesis, low-energy CRs accelerated in shocks interact with the ambient medium and produce LiBeB via spallations (H,α+ C,N,O $\rightarrow$ LiBeB) or fusion reaction of α-particles ($\alpha + \alpha \rightarrow ^{6,7}$Li). Theoretical CR nucleosynthesis models predict strong correlations between BeB abundances and metallicity, consistent with observations although it is difficult to explain the observed linear dependences if the Galactic CRs consist of protons and α-particles.

Despite a great deal of efforts to investigate these processes, the origins of LiBeB are not fully understood and there remain some observational features conflicting with theoretical predictions. For instance, theoretical predictions for LiBeB production from Galactic CRs indicate quadratic relations between B(Be) abundances and metallicity, while observations clearly show linear relations. To consist with observational trend, CNO CRs from superbubbles (Higdon *et al.* 1998) and Type Ic supernovae (Fields *et al.* 2002; Nakamura & Shigeyama 2004) have been suggested. However, the CR spallations cannot be the only source of boron isotopes because the CR spallations do not reproduce the high ratio of ^{11}B to ^{10}B observed in meteorites. Therefore another ^{11}B source is necessary.

To solve these unsolved problems and consider the Galactic chemical evolution concerning with the light elements, it is necessary to accurately evaluate the contribution of each LiBeB productive process. Here we focus on the B isotopes from core-collapse SNe, in particular energetic Type Ic SNe (SNe Ic). The progenitor of an SN Ic is a C/O star and its H and He envelopes have been stripped during the stellar evolution. Although the explosion mechanism of SNe Ic has not clarified, neutrinos should be one of main carriers of the gravitational energy released from the collapsing core. The neutrino emission from a collapsing proto-neutron star evolved from a $\sim 40 M_\odot$ star has been investigated (Sumiyoshi *et al.* 2006). Even in the case that the central core of such a star becomes a black hole, a temporally formed proto-neutron star emits a huge amount of neutrinos before collapsing to the black hole. On the other hand, after the black hole formation, neutrinos are considered to be emitted from accretion disk surrounding the newly formed black hole (e.g. Kohri *et al.* 2005; Surman & McLaughlin 2005). Therefore, a huge amount of neutrinos are emitted from the central region of an SN Ic and the ν-process is expected to occur in the exploding supernova material. We investigate the ν-process in SN Ic for the first time. In addition, LiBeB production through spallations between the SN ejecta and the interstellar/circumstellar matter is considered. In §2, we present our calculations of supernova explosion (§2.1), nucleosynthesis by the ν-process (§2.2), and by spallations (§2.3). Section §3 discusses our results and clarifies the important role of SNe Ic in the light element synthesis.

https://doi.org/10.1017/S1743921310004631 Published online by Cambridge University Press

2. Calculations and results

2.1. *Supernova explosion*

Here we consider a very energetic explosion of a 15 $M_\odot$ C/O star with the explosion energy $E_{\rm ex} = 3 \times 10^{52}$ ergs corresponding to SN 1998bw (Nakamura *et al.* 2001). The explosion energy is released at the center of the progenitor star as thermal energy. Resulting shock wave accelerates the stellar materials and explode the progenitor as a supernova. Time evolution of physical quantities in the progenitor are calculated with 1-dimensional hydrodynamic code taking the effects of special relativity into account. We solve the special relativistic hydrodynamic equations in Lagrangian coordinates with an ideal equation of state involving gas and radiation pressure. Adiabatic indices are treated as functions of pressure and gas density. Details on the numerical code are described in Nakamura & Shigeyama (2004).

2.2. *The Neutrino-Process*

Light element synthesis in the Type Ic supernova is calculated as a post process. We use a nuclear reaction network consisting of 291 species of nuclei and taking into account the ν-process (Yoshida *et al.* 2008).

