Proc. 15th Int. Symp. Origin of Matter and Evolution of Galaxies (OMEG15)
JPS Conf. Proc. **31**, 011028 (2020)
https://doi.org/10.7566/JPSCP.31.011028

Nuclear Cosmochronometer for Supernova Neutrino process

Takehito Hayakawa[1,2], Motohiko Kusakabe[3], Toshitaka Kajino[3,2,4], Myung-Ki Cheoun[5], Heamin Ko[5], Grant J. Mathews[6], Alexey Tolstov[7], Ken'ichi Nomoto[7], Satoshi Chiba[8], Toshihiko Kawano[9], Masa-aki Hashimoto[10], Masaomi Ono[11]

[1]*National Institutes for Quantum and Radiological Science and Technology, 2-4 Shirakata, Tokai, Naka, Ibaraki 319-1106, Japan*
[2]*National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*
[3]*Beihang University, 37 Xueyuan Road, Haidian-qu, Beijing 100083, China*
[4]*The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*
[5]*Soongsil University, Seoul 156-743, Korea*
[6]*University of Notre Dame, Notre Dame, Indiana 46556, USA*
[7]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan*
[8]*Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 113-0033, Japan*
[9]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[10]*Department of Physics, Kyushu University, Fukuoka 819-0395, Japan*
[11]*RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan*

E-mail: hayakawa.takehito@qst.go.jp

(Received September 2, 2019)

We have proposed a short-lived radioisotope ^{98}Tc as the nuclear cosmochronometer to evaluate the time from the last supernova ν-process to the solar system formation (SSF). We have calculated the supernova ν-process using a SN 1987A model with neutrino-induced reaction cross sections. The calculated result is consistent with the observed upper limit of ^{98}Tc/^{98}Ru at the SSF.

KEYWORDS: ν process, nuclear cosmochronometer, primitive meteorite

1. Introduction

The ν process has been proposed [1] as the mechanism for the origin of several rare isotopes of light and heavy elements such as ^{7}Li, ^{11}B, ^{19}F, ^{138}La, and ^{180}Ta [1–3]. During an early phase of a core-collapse supernova (SN) explosion, energetic neutrinos are emitted from the proto-neutron star. When these neutrinos pass through the outer layers of the star they can induce nuclear reactions on ambient nuclei. Although many nuclides are, in principle, generated by the neutrino-induced reactions, the produced abundances are usually negligibly small compared to production by other major processes such as the s or r process. When an isotope is not produced by major processes, the ν-process is dominant in produciton of the isotope.

Radioisotopes with half-lives of $10^6 - 10^8$ y have been used as nuclear cosmochronometers to measure the time from the last nucleosynthesis event such as a SN or an s-process event in an asymptotic giant branch star to the solar system formation (SSF) [4–6]. The radioactive isotope ^{92}Nb decays to the daughter nucleus ^{92}Zr by β decay with a half-life of 3.47×10^7 y. Because its half-life is much shorter than the age of the solar system of about $4.6{\times}10^9$ y, ^{92}Nb does not naturally exist at the present solar system. Progress in meteorite science, however, has led to measurements of the abundance of ^{92}Nb at the SSF [7, 8]. It was found an excess of the abundance of ^{92}Zr in primitive meteorites that was produced by β decay of ^{92}Nb after the SSF. Thus, ^{92}Nb has the potential to be used as a similar nuclear chronometer. To evaluate the age from the last astrophysical event to the SSF, one should calculate the initial abundance at the nucleosynthesis event. Hayakawa et al. [9] have proposed the ν process origin for ^{92}Nb and presented that the observed abundance ratio of ^{92}Nb/^{93}Nb at the SSF can be reproduced by the ν process. The radioisotope ^{98}Tc ($T_{1/2}$ = 4.2×10^{6} y) is another candidate for the ν-process chronometer [10], although only an upper limit of ^{98}Tc/^{98}Ru < 6×10^{-5} has been reported [11] for the ^{98}Tc initial abundance at the SSF.

