Nuclear cosmochronometers for supernova neutrino-process

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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 (ν 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 ν 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 ν 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 β 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

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found by analysis of primitive meteorites [9–13]. Thus, ^{92}Nb has the potential to be used as a nuclear cosmochronometer for a nucleosynthesis episode which produces ^{92}Nb. However, the astrophysical origin of ^{92}Nb has not been established. Hayakawa et al. [14] have proposed the ν process origin for ^{92}Nb. Furthermore, the radioisotope ^{98}Tc ($T_{1/2}$ = 4.2×10^{6} y) is another candidate for the ν-process cosmochronometer [15], although only an upper limit of ^{98}Tc/^{98}Ru < 6×10^{-5} has been reported [16] for the ^{98}Tc initial abundance at the SSF.

2 Supernova ν-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}Nb [14], ^{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. Figure 1 shows a partial nuclear

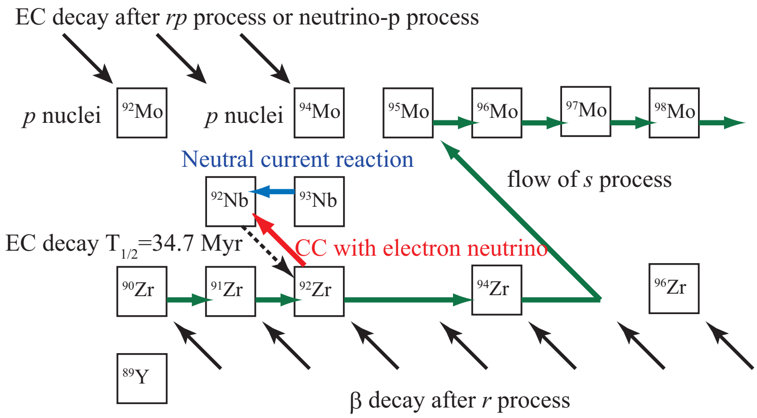

Figure 1. Nucleosynthesis flow and key nuclear reactions around ^{92}Nb

chart and nucleosynthesis flows around ^{92}Nb. ^{92}Nb is predominantly generated by the CC reaction with ν_e on ^{92}Zr and it is also produced by the NC reaction on ^{93}Nb. Figure 2 shows nucleosynthesis flows for ^{98}Tc. Among the CC reactions with ν_e, the ^{98}Mo(ν_e, e$^-$)^{98}Tc reaction is the dominant reaction. There are two NC reactions: ^{99}Ru(ν, ν'p)^{98}Tc and ^{99}Tc(ν, ν'n)^{98}Tc. One of the remarkable features for ^{98}Tc production is that ^{98}Tc is also produced by the CC reaction with $\overline{\nu_e}$ though the ^{99}Ru($\overline{\nu}_e$, e$^+$n)^{98}Tc and ^{100}Ru($\overline{\nu}_e$, e$^+$2n)^{98}Tc reactions. This suggests that the ^{98}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 ν-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 [21]. 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

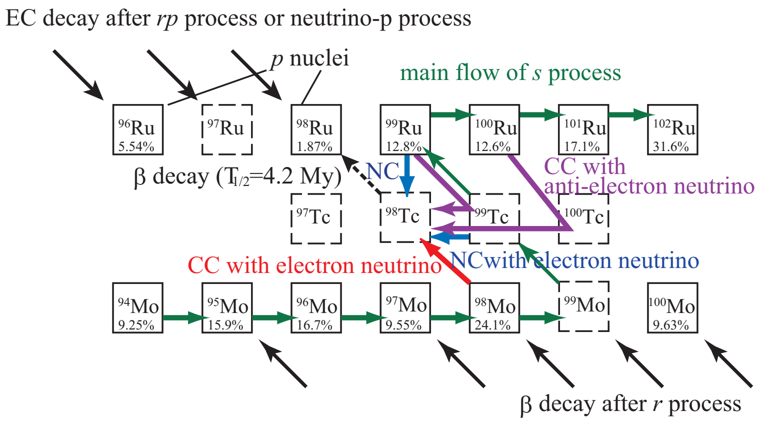

Figure 2. Nucleosynthesis flow and key nuclear reactions around ^{98}Tc

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

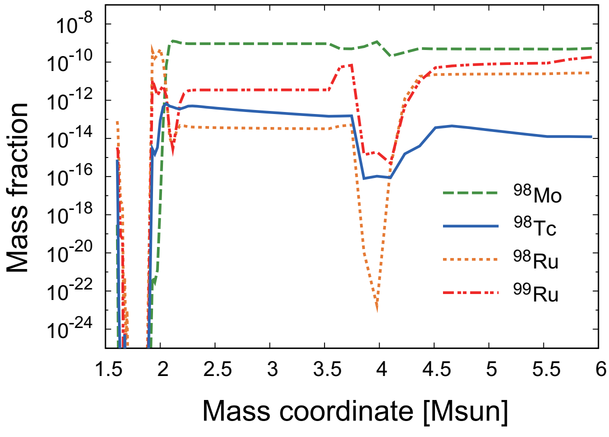

Figure 3. Calculated abundances. The solid line indicates the abundance of ^{98}Tc. The dashed, dotted, dashed double-dotted lines are ^{98}Mo, ^{98}Ru, and ^{99}Ru, respectively.

Figure 3 shows the calculated abundances. Integrating the layers within the mass range of 1.8 < M < 3.7, we obtain masses of 5.1×10^{-13} and 3.4×10^{-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 ν-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

$$\left[\frac{^{98}\mathrm{Tc}}{^{98}\mathrm{Ru}}\right]_{SSF} = \frac{fN(^{98}\mathrm{Tc})_{SN}e^{-\Delta/\tau98}}{N(^{98}\mathrm{Ru})_{\odot} + fN(^{98}\mathrm{Ru})_{SN}} \ , \tag{1}$$

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, Δ is the time from the SN to SSF, and f is the dilution fraction. The timescales Δ in the range of 3×10^7–10^8 y have been previously estimated from several short-lived radioisotopes [7]. The dilution factor has been estimated to the values from 7×10^5 to 2×10^3. The initial solar abundance of ^{92}Nb has been reproduced using the SN ν-process model with the parameters of $\Delta = 10^6$ (or 3×10^7 y) and $f = 3\times10^{-3}$ [14]. The ^{98}Tc/^{98}Ru ratios calculated using the ν-process model 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 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 ν-process.

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