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Short-lived radioisotope ^{98}Tc synthesized by supernova neutrino process

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Abstract

The isotope ^{98}Tc decays to ^{98}Ru with a half-life of 4.2×10^6y and could have been present in the early solar system. In this Letter, we report on the first calculations of the production of ^{98}Tc by neutrino-induced reactions in core-collapse supernovae (the ν-process). Our predicted ^{98}Tc abundance at the time of solar system formation is not much lower than the current measured upper limit raising the possibility for its detection in the not too distant future. We show that if the initial abundance were to be precisely measured, the ^{98}Tc nuclear cosmochronometer could be used to evaluate a much more precise value of the duration time from the last core-collapse supernova to the formation of the solar system. Moreover, a unique and novel feature of ^{98}Tc ν-process nucleosynthesis is the large contribution ($\sim$20%) from charged current reactions with electron anti-neutrinos. This means that ^{98}Tc becomes a unique new ν-process probe of the temperature of the electron anti-neutrinos.

Neutrinos are a key component of the physics of core-collapse supernovae (SNe) and their associated nucleosynthesis. The nucleosynthesis by neutrino-induced reactions in SNe (the ν-process) has been proposed [1, 2] as the mechanism for the origin of several rare isotopes of light-to-heavy elements. A large number of energetic neutrinos are emitted from the proto-neutron star formed during an early phase of a core-collapse SNe. When these neutrinos pass through the outer layers of the progenitor star they can induce nuclear reactions on atomic nuclei. The ν-process is also important for estimating the neutrino energy spectra emitted from proto-neutron stars [2, 3] and understanding neutrino oscillations [4, 5]. The six neutrino species, electron neutrino, muon neutrino, tau neutrino, and their anti-neutrinos, 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. Their energy hierarchy is $\langle\nu_e\rangle < \langle\overline{\nu}_e\rangle < \langle\nu_{\mu,\tau}, \overline{\nu}_{\mu,\tau}\rangle$ [6, 7]. These neutrino temperatures are critical components of the physics of the proto-neutron stars and the associated SN explosions. However, when neutrinos pass through the outer layers the neutrino flavor can be changed by the Mikheyev-Smirnov-Wolfenstein (MSW) matter mixing neutrino oscillations [4, 5]. This MSW flavor change occurs near the bottom of the C/O-rich layers. As a result, the energy spectra of neutrinos propagating through the outer layers can be swapped from those passing through the inner layers. Therefore, it is important to investigate the production by the ν-process in the inner O/Ne/Mg-rich layers. These interactions record the neutrino energy emitted from the proto-neutron star in nucleosynthetic products.

The ν-process can only play a significant role in the synthesis of rare isotopes. Although many nuclides can experience neutrino-induced reactions in SNe, the produced abundances are usually negligibly small compared to production by other major nucleosynthesis processes such as s and r processes. Hence, only a limited number of nuclides have been designated as the ν-isotopes; they are ^{7}Li, ^{11}B, ^{19}F, ^{138}La, and ^{180}Ta [1, 2]. Among them, ^{7}Li and ^{11}B are generated in the outer C/O-rich and He-rich layers, whereas the other nuclides ^{19}F, ^{138}La, and ^{180}Ta are synthesized near the bottom of O/Ne/Mg-rich layers. For ^{19}F, the dominant source in the Galaxy is thought to be low mass AGB stars [8], and the contribution of the ν-process to the solar ^{19}F abundance is estimated to be only 25$-$75% [5]. Therefore, among possible ν-isotopes, only the two isotopes ^{138}La and ^{180}Ta are likely to have been synthesized primarily in the inner layers by the ν-process [1, 2]. However, until Hayakawa et al. [9] resolved the isomer production problem for ^{180}Ta, the solar abundances of these two nuclides could not be consistently explained by the ν-process. Progress in meteorite science has led to measurements of the abundance of the short-lived radioactivity ^{92}Nb ($T_{1/2}$=3.5×10^7 y) at the time of solar system formation (SSF). Hayakawa et al. [10] have proposed a SN ν-process origin for ^{92}Nb and reproduced the abundance of ^{92}Nb at the SSF by a SN explosion model with calculated neutrino-nucleus interactions. Indeed, at that time there was an ambiguity in the measurements between a high and low value for the ^{92}Nb/^{93}Nb ratio. The ν-process could only explain the lower value, which has since been confirmed by other measurements [11].