2. Supernova ν-process calculation

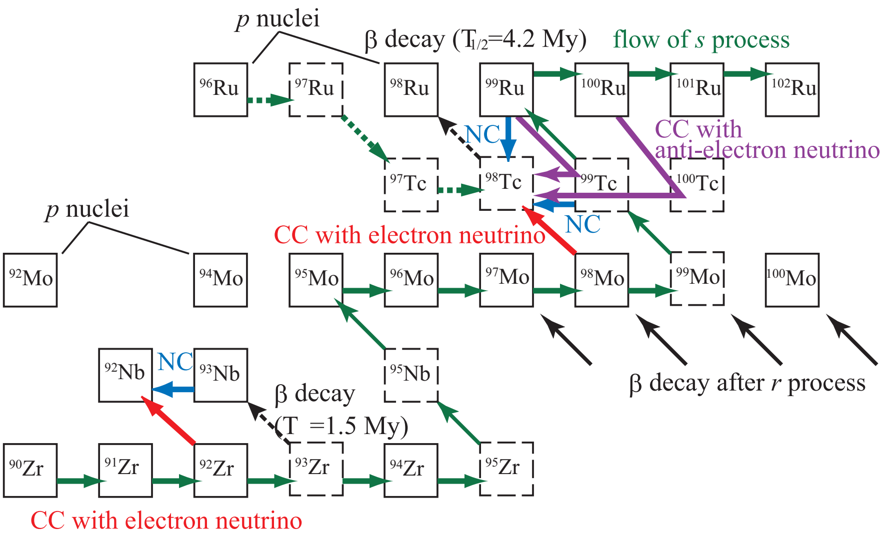

Fig. 1. A partial nuclear chart around ^{98}Tc and nucleosynthesis flows.

Neutrino-nucleus interactions are key physics for understanding the neutrino process. The neutrino-induced reactions can be classified into three groups: the charged current (CC) reaction with electron neutrinos, the CC reaction with electron anti-neutrinos, and the neutral current (NC) reaction with all six neutrinos plus anti-neutrinos [10]. Previous studies for ^{92}Nb [9], ^{138}La, and ^{180}Ta [1, 2] have shown that individual ν-process isotopes are predominantly synthesized by the CC reaction with ν_e and the NC reaction. Furthermore, the contribution of the CC reaction with ν_e is typically larger than that of the NC reactions by a factor of 2−8 [2]. Therefore, the abundances of heavy ν-process isotopes, in particular, are sensitive to the average energy of the electron neutrinos among all 6 species. Figure 1 shows a partial nuclear chart and neucleosynthesis flows around ^{92}Nb and ^{98}Tc. ^{98}Tc is predominantly produced by the CC reaction with ν_e and the NC reactions. Among the CC reactions with ν_e, the ^{98}Mo(ν_e, e$^-$)^{98}Tc reaction is the dominant reaction. For the NC reaction, there are two reactions: ^{99}Ru(ν, ν'p)^{98}Tc and ^{99}Tc(ν, ν'n)^{98}Tc. Although ^{99}Tc is unstable with a half-life of 2.11×10^{5} y, it is produced by the β^--decay of ^{99}Mo with a short half-life of 2.7 d during the weak s-processes. A feature that should be noted is that ^{98}Tc should be produced by the CC reaction with $\overline{\nu_e}$. The production proceeds via the ^{99}Ru($\overline{\nu}_e$, e$^+$n)^{98}Tc and ^{100}Ru($\overline{\nu}_e$, e$^+$2n)^{98}Tc reactions as shown in Fig. 1.

We perform calculations of the neutrino-induced reaction cross sections using a QRPA model [12]. The branching ratios are calculated using a Hauser-Feshbach calculation with a CCONE nuclear reaction calculation code [13]. We have calculated ν-process production rates using a core-collapse SN model for SN 1987A [14]. We use a 20 $M_\odot$ progenitor with a 6 $M_\odot$ He core and an explosiowith kinetic energy of 10^{51} erg. The neutrino flux is taken to decay exponentially with a time constant of 3 s. A solar abundance distribution normalized to a metallicity of $Z_\odot/4$ is adopted for the initial composition of the progenitor star. We then calculated evolution of the progenitor star including the weak s-processes based upon calculated neutron capture reactions [15], and used the resultant mass distribution of heavy isotopes as seed nuclei in the He, C/O, and O/Ne/Mg rich shells [16].

The average temperature of the neutrinos is a critical input for the ν-process nucleosynthesis. The six neutrino species can be treated as three groups: electron neutrino, electron anti-neutrino, and the other four neutrinos. These three groups are expected have different temperatures at the time when they are emitted from proto-neutron stars. Previous studies [17] 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.