Neutrinos are considered to be emitted from a collapsing proto-neutron star (e.g. Sumiyoshi *et al.* 2006) and/or the innermost region just above a black hole (e.g. Surman & McLaughlin 2005). However, properties of the neutrinos, particularly in SNe Ic, are still uncertain. So, we use the following neutrino model extended from a supernova neutrino model taken in Yoshida *et al.* (2008). We suppose that neutrino luminosity decreases exponentially with the decay time of 3 s while the neutrino temperature of each species does not change with time. The total energy carried out by neutrinos is assumed to be 3×10^{53} ergs.

We consider two models for these constant neutrino temperatures. In the first model, the temperatures of ν_e, $\bar{\nu}_e$, and $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ are set to be $T_{\nu_e} = 3.2$ MeV, $T_{\bar{\nu}_e} =$ 5 MeV, and $T_{\nu_{\mu,\tau}}$=6 MeV, respectively. This temperature model is referred to as the "normal" $T_{\nu_{\mu,\tau}}$ model. The light element synthesis in an $\sim 20M_\odot$ Type II supernova with the normal temperature model well reproduces the supernova contribution of the ^{11}B production during Galactic chemical evolution (Yoshida *et al.* 2005, 2008). The third peak of r-process elements is also achieved in neutrino-driven wind models with this temperature model. In the second model, the temperature of $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ is set to be $T_{\nu_{\mu,\tau}} = 8$ MeV. The same values as the normal model are adopted for T_{ν_e} and $T_{\bar{\nu}_e}$. This temperature model is referred to as the high $T_{\nu_{\mu,\tau}}$ model. A newly forming proto-neutron star in an SN Ic should be more compact than that of an SN II. Therefore, the neutrino temperature of the collapsing proto-neutron star is larger than that of SNe II (e.g. Sumiyoshi *et al.* 2006).

The mass fraction distributions of ^{11}B, ^{11}C, ^{10}B, ^{7}Li, and ^{7}Be in the SN Ic are shown in Figure 1. The mass fractions are of the order of $\sim 10^{-8}$ for ^{11}B and ^{11}C and $\sim 10^{-11} - 10^{-10}$ for ^{10}B, ^{7}Li, and ^{7}Be. The yield of each species strongly depends on the corresponding branching ratio of the reactions. The light elements are mainly produced in the O/Ne layer ($M_r > 7.4M_\odot$). The mass fractions in the O/Si layer ($4.6M_\odot < M_r < 7.4M_\odot$) are smaller than in the outer layer. The Si/S layer ($3.7M_\odot < M_r < 4.6M_\odot$) where carbon burned out indicates no light elements. The mass fractions of some light elements are also large in the innermost region where α-rich freeze out is achieved ($M_r < 2.6M_\odot$) and complete Si-burning occurs ($2.6M_\odot < M_r < 3.5M_\odot$). There are no qualitative differences in the mass fraction distributions between the normal and high $T_{\nu_{\mu,\tau}}$ models.

https://doi.org/10.1017/S1743921310004631 Published online by Cambridge University Press

