Nuclear cosmochronometers for supernova neutrino-process

Takehito Hayakawa\textsuperscript{1,2,*}, Heamin Ko\textsuperscript{3}, Myung-ki Cheoun\textsuperscript{3}, Motohiko Kusakabe\textsuperscript{4}, Toshitaka Kajino\textsuperscript{4,5,6}, Satoshi Chiba\textsuperscript{7}, Ken'ichi Nomoto\textsuperscript{8}, Masa-aki Hashimoto\textsuperscript{9}, Masaomi Ono\textsuperscript{10}, Toshihiko Kawano\textsuperscript{11}, and Grant J. Mathews\textsuperscript{12}

\textsuperscript{1}National Institutes for Quantum Science and Technology, Ibaraki 319-1106, Japan
\textsuperscript{2}Institute of Laser Engineering, Osaka University, Osaka 567-0871, Japan
\textsuperscript{3}Soongsil University, Seoul 156-743, Korea
\textsuperscript{4}Beihang University, Beijing 100083, China
\textsuperscript{5}National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
\textsuperscript{6}The University of Tokyo, Tokyo 113-0033, Japan
\textsuperscript{7}Tokyo Institute of Technology, Tokyo 113-0033, Japan
\textsuperscript{8}Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo, Chiba 277-8583, Japan
\textsuperscript{9}Kyushu University, Fukuoka 812-8581, Japan
\textsuperscript{10}RIKEN, Saitama 351-0198, Japan
\textsuperscript{11}Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
\textsuperscript{12}University of Notre Dame, Notre Dame, IN 46556, USA

Abstract. The short-lived unstable isotopes with half-lives of 0.1−10 My have been used as nuclear cosmochronometers to evaluate from an astrophysical event such as supernova (SN) explosion or AGB s-process to the solar system formation. We have proposed shorted-lived radioisotopes of $^{92}$Nb and $^{98}$Tc as the nuclear cosmochronometers for supernova neutrino-process.

1 Introduction

A huge number of neutrinos emitted in core-collapse supernova (SN) explosions ($\nu$ process) [1] play an important role in stellar nucleosyntheses of rare some nuclides such as $^7$Li, $^{11}$B, $^{19}$F, $^{138}$La, and $^{180}$Ta [1–4]. When the high-energy neutrinos pass through the outer layers of the star they can induce nuclear reactions on pre-existing nuclei. Many nuclides are, in principle, generated by the $\nu$ process in SNe but the produced abundances are smaller than production by other major processes such as the $s$ or $r$ process by a few orders of magnitude. Thus, the $\nu$ process can only play a significant role in the synthesis of a rare isotope when the isotope is not produced by the major processes.

Short-lived unstable isotopes with half-lives of $10^6$–$10^8$ y have been used as nuclear cosmochronometers to evaluate the time from an astrophysical event such as an AGB $s$-process or a SN explosion to the solar system formation (SSF) [5–8]. The unstable isotope $^{92}$Nb decays to the daughter nucleus $^{92}$Zr by $\beta$ decay with a half-life of 3.47×$10^7$ y. Although $^{92}$Nb does not naturally exist at the present solar system, its existence at the SSF has been...
found by analysis of primitive meteorites [9–13]. Thus, $^{92}\text{Nb}$ has the potential to be used as a nuclear cosmochronometer for a nucleosynthesis episode which produces $^{92}\text{Nb}$. However, the astrophysical origin of $^{92}\text{Nb}$ has not been established. Hayakawa et al. [14] have proposed the $\nu$ process origin for $^{92}\text{Nb}$. Furthermore, the radioisotope $^{98}\text{Tc}$ ($T_{1/2} = 4.2 \times 10^6$ y) is another candidate for the $\nu$-process cosmochronometer [15], although only an upper limit of $^{98}\text{Tc}/^{98}\text{Ru} < 6 \times 10^{-5}$ has been reported [16] for the $^{98}\text{Tc}$ initial abundance at the SSF.