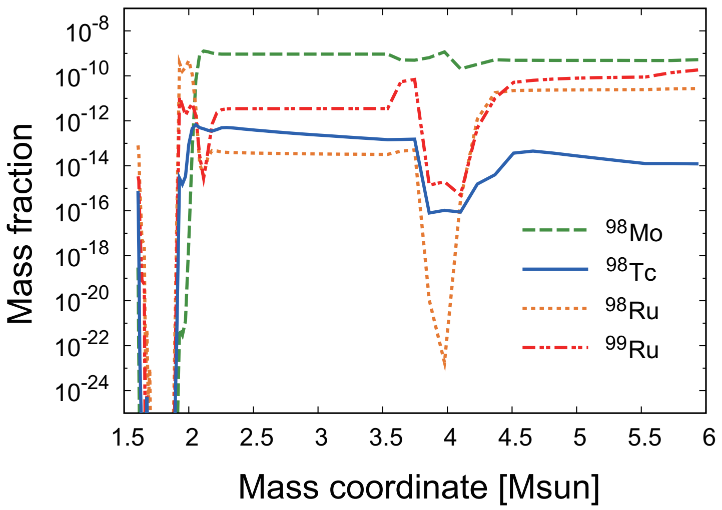

Fig. 2. Calculated abundances as a function of interior mass from the SN ν-process with a SN 1987A model.

Figure 2 shows the calculated abundances. In the mass coordinate region of 2.2 < M < 3.7, the ^{98}Tc abundance slightly decreases with increasing mass coordinate. This can be understood by the relationship between the areal density of neutrinos and the mass coordinate. Integrating the layers within the mass range of 1.8 < M < 3.7, we obtain masses of 5.1×10^{-13} and 3.4×10^{-11} $M_\odot$ for ^{98}Tc and ^{98}Ru, respectively. One of the unique features of ^{98}Tc production by the ν-process is the fact that the contribution from the CC reactions with electron anti-neutrinos is relatively large compared to that of other heavy ν-process isotopes as discussed above. When we calculate the ^{98}Tc production using the SN model without electron anti-neutrinos the integrated mass fraction of ^{98}Tc decreases by approximately 20% compared to one with all six neutrino spices. In previous studies, the contribution of the CC reaction with electron anti-neutrinos to ^{92}Nb, ^{138}La, and ^{180}Ta was considered to be negligibly small. Therefore, among heavy ν-process isotopes, ^{98}Tc is the most sensitive to the temperature of the electron anti-neutrinos.

3. Age from the last SN to SFF

To evaluate the abundance ratio of ^{98}Tc/^{98}Ru at the time of SSF, one should consider the mixing between the ejecta from a SN and the ambient solar material. It is assumed that radioisotopes are produced by the single injection of material from a nearby SN before the SSF or at an early stage of

SSF and then are mixed with the collapsing protosolar cloud. The unstable isotope ^{98}Tc is produced by the last SN and ^{98}Tc decays away during the time Δ from the SN event until the mixing with the protosolar cloud. The isotopic abundance ratio at the time of SSF can then be expressed as

$$\left[\frac{^{98}\mathrm{Tc}}{^{98}\mathrm{Ru}}\right]_{SSF} = \frac{fN(^{98}\mathrm{Tc})_{SN}e^{-\Delta/\tau 98}}{N(^{98}\mathrm{Ru})_{\odot} + fN(^{98}\mathrm{Ru})_{SN}} \quad , \tag{1}$$

where $N(^{98}\mathrm{Tc})_{SN}$ and $N(^{98}\mathrm{Ru})_{SN}$ are the numbers of ^{98}Tc and ^{98}Ru, respectively, in the SN ejecta, $N(^{98}\mathrm{Ru})_{\odot}$ is the number of the initial ^{98}Ru nuclei in the collapsing cloud, and f is the dilution fraction, i.e., the fraction of the ejected material that mixes with the final protosolar cloud.

The timescales for Δ have been previously estimated [5] from several short-lived r-process chronometers, for example ^{129}I, ^{107}Pd, and ^{182}Hf, with half-lives within 10^6–10^8 y. The evaluated time scale falls within the range of 3×10^7–10^8 y [5]. Values of the dilution factor based upon other radioisotopes such as ^{26}Al, ^{41}Ca, and ^{53}Mn [4, 19] vary from 7×10^5 to 2×10^3. Hayakawa et al. reproduced the initial solar abundance of ^{92}Nb with $\Delta = 10^6$ or 3×10^7 y and $f = 3\times10^{-3}$ [9].