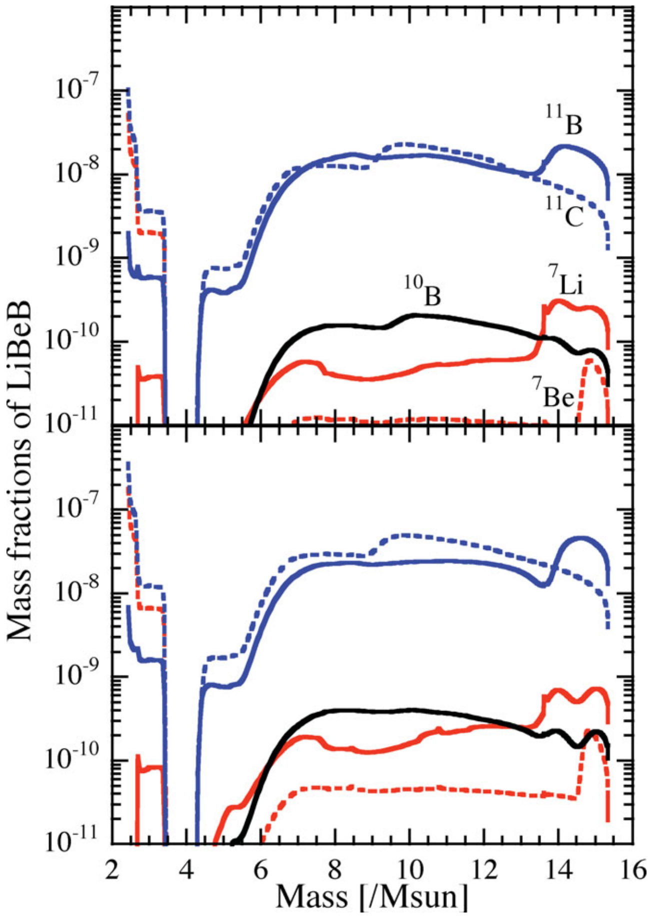

Figure 1. The mass fraction distributions of light elements produced via the ν-process as functions of the mass coordinate. Shown are the cases of the SN 1998bw model ($M_{\rm CO} = 15 M_\odot$, $E_{\rm ex} = 3 \times 10^{52}$ ergs) with $T_{\nu_e} = 3.2$ MeV, $T_{\bar{\nu}_e} = 5$ MeV, and $T_{\nu_{\mu\tau}} = 6$ MeV (*top*) and 8 MeV (*bottom*) at 75 seconds after the energy release.

The mass fraction of each species in the high $T_{\nu_{\mu,\tau}}$ model at a given mass coordinate is roughly twice as the corresponding one in the normal $T_{\nu_{\mu,\tau}}$ model.

Some of light elements produced through ^{12}C-neutrino reactions are decomposed by explosive nucleosynthesis occurring immediately after the shock arrival. ^{11}B, ^{11}C, and ^{10}B are decomposed by collisions with protons and α-particles. ^{7}Li and ^{7}Be are photodisintegrated to ^{3}H and ^{3}He, respectively. After the shock passage, the exploding and cooling materials are still irradiated by neutrinos, so that light elements are produced through the ν-process again. We note that the mass fractions of ^{11}B, ^{7}Li, and ^{7}Be in the outermost region ($M_r > 13.5 M_\odot$) are larger than the corresponding ones in the inner region because they are not decomposed in explosive nucleosynthesis.

In the innermost region, light elements are produced after the termination of the nuclear statistical equilibrium. The main product in α-rich freeze out is ^{4}He. About 20% of ^{4}He by mass fraction is also produced in complete Si-burning. The ν-process of ^{4}He produces ^{3}H and ^{3}He in cooling materials. The α-capture reactions followed by the ν-process produce ^{7}Li and ^{7}Be. Furthermore, ^{11}B and ^{11}C are produced by α-captures and ^{10}B is produced through ^{7}Be$(\alpha, p)^{10}$B.

In both cases of $T_{\nu_{\mu,\tau}}$ a significant amount of ^{11}B is synthesized ($2.69 \times 10^{-7} M_\odot$ for the normal $T_{\nu_{\mu,\tau}}$ model and $5.46 \times 10^{-7} M_\odot$ for the high $T_{\nu_{\mu,\tau}}$ model). It should be noted that the amounts of ^{11}B produced through the ν-process include those of ^{11}C which decays to ^{11}B with a half life of 20 minutes. The yield of ^{7}Li is on the order of $10^{-9} - 10^{-8} M_\odot$ in the SN Ic model. This yield is much smaller than that produced in SNe II (e.g. Yoshida *et al.* 2008). Most of ^{7}Li in SNe II is produced through the ν-process of ^{4}He and the following α-capture reactions in the He-rich layer. On the other hand, almost all H and He layers of SN Ic progenitors have been stripped via stellar wind and/or binary effect before explosion. The yields of ^{6}Li, ^{9}Be, and ^{10}B are on the order of or below $10^{-9} M_\odot$. They are also much smaller than the ^{11}B yield. This is due to smaller branching ratios of neutrino-^{12}C reactions (Yoshida *et al.* 2008).