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 NC reaction with all six neutrinos plus anti-neutrinos. Previous studies on ^{92}Nb [10], ^{138}La, and ^{180}Ta [1, 2] have shown that each ν nucleus is predominantly synthesized by two neutrino-induced reactions: the CC reaction with ν_e and the NC reactions. 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]. Hence, the contribution of the electron neutrinos to the total production is approximately 70−90%. Therefore, the abundances of heavy ν-isotopes in particular are sensitive to the temperature of the electron neutrinos among all 6 species. The other 5 species (and electron neutrino) also contribute to the production via the NC reactions. Because the temperature of the electron anti-neutrinos is lower than those of $\nu_{\mu,\tau}, \overline{\nu}_{\mu,\tau}$ [6, 7], the contribution of the electron anti-neutrino is limited to approximately 1−4%. There is no known isotope whose abundance is sensitive to the temperature of electron anti-neutrinos. In order to understand the supernova neutrino physics, however, one should know the energy spectra of all three groups. It is therefore highly desirable to find another ν-isotope sensitive to the electron anti-neutrino temperature.

The radioisotope ^{98}Tc ($T_{1/2} = 4.2\times10^6$ y) is a candidate for such an anti-neutrino sensitive ν-isotope synthesized in O/Ne/Mg-rich layers. It has been suggested that the astrophysical origin of ^{98}Tc could be via photodisintegration reactions in SNe (the γ-process) [12] or explosive nucleosynthesis in Type Ia SNe [13, 14]. However, its origin has remained an open question. One of the difficulties in solving this problem comes from a fact that only an upper limit of ^{98}Tc/^{98}Ru $< 6\times10^{-5}$ has been reported [15] for the ^{98}Tc initial abundance at the SSF. In this letter, we report on a calculation based on the SN ν-process as the astrophysical production mechanism for ^{98}Tc. This investigation into a new ν-process isotope could provide new clues into the physics of SN neutrinos and the astronomical history before the SSF. We present numerical calculations using a 1987A SN model with neutrino-induced charged current reactions for electron neutrinos and electron anti-neutrinos, along with neutral current reactions for all 6 neutrino species. We also calculate the expected values for the ^{98}Tc/^{98}Ru ratios at the time of SSF using a late input model.

As noted previously, previous studies on ^{92}Nb [10], ^{138}La, and ^{180}Ta [1, 2] have shown that each ν nucleus is predominantly synthesized by the CC reaction with ν_e on an isobar whose atomic number is one less than the ν nucleus, (for example ^{180}Hf(ν_e, e$^-$)^{180}Ta). However, the contribution from the CC reaction with $\overline{\nu_e}$ on an isobar whose atomic number is one larger than the ν nucleus, for example ^{180}W($\overline{\nu}_e$, e$^+$)^{180}Ta, is negligibly small. This is because the heavy isobar is usually a p-nucleus, for which the isotopic abundance is minuscule (0.12% for ^{180}W) and it is mostly destroyed by neutron irradiation during the weak s-process during the earlier evolution of the progenitor star [16, 17]. Therefore, the abundances of heavy ν-isotopes in particular are sensitive to the temperature of the electron neutrinos among all 6 species, but not sensitive to that of the electron anti-neutrinos.

^{98}Tc is also 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, we consider 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. Because the neutrino-induced reaction cross-sections are extremely small, measurements of neutrino-nucleus interactions on heavy nuclei are very difficult. Thus, one must calculate the cross sections theoretically. However, individual neutrino reaction cross sections depend upon the detailed nuclear structures of the nuclei involved [18]. Thus, it is necessary to calculate the relevant cross-sections using a detailed nuclear structure model. For the CC with ν_e and NC reactions, we use calculated results deduced using the quasiparticle random phase approximation (QRPA) in the previous study of [19].

