Supernova Nucleosynthesis, Radioactive Nuclear Reactions and Neutrino-Mass Hierarchy

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Abstract. The ν-process nucleosynthesis in core-collapse supernovae is a sensitive probe of unknown neutrino mass hierarchy through the MSW effect. We carefully studied the uncertainties of almost one hundred ν-induced and nuclear reactions associated with the nucleosynthesis and found that the ν-^{16}O and ^{11}C(α,p)^{14}N reactions among them have the biggest effect on the final ^{7}Li/^{11}B isotopic abundance ratio. The neutrino mass hierarchy is constrained in our nucleosynthetic method with measured ^{7}Li/^{11}B value in SiC-X presolar grains. The inverted hierarchy is statistically more favored at the 2-σ C.L. [1].

1 Introduction

Core-collapse supernova (CCSN) ejects a huge number of three-flavour neutrinos and antineutrinos which provide observational signals through the Mikheyev–Smirnov–Wolfenstein (MSW) matter effect [2, 3]. Neutrinos propagate through the inner iron core and several layers and eventually reach the He layer. When the electron number density satisfies the specific MSW resonance condition, the flavor conversion occurs between $\bar{\nu}_e$ and $\bar{\nu}_{\mu,\tau}$ for the inverted hierarchy and ν_e and $\nu_{\mu,\tau}$ for the normal hierarchy, respectively. Thus, the energy spectra of three-flavor neutrinos vary as a function of radius depending on the mass hierarchy.

These neutrinos interact with abundant nuclei in each layer, and various isotopes such as ^{7}Li, ^{11}B, ^{19}F, ^{92}Nb, ^{98}Tc, ^{138}La, ^{180}Ta, etc. are synthesized [4–7]. The neutrino oscillation effect that depends on the mass hierarchy considerably changes the final yields of these nuclei via the charged current interactions. The isotopic abundances in CCSNe are the very unique and sensitive probe of the neutrino mass hierarchy. Both ^{7}Li and ^{11}B were discovered [8] in presolar silicon-carbide X (Si-C X) grains which form from the supernova (SN) ejecta. The measured ^{7}Li/^{11}B ratio could be used to constrain the neutrino mass hierarchy.

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^{7}Li is synthesized mostly in the He layer, while ^{11}B is synthesized over the entire region from O-Ne-Mg to He layers [1]. In order to provide nuclear abundances of ^{7}Li and ^{11}B, we need to study how reliable the ν-nucleus cross sections are. We also need to study the nuclear reactions which secondarily destroy or produce them. The important ν-nucleus cross sections include those for the production of unstable nuclei ^{7}Be which decay to ^{7}Li in 53.22 days by electron capture and ^{11}C and ^{11}Be which decay to ^{11}B in 20.34 min and 13.76 sec by $\beta^{+/-}$-decays, respectively. We studied the sensitivity of the final yields of the A = 7 and 11 nuclear systems to all ν-induced reactions on ^{4}He, ^{12}C and ^{16}O. The secondary nuclear reactions include both radioactive and stable nuclear reactions such as ^{11}C(α,p)^{14}N and ^{11}B(α,n)^{14}N. We studied the sensitivity of the final yields to the 91 nuclear reactions.

In this paper we report the result of our theoretical studies of the sensitivity of the A = 7 and 11 abundances to the ν-^{16}O and ^{11}C(α,p)^{14}N reactions because these two reactions have the biggest effect on changing the ^{7}Li/^{11}B isotopic abundance ratio among all reactions which we studied. We then discuss how to constrain the neutrino-mass hierarchy by comparing our theoretical prediction with the measured ^{7}Li/^{11}B ratio in the presolar Si-C X grains [1].

2 Supernova Model

We adopt the pre-SN model for SN 1987 calculated [9] for metallicity of Large Magellanic Cloud. The initial mass of the progenitor star is $20M_\odot$, and the star evolves to a helium core of $6M_\odot$. The hydrodynamic evolution of exploding materials and nucleosynthesis were calculated in the same method adopted in [7]. The total neutrino energy is 3×10^{53} erg, the exponential decay timescale of neutrino luminosity is 3 s, and the neutrino temperatures are set to be 3.2 MeV for ν_e, 5.0 MeV for $\bar{\nu}_e$, and 6.0 MeV for ν_x, where ν_x stands for ν_μ, $\bar{\nu}_\mu$, ν_τ and $\bar{\nu}_\tau$ [6]. Details are reported in [1].