## 2 Supernova $\nu$-process calculation

There are six species of neutrinos: electron neutrinos, muon neutrinos, tau neutrinos and their anti-neutrinos. The neutrino-induced reactions can be classified into three groups: the neutral current (NC) reaction with all six neutrinos, the charged current (CC) reaction with electron neutrinos, and the CC reaction with electron anti-neutrinos [15]. Previous studies for $^{92}\text{Nb}$ [14], $^{138}\text{La}$, and $^{180}\text{Ta}$ [1, 2] have shown that individual $\nu$-process isotopes are predominantly synthesized by the CC reaction with $\nu_e$ and the NC reaction. Figure 1 shows a partial nuclear chart and nucleosynthesis flows around $^{92}\text{Nb}$. $^{92}\text{Nb}$ is predominantly generated by the CC reaction with $\nu_e$ on $^{92}\text{Zr}$ and it is also produced by the NC reaction on $^{93}\text{Nb}$. Figure 2 shows nucleosynthesis flows for $^{98}\text{Tc}$. Among the CC reactions with $\nu_e$, the $^{98}\text{Mo}(\nu_e, e^-)^{98}\text{Tc}$ reaction is the dominant reaction. There are two NC reactions: $^{99}\text{Ru}(\nu, \nu'p)^{98}\text{Tc}$ and $^{99}\text{Tc}(\nu, \nu'n)^{98}\text{Tc}$. One of the remarkable features for $^{98}\text{Tc}$ production is that $^{98}\text{Tc}$ is also produced by the CC reaction with $\nu_e$ though the $^{99}\text{Ru}(\nu_e, e^+n)^{98}\text{Tc}$ and $^{100}\text{Ru}(\nu_e, e^+2n)^{98}\text{Tc}$ reactions. This suggests that the $^{98}\text{Tc}$ abundance may be sensitive to the average energy of the electron anti-neutrinos. We have performed calculations of the neutrino-induced reaction cross sections using a QRPA model [17] and the branching ratios are calculated using a Hauser-Feshbach calculation with a CCONE nuclear reaction calculation code [18]. We have calculated $\nu$-process production rates using a core-collapse SN model for SN 1987A with an kinetic energy of $10^{51}$ erg [19]. We have used a 20 $M_\odot$ progenitor with a 6 $M_\odot$ He core with a metallicity of $Z_\odot/4$. Because the neutron-induced reaction cross sections in the proton rich-side have not been well studied, we have calculated the neutron capture cross sections in this mass region [20]. We have calculated evolution of the progenitor star including the weak $s$-processes [20] with the calculated neutron capture reactions. The neutrino flux decays exponentially with a time constant of 3 s. The six neutrino species can be treated as three groups: electron neutrino, electron anti-neutrino, muon neutrino, muon anti-neutrino, tau neutrino, and tau anti-neutrino. The reaction cross sections are calculated using a QRPA model [17].
Figure 2. Nucleosynthesis flow and key nuclear reactions around $^{98}$Tc

anti-neutrino, and the other four neutrinos. Previous studies [22] for the energy spectra of the neutrinos have suggested the following energy hierarchy: $\langle \nu_e \rangle < \langle \bar{\nu}_e \rangle < \langle \nu_{\mu,\tau}, \bar{\nu}_{\mu,\tau} \rangle$. In the present calculation, we adopt average energies of $kT = 3.2, 5.0, 6.0$ MeV for $\langle \nu_e \rangle$, $\langle \bar{\nu}_e \rangle$, and $\langle \nu_{\mu,\tau}, \bar{\nu}_{\mu,\tau} \rangle$, respectively.

Figure 3 shows the calculated abundances. Integrating the layers within the mass range of $1.8 < M < 3.7$, we obtain masses of $5.1 \times 10^{-13}$ and $3.4 \times 10^{-11}$ M$_\odot$ for $^{98}$Tc and $^{98}$Ru, respectively. The contribution from the CC reactions with electron anti-neutrinos is relatively large compared to that of other heavy $\nu$-process isotopes. The integrated mass fraction of $^{98}$Tc decreases by approximately 20% compared to one with all six neutrino spices without
the CC reactions with electron anti-neutrinos. $^{98}$Tc is the most sensitive to the temperature of the electron anti-neutrinos among heavy elements because the contribution of the CC reaction with electron anti-neutrinos to $^{92}$Nb, $^{138}$La, and $^{180}$Ta was considered to be negligibly small in the previous studies.

3 Age from the last SN to SFF

It is assumed that short-lived unstable isotopes are produced by a nearby SN before the SSF and subsequently they are mixed with the collapsing protosolar cloud. The isotopic abundance ratio at the time of SSF can then be expressed as

$$\frac{N(98\text{Tc})_{SSF}}{N(98\text{Ru})_{SSF}} = \frac{f N(98\text{Tc})_{SN} e^{-\Delta/\tau}}{N(98\text{Ru})_{SN} + f N(98\text{Ru})_{SN}},$$

where $N(98\text{Tc})_{SN}$ and $N(98\text{Ru})_{SN}$ are the numbers of $^{98}$Tc and $^{98}$Ru, respectively, in the SN ejecta, $N(98\text{Ru})_{\odot}$ is the number of the initial $^{98}$Ru nuclei in the collapsing cloud, $\Delta$ is the time from the SN to SSF, and $f$ is the dilution fraction. The timescales $\Delta$ in the range of $3\times10^7-10^8$ y have been previously estimated from several short-lived radioisotopes [7]. The dilution factor has been estimated to the values from $7\times10^5$ to $2\times10^3$. The initial solar abundance of $^{92}$Nb has been reproduced using the SN $\nu$-process model with the parameters of $\Delta = 10^6$ (or $3\times10^7$ y) and $f = 3\times10^{-3}$ [14]. The $^{98}$Tc/$^{98}$Ru ratios calculated using the $\nu$-process model and $f = 3\times10^{-3}$ are $^{98}$Tc/$^{98}$Ru = $1.3\times10^{-5}$ and $1.1\times10^{-7}$ for $\Delta = 10^6$ and $3\times10^7$ y, respectively. These calculated ratios are lower than the measured upper limit of $^{98}$Tc/$^{98}$Ru < $6\times10^{-5}$ [16]. Thus, it is possible to explain both the initial abundances of $^{92}$Nb and $^{98}$Tc by the contribution of a single SN $\nu$-process.

References