Here, we would like to point out the novel result that ^{98}Tc should be produced by the CC reactions 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$^+$2n)^{98}Tc reactions as shown in Fig. 1. This fact suggests the new possibility that ^{98}Tc production may be a diagnostic of the temperature of the electron anti-neutrinos. Note, that we do not consider the ^{98}Ru($\overline{\nu}_e$, e$^+$)^{98}Tc reaction because the abundance of ^{98}Ru is lower than that of ^{98}Mo by an order of magnitude and it should, therefore, be partly destroyed in the weak s-processes. For the CC reaction with $\overline{\nu_e}$, we perform new calculations of the neutrino-induced reaction cross sections using a QRPA model [19] and a Hauser-Feshbach calculation with a CCONE nuclear reaction calculation code [20]. This QRPA method has been successfully applied to describe the relevant neutrino-induced reaction data for ^{138}La and ^{180}Ta [21]. We generated the ground state and excited states of the target nucleus by applying a one-quasiparticle creation operator to the even-even core nucleus that was assumed to be in the Bardeen-Cooper-Schrieffer ground state. We include neutron-proton (np) pairing as well as neutron-neutron (nn) and proton-proton (pp) pairing correlations to treat odd-A and odd-odd nuclei in the same framework. In medium or medium-heavy nuclei, the np pairing is usually expected to contribute to some extent for the relevant transitions because of the small energy gaps between the proton and neutron energy spaces. For two-body interactions inside nuclei, the Brueckner G matrix was employed by solving the Bethe-Salpeter equation based upon the Bonn CD potential for the nucleon-nucleon interactions in free space.

A nucleus populated by a neutrino-induced reaction can decay to its ground state by the emission of a γ-ray or a cascade of γ-rays. Furthermore, if the excitation energy of a populated state in a compound nucleus is higher than the particle threshold, it can decay to another nuclide by the emission of a particle such as a proton or neutron. Thus, the final residual abundance is determined by the branching ratios for various decays from excited states. These branching ratios were calculated using a Hauser-Feshbach calculation with the CCONE code [20]. Figure 2 shows the calculated energy-averaged cross sections for Fermi-Dirac distributions of negligible chemical potential. This result shows that the cross section for the ^{99}Ru($\overline{\nu}_e$, e$^+$n)^{98}Tc reaction is larger than that of the ^{100}Ru($\overline{\nu}_e$, e$^+$2n)^{98}Tc reaction by an order of magnitude. Before the SN explosion, the ^{98}Tc nucleus is produced by the nucleosynthesis reaction flow of ^{96}Ru(n, γ)^{97}Ru(EC decay)^{97}Tc(n, γ)^{98}Tc in the weak s-process. Because the critical neutron capture reaction cross sections on the unstable isotopes ^{97}Ru, ^{97}Tc, and ^{98}Tc have not been measured, we systematically calculate the cross sections of isotopes including these nuclides in the A=90 mass region using a Hauser-Feshbach code [22], where systematic behavior of model parameters is investigated by looking at the experimentally known capture cross sections on nearby isotopes. We also include resonances whenever the resonance parameters are available.

We calculate ν-process production rates using a core-collapse SN model for 1987A [23]. We use a 6 $M_\odot$ He star as the progenitor with an explosion 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 the evolution of the progenitor star including the weak s-process, and used the resultant mass distribution of heavy isotopes as seed nuclei in the He, C/O, and O/Ne/Mg-rich shells [24]. We use the supernova hydrodynamical model 14E1 [25] that reproduces the light curve of SN 1987A.