3 Result and Discussions

3.1 ν-process nucleosynthesis of ^{7}Li, ^{7}Be, ^{11}B and ^{11}C

As displayed in Fig. 1, both ^{7}Li+^{7}Be and ^{11}B+^{11}C abundances depend strongly on neutrino mass hierarchies. The integrated yields in normal hierarchy (blue curves) are higher than those calculated in inverted hierarchy (red curves). Since the original temperatures are different from one another $T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}$ at the neutrino-spheres, the MSW-effect makes more efficient swapping of the neutrino energy spectra between T_{ν_e} and T_{ν_x} than the swapping between $T_{\bar{\nu}_e}$ and T_{ν_x}. As a result, ν_e has the largest enhancement of the high energy component after high-density MSW resonance occurs. This leads to stronger charged current reactions via ν_e than $\bar{\nu}_e$ to enhance the production through, for example ^{4}He(ν_e, e^-p)^{3}He(α,γ)^{7}Be and ^{12}C(ν_e, e^-p)^{11}C, etc., in the normal hierarchy (blue curves).

Stellar interior is divided into four layers, i.e. O-Ne-Mg layer (region I), O-C layer (II), C-He layer (III) and He layer (IV) in Fig. 1. Most of ^{7}Li, ^{7}Be, ^{11}B and ^{11}C are respectively produced in the regions of Lagrangian masses of 4.5–6.0 $M_\odot$ in IV, 3.5–5.5 $M_\odot$ in II–IV, 1.8–5.5 $M_\odot$ in I–IV, and 1.8–5.7 $M_\odot$ in I–IV. Among them, ^{11}B and ^{11}C are of particular interest. In the ^{16}O-rich layers I and II, both nuclei are predominantly produced by the ^{16}O+ν reaction. Suzuki et al. [10] have recently calculated ^{16}O+ν reaction cross sections precisely by using modern shell-model Hamiltonian which includes spin-isospin flip interaction with tensor force. This shell model calculation describes very well several nuclear properties such as magnetic-moments of p-shell nuclei, Gamow-Tellar strength for ^{12}C→^{12}N and ^{14}C→^{14}N, ^{12}C+ν reaction cross sections via both charged and neutral current interactions, and exotic nuclear properties of neutron-rich unstable nuclei. Our nucleosynthesis calculation using

Suzuki's new ^{16}O+ν rates gives one order of magnitude larger ^{11}B+^{11}C abundances (solid curves) than those using Hoffman & Woosley's rate [11] (dashed curves) in region I.

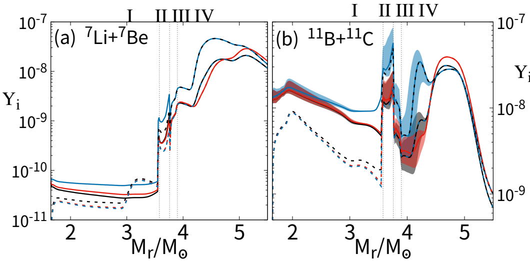

Figure 1. The calculated abundances of (a) ^{7}Li+^{7}Be and (b) ^{11}B+^{11}C as a function of Lagrangian mass coordinate in units of $M_{\odot}$. Red and blue lines correspond to inverted and normal hierarchies, respectively. Colored bands reflect the uncertainty of the ^{11}C$(\alpha, p)^{14}$N reaction rate. Solid and dashed lines are the results using Suzuki et al. [10] and Hoffman & Woosley [11] rates for ^{16}O+ν, respectively.

3.2 Sensitivity to the nuclear reactions

We calculated the sensitivity of nuclear abundances to all ν-^{4}He, ^{12}C and ^{16}O reaction rates whose uncertainties are estimated to be ±20% and ±10% for charged and neutral current reactions, respectively [1]. These uncertainties result in changes in the final yields by less than 20% and 10% because of the non-linear response made by the secondary nuclear reactions.

The reaction rates for ^{11}C(α,p)^{14}N, ^{11}C(n,p)^{11}B and ^{11}B(α,n)^{14}N among 91 nuclear reactions have rather large uncertainties. In particular, the first one was found to affect strongly the final abundances of ^{11}C and ^{11}B. Although some of the other reactions also have error bars in the measured reaction cross sections or theoretical estimates, those uncertainties result in less than a few % change in the final yields [1].