The calculated ratios with the ^{98}Tc mass of 5.1×10^{-13} $M_{\odot}$ produced by the ν-process and $f = 3\times10^{-3}$ are ^{98}Tc/^{98}Ru = 1.3×10^{-5} and 1.1×10^{-7} for $\Delta = 10^6$ and 3×10^7 y, respectively. These expected initial ratios are lower than the measured upper limit of ^{98}Tc/^{98}Ru < 6×10^{-5} [11]. Thus, it is possible to explain both of the initial abundance of ^{92}Nb and the upper limit to the ^{98}Tc abundance in the early solar system by a single SN ν-process. We stress that ^{98}Tc whose half-life is a factor of 9 shorter than that of ^{92}Nb is more sensitive to the duration time. Therefore, if the initial abundance of ^{98}Tc is ever precisely measured by meteorite analysis, it could be used to constrain the duration time from the last core-collapse SN to the SSF.

References

[1] S. E. Woosley, D. H. Hartmann, R. D. Hoffman, and W. C. Haxton, Astrophys. J. **356**, 272 (1990).
[2] A. Heger, E. Kolbe, W. C. Haxton, K. Langanke, G. Martínez-Pinedo, and S. E. Woosley, Phys. Lett. B **606**, 258 (2005).
[3] S. M. Austin, A. Heger, and C. Tur, Phys. Rev. Lett. **106**, 152501 (2011).
[4] B. S. Meyer and D. D. Clayton, Space Sci. Rev. **92**, 133 (2000).
[5] N. Dauphas, T. Rauscher, B. Marty, L. Reisberg, Nucl. Phys. A **719**, 287c (2003).
[6] M. Lugaro, M. Pignatari, U. Ott, K. Zuber, C. Travaglio, G. Gyürky, and Z. Fülöp, Proc. National Academy of Sci. of Uni. States of America, **113**, 907 (2016).
[7] M. Schönbächler, M. Rehkämper, A. N. Halliday, D. C. Lee, M. Bourot-Denise, B. Zanda, B. Hattendorf, D. Günther, Science **295**, 1705 (2002).
[8] T. Iizuka, Y. J. Laib, W. Akram, Y. iAmelin, M. Schönbächler, Earth Plan. Sci. Lett. **439**, 172 (2016).
[9] T. Hayakawa, K. Nakamura, T. Kajino, S. Chiba, N. Iwamoto, M.K. Cheoun, G.J. Grant, Astrophys. J. **779**, L9 (2013).
[10] T. Hayakawa, H. Ko, M.-K, Cheoun, M. Kusakabe, T. Kajino, M. K. Usang, S. Chiba, K. Nakamura, A. Tolstov, K. Nomoto, M. Hashimoto, T. Kawano, G. J. Mathews, Phys. Rev. Lett. **121**, 102701 (2018).
[11] H. Becker, R. J. Walker, Chem. Geol. **196**, 43 (2003).
[12] M. -K. Cheoun, E. Ha, T. Hayakawa, S. Chiba, K. Nakamura, T. Kajino, G. J. Mathews, Phys. Rev. C, **85**, 065807 (2012).
[13] O. Iwamoto, N. Iwamoto. S. Kunieda, F. Minato, K. Shibata, Nucl. Data sheets, **131**, 259 (2016).
[14] T. Shigeyama, K. Nomoto, M. Hashimoto, Astrophys. Astronm. **196**, 141 (1988).
[15] T. Kawano, P. Talou, M. B. Chadwick, T. Watanabe, J. Nucl. Sci. Technol., 47, 462 (2010).
[16] Y. Kikuchi, M. Hashimoto, M. Ono, F. Fukuda Prog. Theor. Exp. Phys. **2015(6)**, 063E01 (2015).
[17] T. Fischer, G. Martinez-Pínedo, M. Hempel, and M. Liebendörfer, Phys. Rev. D **85**, 083003 (2012).
[18] S. Blinnikov, P. Lundqvist, O. Bartunov, K. Nomoto, K. Iwamoto, Astrophys. J. **532**, 1132 (2000).
[19] A. Takigawa, J. Miki, S. Tachibana, G. R. Huss, N. Tominaga, H. Umeda, and K. Nomoto. Astrophys. J. **688**, 1382 (2008).