The average temperature of the neutrinos is a critical input for ν-process nucleosynthesis. In a previous study [9], based upon the SN calculations of Heger et al. 2005 [2], it has been shown that the solar abundances of the two heavy ν-process nuclides ^{138}La and ^{180}Ta can be produced in the correct relative abundances by a ν-process with an averaged electron and anti-electron neutrino energy of kT = 4 MeV and an average neutrino energy for the other four neutrinos of kT =6 MeV. However, previous studies [6, 7] for the energy spectra of neutrinos emitted from proto-neutron stars have suggested the following energy hierarchy: $\langle\nu_e\rangle < \langle\overline{\nu}_e\rangle < \langle\nu_{\mu,\tau}, \overline{\nu}_{\mu,\tau}\rangle$. Thus, we here 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. This temperature set was also used in the previous study of [3].

Figure 3(a) shows the calculated mass fractions. In general, the neutrino-induced reaction rate is proportional to the material density which decreases with increasing mass coordinate. In the mass coordinate regions of 2.2 $M_\odot < M <$ 3.7 $M_\odot$ and 4.3 $M_\odot < M <$ 6.0 $M_\odot$, the ^{98}Tc abundance slightly decreases with increasing mass coordinate. To estimate the contribution of the neutrino-induced reactions, we present the result without all neutrinos, where the luminosities of the neutrinos are set to zero [see the dashed line in Fig. 3(b)]. This indicates that ^{98}Tc is predominantly produced by the neutrino-induced reactions. A small peak around the mass coordinate of M = 2 $M_\odot$ is due to production by the γ-process [16, 17] [see the dashed line in Fig. 3(b)], although its contribution is lower than that of the neutrino-induced reactions. In layers deeper than M = 1.8, newly synthesized isotopes are again destroyed by photodisintegration reactions because of the high temperature. These trends are similar to the calculated results for heavy ν-process isotopes in previous studies [2, 10].

Integrating the layers within the mass range of 1.8 $M_\odot < M < 6.0$ $M_\odot$, we obtain masses of 1.2×10^{-12} and 4.7×10^{-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 of electron anti-neutrinos to ^{98}Tc is relatively large compared to that to other heavy ν-process isotopes. To investigate quantitatively its contribution, we also calculate the ^{98}Tc production using the SN model without $\overline{\nu_e}$, where we set only the luminosity of $\overline{\nu_e}$ to zero. The ^{98}Tc abundance without $\overline{\nu_e}$ is lower than that with all neutrinos in most layers [see Fig. 3(b)]. The integrated mass fraction of ^{98}Tc in the mass range of 1.8 $M_\odot < M < 6.0$ $M_\odot$ is 9.4×10^{-13} $M_\odot$. By comparing the mass of 9.4×10^{-13} $M_\odot$ with 1.2×10^{-12} $M_\odot$ obtained by a calculation with all neutrino reactions included, one can deduce that the fraction of contribution from the electron anti-neutrinos to the total production is approximately 20%. This unique result indicates that the ν-process synthesis of ^{98}Tc is sensitive to the temperature of the electron anti-neutrinos. As noted previously, the contributions of the electron anti-neutrino to the total production of the other heavy ν-isotopes are only approximately 1−4%. Therefore, ^{98}Tc is a potential unique new probe for estimating the electron anti-neutrino temperature.

To evaluate the abundance ratio of ^{98}Tc/^{98}Ru at the time of SSF, one should consider the mixing between the ejecta from the SN and the ambient solar material. In a previous study [10], a late input model was adopted to explain the initial solar abundance of ^{92}Nb. In this scenario, radioisotopes are produced by the single injection of material from a nearby SN before the SSF or at an early stage of SSF; the material ejected from the last SN will be diluted and then mixed with the collapsing protosolar cloud. In the late input model, the abundance ratio of ^{98}Tc/^{98}Ru at SSF can be obtained [26] from:

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

where $N(^{98}\mathrm{Tc})_{SN}$ and $N(^{98}\mathrm{Ru})_{SN}$ are the number 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 event until the mixing with the protosolar cloud, and f is a dilution fraction, i.e., the fraction of the ejected material that mixes with the final protosolar cloud of 1 $M_\odot$. Values of the dilution factor based upon other radioisotopes such as ^{26}Al and ^{53}Mn [26, 27] vary from 7×10^5 to 2×10^3. The time scale evaluated from these radioisotopes falls within the range of 1×10^6−5×10^7 y [26, 27]. Hayakawa et al. [10] reproduced the initial solar abundance ratio of ^{92}Nb/^{93}Nb $\simeq 10^{-5}$ [11, 28] with $\Delta = 10^6$ or 3×10^7 y and $f = 3\times10^{-3}$.