2.3. *Spallation reactions*

Supernova explosions accelerate and expel the stellar materials into the interstellar space, polluting the universe with newly synthesized elements. The progenitors of SNe Ic are so compact that a very small fraction of ejecta can be accelerated nearly to the speed of light, interact with the interstellar matter (Nakamura & Shigeyama 2004) or the circumstellar matter (Nakamura *et al.* 2006), and produce the light element isotopes via spallation reactions of CNO with protons or α-particles. The surface layers of SNe Ic, which are composed of C and O, impinge on the H or He nuclei in the ambient medium and spall into LiBeB. Here we use the result for a SN 1998bw model constructed by Nakamura & Shigeyama (2004). 0.3% ($0.04 M_\odot$) of the ejecta attain enough energy ($\gtrsim 10$ MeV/A) to undergo spallations (see eq. 2.2). They solved the transfer equation for each element i expressed as

$$\frac{\partial F_i(\epsilon,t)}{\partial t} = \frac{\partial[\omega_i(\epsilon)F_i(\epsilon,t)]}{\partial \epsilon} - \frac{F_i(\epsilon,t)}{\Lambda}\rho v_i(\epsilon), \tag{2.1}$$

where Λ is the loss lengths in g cm^{-2}, ρ denotes the mass density of the ISM, $v_i(\epsilon)$ the velocity of the element i with an energy per nucleon of ϵ. The initial condition for the mass of element i with an energy per nucleon ϵ at time $t = 0$, $F_i(\epsilon, t = 0)$, is derived from the numerical calculations of explosions or an empirical formula

$$\frac{M(>\epsilon)}{M_{\rm ej}} = A\left(\frac{E_{\rm ex}/10^{51}\,{\rm ergs}}{M_{\rm ej}/1\,M_\odot}\right)^{3.4} \times \left(\frac{\epsilon}{10\,{\rm MeV}}\right)^{-3.6}, \tag{2.2}$$

where $M_{\rm ej}$ is the mass of the ejecta and the constant A is equal to 1.9×10^{-4} for the current model. Then the yield of a light element l via the $i + j \rightarrow l + \cdots$ reaction is estimated from

$$\frac{dN_l}{dt} = n_j \int \sigma^l_{i,j}(\epsilon)\frac{F_i(\epsilon,t)}{A_i m_p} v_i(\epsilon) d\epsilon, \tag{2.3}$$

where N_l is the number of the produced light element l, n_j is the number density of an element j in the interstellar matter, $\sigma^l_{i,j}$ the cross section of $i + j \rightarrow l + \cdots$ reaction given by Read & Viola (1984), A_i the mass number of the element i. The interstellar matter is assumed to be composed of neutral H and He with the number densities of $n_{\rm H} = 1\,{\rm cm}^{-3}$ and $n_{\rm He} = 0.1\,{\rm cm}^{-3}$.

Their results show that the mass of ^{11}B produced via spallation reactions is $1.34 \times 10^{-6} M_\odot$, which is larger than that synthesized via the ν-process even in the high $T_{\nu_{\mu,\tau}}$ model. The resultant isotopic ratio of ^{10}B/^{11}B ($\sim 1/3$) in this model is predominantly determined by the ratio of cross sections of the reaction p,α + O $\rightarrow^{10}$B to that of p,α + O $\rightarrow^{11}$B.

https://doi.org/10.1017/S1743921310004631 Published online by Cambridge University Press

3. Conclusions

Nakamura & Shigeyama (2004) concluded that SNe Ic may not play an important role in B isotope productions because of the low isotope ratios $^{11}B/^{10}B \sim 2.8$ compared with observations in meteorites (4.05 ± 0.05), and other ^{11}B sources like the ν-process in SNe II are necessary. We estimate the production of light elements including boron isotopes via the ν-process in an SN Ic and find that SNe Ic can be as powerful ^{11}B producers as SNe II. The resulting number ratios of B isotopes from both the ν-process and spallations $^{11}B(+^{11}C)/^{10}B = 3.66-4.28$ well match with observations. It is reasonable to assume the small radii of neutrino spheres because of the compactness of SN Ic progenitors, leading to the high temperatures of emitted neutrinos and anti-neutrinos. High $T_{\nu_{\mu\tau}}$ results in high LiBeB yields through neutral current reactions in the ν-process, which raises the potential role of SNe Ic in the light element production.