^{11}C is produced at $T_9 = T/(10^9\ \mathrm{K}) \approx 0.2 - 1.0$ in SN ν-process. It subsequently encounters the secondary destruction process ^{11}C$(\alpha, p)^{14}$N whose most effective temperature corresponds to the Gamow window energy ~ 0.3 MeV. Hayakawa et al. [12] carried out the direct measurement of this reaction cross sections for the first time, and Ingalls et al. [13] studied reverse reaction. Although these experiments cover 0.6 MeV $< E_{\mathrm{CM}} <$ 1.3 MeV, they did not reach E_{CM} = 0.3 MeV. There still exists five resonances at $E_{\mathrm{CM}} <$ 0.6 MeV. We therefore estimated the contribution of these resonances by assuming the Wigner limit in Breit-Wigner formula, which serves an upper limit on the total cross section, in addition to the non-resonant contribution as a lower limit. We then found that the newly estimated upper limit could be factors of $\sim$ 4 and 40 larger at $T_9 \sim 0.3$ and 0.15, respectively, than the standard rate of CF88 [14] in JINA reaclib database [15]. The ν-process nucleosynthesis of ^{11}B and ^{11}C is thus subject to large uncertainties as shown in Fig. 1.

3.3 Constraining the ν-mass hierarchy from meteoritic ^{7}Li/^{11}B

Because the lifetimes of ^{11}C and ^{7}Be are negligible compared with the age of SN remnant, they finally decay to ^{11}B and ^{7}Li. Therefore, the calculated ratio (^{7}Li+^{7}Be)/(^{11}B+^{11}C) provides the key information.

The pre-solar grains form from the dusts which condensate during the cooling process of SN ejecta. The efficiency of the SN ejecta from each layer is not known very well because

Table 1. Calculated abundance ratios (^{7}Li+^{7}Be)/(^{11}B+^{11}C) in our nucleosynthesis model. Associated errors represent uncertainties of the final yields as shown in Fig. 1 which arise from the uncertainty (2-σ C.L.) of the nuclear reaction rate for ^{11}C(α, p)^{14}N. See text for the four cases.

ejected layers	I+II+III+IV	II+III+IV	III+IV	IV
inverted hierarchy	$0.559^{+0.030}_{-0.060}$	$0.961^{+0.039}_{-0.077}$	$1.045^{+0.031}_{-0.038}$	$1.077^{+0.025}_{-0.025}$
normal hierarchy	$0.798^{+0.119}_{-0.167}$	$1.353^{+0.292}_{-0.347}$	$1.612^{+0.319}_{-0.295}$	$1.726^{+0.312}_{-0.273}$

of the complicated hydrodynamic processes. We assume therefore the four cases in which the nucleosynthesis products are ejected in different manner as tabulated in Table 1. We also assume that the materials of SN ejecta are well mixed during the ejection process. Mathews et al. [5] inferred the constraint ^{7}Li/^{11}B < 0.56 at the 2-σ C.L. from the measured abundances of ^{7}Li and ^{11}B discovered in presolar SiC-X grains [8]. Only the inverted hierarchy in case I+II+III+IV of Table 1 meets with this constraint.

4 Conclusion

Still unknown neutrino mass hierarchy affects the final abundances of ^{7}Li, ^{7}Be, ^{11}B and ^{11}C in the SN ν-process nucleosynthesis. The final ^{11}C abundance among them was found to be subject to uncertainties of ^{11}C(α, p)^{14}N reaction rate. Although we assumed a single set of neutrino energy spectra and decay constant of their luminosities in a single SN progenitor model, the calculated abundance ratio ^{7}Li/^{11}B does not depend strongly on these model parameters as far as $T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}$ is satisfied. This is because of the self-regulating reaction mechanism that balances between production and destruction of these nuclei in a narrow temperature range [6, 16]. The inverted hierarchy is suggested to be statistically more favored at the 2-σ C.L. We however need more theoretical calculations in many different models. It is also highly desirable to measure the ^{11}C(α,p)^{14}N reaction cross sections at lower energies and to find more samples of presolar SiC-X grains which include both ^{7}Li and ^{11}B.

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