Because the half-life of ^{92}Nb is too long to estimate Δ precisely in the range of 10^6–10^8 y, the ^{92}Nb abundance is not sensitive to Δ. In contrast, ^{98}Tc whose half-life is a factor of 9 shorter than that of ^{92}Nb is more sensitive to Δ. We consider that ^{98}Tc produced in all layers in the mass range throughout 1.7 $M_\odot$ < M < 6.0 $M_\odot$ and that material is homogenously mixed into the pre-solar materials. We calculate the ^{98}Tc/^{98}Ru initial ratio using the parameters used for ^{92}Nb. The calculated ratios with the ^{98}Tc mass of 1.2×10^{-12} $M_\odot$ produced by the ν-process and $f = 3\times10^{-3}$ are ^{98}Tc/^{98}Ru = 2.9×10^{-5} and 2.4×10^{-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} [15]. Thus, when the initial ratio of ^{98}Tc/^{98}Ru is measured, ^{98}Tc could be used as nuclear cosmochronometer to measure the duration time from the last core-collapse SN to the SSF. Furthermore, if the duration time is precisely evaluated using other chronometers such as ^{26}Al and ^{53}Mn, ^{98}Tc can constrain the temperature of the electron anti-neutrino in SNe.

In summary, we have calculated the ^{98}Tc abundance using a SN ν-process model that includes neutrino-nucleus interactions based upon detailed nuclear structure calculations. The expected ratio of ^{98}Tc/^{98}Ru at SSF based upon a late input model is lower than the current measured upper limit. If the initial abundance ratio of ^{98}Tc/^{98}Ru could be precisely measured, the ^{98}Tc nuclear cosmochronometer could more precisely evaluate the duration from the last SN to the SSF. The contribution of the CC reaction with electron anti-neutrino to the total ^{98}Tc production has been estimated to be as much as 20%, leading to the conclusion that ^{98}Tc may be a unique new means to determine the average temperature of the electron anti-neutrino among the heavy ν-process isotopes. If the temperature of the electron anti-neutrinos emitted from proto-neutron stars were to be determined, it would be useful for understanding the SN explosion mechanism as well as the neutrino oscillations, and for the prediction of astronomical observations of SN neutrinos.

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[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] T. Yoshida, T. Kajino, D. H. Hartmann, Phys. Rev. Lett. **94**, 231101 (2005).

[4] T. Yoshida et al., Astrophys. J. **649**, 319 (2006).

[5] S. M. Austin, A. Heger, and C. Tur, Phys. Rev. Lett. **106**, 152501 (2011).

[6] M. T. Keil, G. G. Raffelt, and H.-T. Janka, Astrophys. J. **590**, 971 (2003).

[7] T. Fischer, G. Martinez-Pínedo, M. Hempel, and M. Liebendörfer, Phys. Rev. D **85**, 083003 (2012).

[8] C. Kobayashi, N. Izutani, A. I. Karakas, T. Yoshida, D. Yong, and H. Umeda, Astrophys. J. Leqtt. **739**, L57 (2011).

[9] T. Hayakawa, T. Kajino, S. Chiba, G.J. Mathews, Phys. Rev. C, **81**, 052801 (2010).

[10] T. Hayakawa, K. Nakamura, T. Kajino, S. Chiba, N. Iwamoto, M.K. Cheoun, G.J. Grant, Astrophys. J. **779**, L9 (2013).

[11] T. Iizuka, Y. J. Laib, W. Akram, Y. iAmelin, M. Schönbächler, Earth Plan. Sci. Lett. **439**, 172 (2016).

[12] N. Dauphas, T. Rauscher, B. Marty, L. Reisberg, Nucl. Phys. A **719**, 287c (2003).