The combined mechanism of light element production described here, the ν-process and spallations, may also be effective in the case of Type Ib supernovae where progenitor stars without H-rich envelope explode. In such a case, the outermost layers consist of He and the α-particle fusion reaction producing lithium isotopes become important. Furthermore, Meynet & Maeder (2002) suggested that the He layers of very metal-poor stars contain primary nitrogen produced during the He-burning phase by the CNO cycle in the H-burning shell stimulated by rotationally-induced diffusion of carbon into the H-burning shell. This nitrogen may enhance the light element production via spallations because the cross sections of spallation reactions involving nitrogen tend to have relatively low energy thresholds and high peak values. Observationally some low-metallicity halo stars have been found to have high abundances of ^{6}Li or ^{9}Be beyond the theoretical predictions , which engages our interest in SNe Ib even if they might not accelerate their envelopes effectively because their progenitors are not so compact as those of SNe Ic.

References

Cameron, A. G. W. 1955, *ApJ*, 121, 144
Fields, B. D., Daigne, F., Cassé, M., & Vangioni-Flam, E. 2002, *ApJ*, 581, 389
Heger, A., Kolbe, E., Haxton, W. C., Langanke, K., Martínez-Pinedo, G., & Woosley, S. E. 2005, Phys. Lett. B, 606, 258
Higdon, J. C., Lingenfelter, R. E., & Ramaty, R. 1998, *ApJl*, 509, L33
Kohri, K., Narayan, R., & Piran, T. 2005, *ApJ*, 629, 341
Maceroni, C., Testa, V., Plez, B., García Lario, P., & D'Antona, F. 2002, *A&A*, 395, 179
Meneguzzi, M., Audouze, J., & Reeves, H. 1971, *A&A*, 15, 337
Meynet, G. & Maeder, A. 2002, *A&A*, 390, 561
Nakamura, K. & Shigeyama, T. 2004, *ApJ*, 610, 888
Nakamura, K., Inoue, S., Wanajo, S., & Shigeyama, T. 2006, *ApJl*, 643, L115
Nakamura, T., Mazzali, P. A., Nomoto, K., & Iwamoto, K. 2001, *ApJ*, 550, 991
Read, S. M. & Viola, V. E. 1984, Atomic Data and Nuclear Data Tables, 31, 359
Rollinde, E., Maurin, D., Vangioni, E., Olive, K. A., & Inoue, S. 2008, *ApJ*, 673, 676
Romano, D., Matteucci, F., Ventura, P., & D'Antona, F. 2001, *A&A*, 374, 646
Spite, F. & Spite, M. 1982,*A&A*, 115, 357
Sumiyoshi, K., Yamada, S., Suzuki, H., & Chiba, S. 2006, Phys. Rev. Lett., 97, 091101
Surman, R. & McLaughlin, G. C. 2005, *ApJ*, 618, 397
Suzuki, T. K. & Inoue, S. 2002, *ApJ*, 573, 168
Ventura, P., D'Antona, F., & Mazzitelli, I. 2002, *A&A*, 393, 215
Woosley, S. E., Hartmann, D. H., Hoffman, R. D., & Haxton, W. C. 1990, *ApJ*, 356, 272
Yoshida, T., Kajino, T., & Hartmann, D. H. 2005, Phys. Rev. Lett., 94, 231101
Yoshida, T., Suzuki, T., Chiba, S.,Kajino, T., Yokomakura, H., Kimura, K., Takamura, A., & Hartmann, D. H. 2008, *ApJ*, 686, 448