[13] C. Travaglio, R. Gallino, T. Rauscher, N. Dauphas, F. K. Rópke, and W. Hillebrandt, Astrophys. J. **795**, 141 (2014).

[14] 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).

[15] H. Becker, R. J. Walker, Chem. Geol. **196**, 43 (2003).

[16] S. E. Woosley and W. M. Howard, Astrophys. J. Suppl. **36**, 285 (1978).

[17] T. Hayakawa, N. Iwamoto, T. Shizuma, T. Kajino, H. Umeda, and K. Nomoto, Phys. Rev.

Lett. **93**, 161102 (2004).

[18] K. Langanke, G. Martinez-Pínedo, P. von Neumann-Cosel, A. Richter, Phys, Rev. Lett. **93**, 202501 (2004).

[19] M. -K. Cheoun, E. Ha, T. Hayakawa, S. Chiba, K. Nakamura, T. Kajino, G. J. Mathews, Phys. Rev. C, **85**, 065807 (2012).

[20] O. Iwamoto, N. Iwamoto. S. Kunieda, F. Minato, K. Shibata, Nucl. Data sheets, **131**, 259 (2016).

[21] M. -K. Cheoun, E. Ha, T. Hayakawa, T. Kajino, S. Chiba, Phys. Rev. C, **82**, 035504 (2010).

[22] T. Kawano, P. Talou, M. B. Chadwick, T. Watanabe, J. Nucl. Sci. Technol., 47, 462 (2010).

[23] T. Shigeyama, K. Nomoto, M. Hashimoto, Astrophys. Astronm. **196**, 141 (1988).

[24] Y. Kikuchi, M. Hashimoto, M. Ono, F. Fukuda Prog. Theor. Exp. Phys. **2015(6)**, 063E01 (2015).

[25] S. Blinnikov, P. Lundqvist, O. Bartunov, K. Nomoto, K. Iwamoto, Astrophys. J. **532**, 1132 (2000).

[26] A. Takigawa, J. Miki, S. Tachibana, G. R. Huss, N. Tominaga, H. Umeda, and K. Nomoto. Astrophys. J. **688**, 1382 (2008).

[27] B. S. Meyer and D. D. Clayton, Space Sci. Rev. **92**, 133 (2000).

[28] M. Schönbächler, M. Rehkämper, A. N. Halliday, D. C. Lee, M. Bourot-Denise, B. Zanda, B. Hattendorf, D. Günther, Science **295**, 1705 (2002).

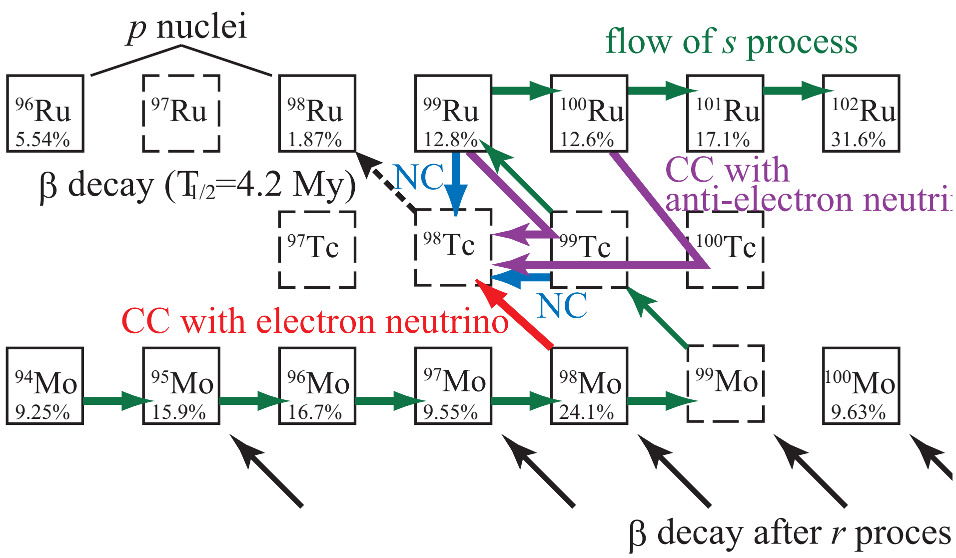

FIG. 1. Partial nuclear chart around ^{98}Tc and associated nucleosynthesis flows. Most Mo and Ru isotopes are synthesized by both the s and r-processes. Because the half-live of ^{99}Mo is only 2.7 d, ^{99}Tc is produced by the weak s-process before the SN explosion. At the SN explosion, ^{98}Tc nuclei are produced by the neutral current reactions of ^{99}Ru and ^{99}Tc. The dominant channel is the charged current reaction of ^{98}Mo. ^{98}Tc is also produced by the charged current reactions of electron anti-neutrinos on ^{99}Ru and ^{100}Ru.

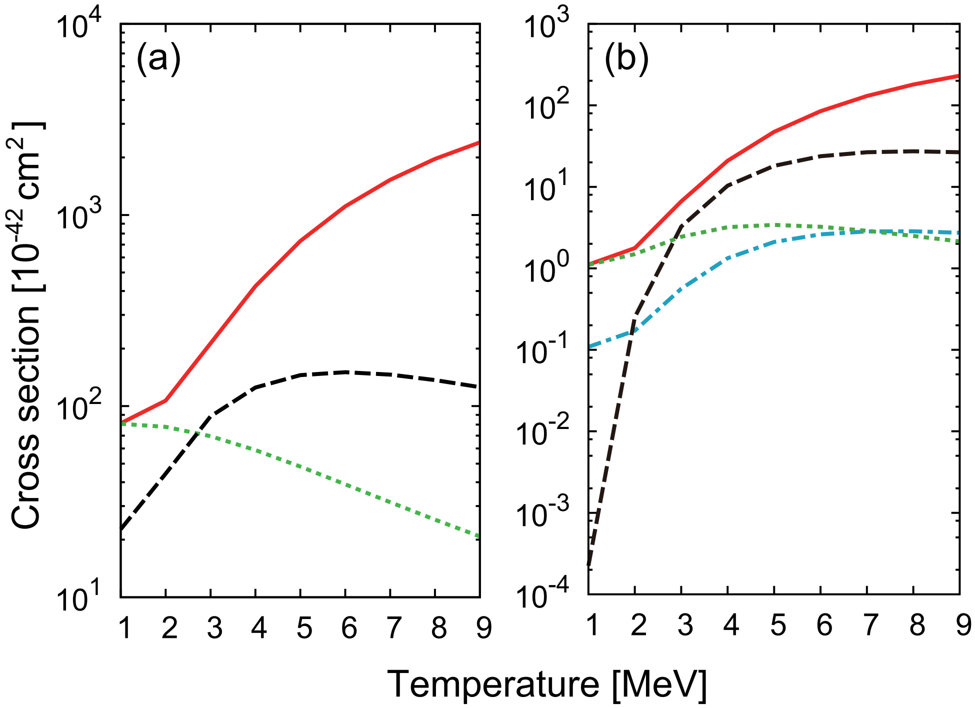

FIG. 2. Calculated average temperature-dependent neutrino-induced cross sections for ^{98}Tc. (a) The charged current reactions with electron anti-neutrinos on ^{99}Ru. (b) The charged current reactions with electron anti-neutrinos on ^{100}Ru. The dashed line denotes the cross section for the production of ^{98}Tc. The dotted and solid lines are the cross section for the production of ^{99}Tc and the total cross section, respectively. The dashed-dot line shows the cross section for ^{100}Tc.

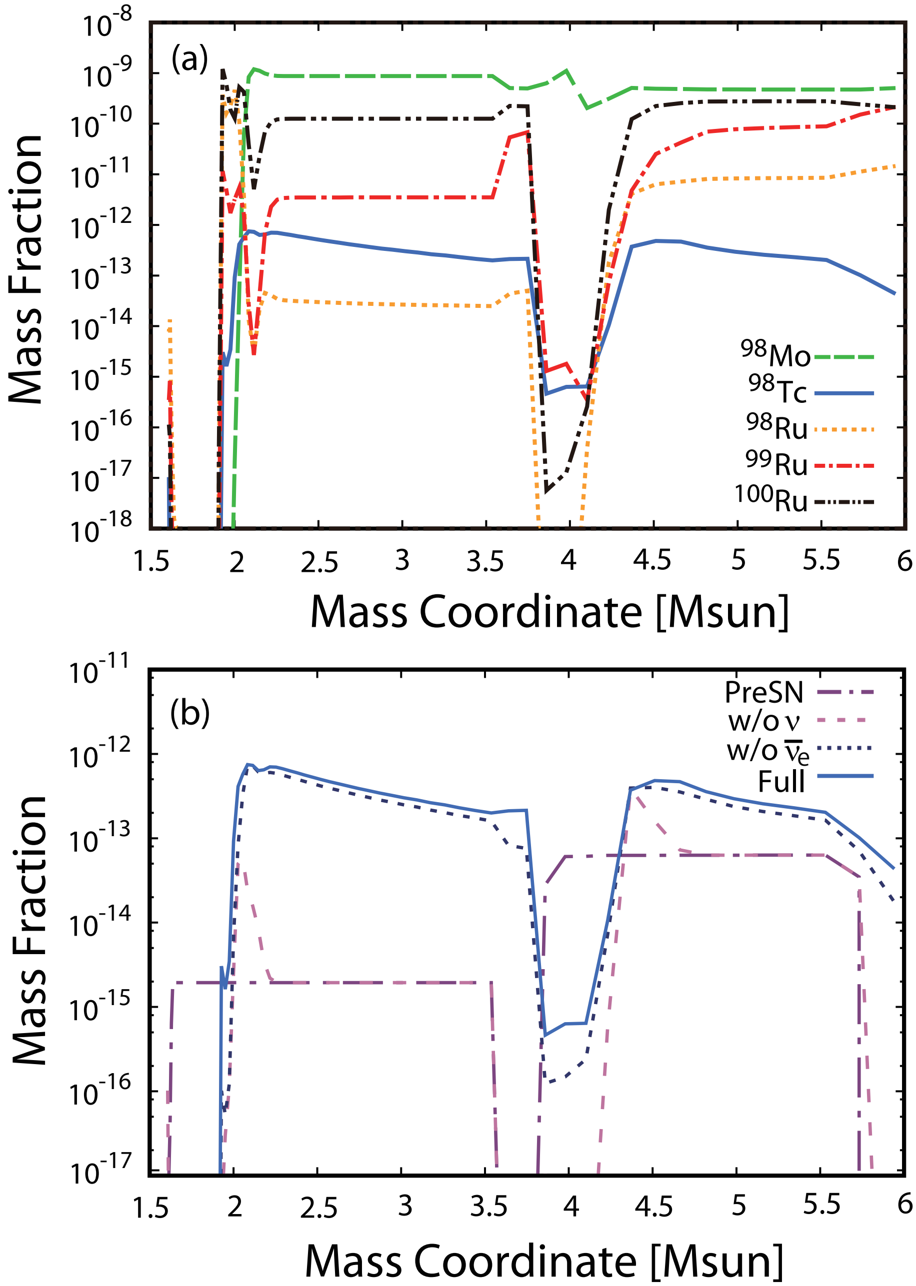

FIG. 3. (a) Calculated abundances as a function of interior mass from the SN ν-process with a 1987A SN model. The solid line (blue) denotes the abundance of ^{98}Tc. The dashed-line (green), dot line (yellow), dashed-two dot line (red), and dashed-dot line (black) show the abundances of ^{98}Mo, ^{98}Ru, ^{99}Ru, and ^{100}Ru, respectively. (b) ^{98}Tc abundances under various neutrino conditions. The dashed-line (light purple) and dot line (dark blue) denote the abundance calculated without all neutrinos and without electron anti-neutrinos, respectively. The dashed-dot line (purple) shows the abundance before SN explosion. (A color version of this figure is available in the online journal.)