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Supernova Neutrino Process and Sensitivity To Neutrino Temperatures

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Some rare isotopes are produced by neutrino-induced reactions in supernova (SN) explosions (ν-process). The isotope ^{92}Nb decays to ^{92}Zr with a half-life of 3.47 $\times$ 10^7 years. Although this isotope does not exist in the present solar system, the initial abundance ratio for ^{92}Nb/^{93}Nb at the time of solar system formation (SSF) have been measured in primitive meteorites. The astrophysical origin of ^{92}Nb, however, has remained unknown. The SN ν-process origin for ^{92}Nb has been proposed and the SN calculation has demonstrated the ν-process origin of ^{92}Nb. The abundances of ν-isotopes depend on neutrino temperatures. In the calculation, the average energies of kT = 3.2, 4.0, 6.0 MeV for the electron neutrino, anti-electron neutrino, and the other neutrinos (ν_μ and ν_τ), respectively, were used. The observed ratio of ^{92}Nb/^{93}Nb $\sim 10^{-5}$ can be explained by the ν-process.

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1. Introduction

The neutrino process in supernova explosions (ν-process) has been proposed as the astrophysical origin of some rare isotopes such as^{7}Li, ^{11}B, ^{19}F, ^{138}La, and ^{180}Ta [1, 2]. During core-collapse supernovae, a huge number of neutrinos are emitted from the proto-neutron star (see Fig. 1). When these neutrinos pass through outer layers of the star they can induce nuclear reactions on pre-existing nuclei. The ν-process can only play a significant role in the syntheses of isotopes which are bypassed by other major processes such as rapid neutron capture processes (r-process) and slow neutron capture processes (s-process). Among elements heavier than iron, two isotopes of ^{138}La and ^{180}Ta have been candidates for the ν-isotopes, because their isotopic abundances are rare and they cannot be produced by either r-process or s-process. However, previous ν-process calculations could not systematically explain the solar abundances of ^{180}Ta and ^{138}La. This originated from the fact that the 1^+ ground state of ^{180}Ta decays with a half-life of only 8.15 h, while the naturally occurring state is the 9^- ^{180}Ta isomer with a half-life $> 10^{15}$ years. In the ν process, low-spin excited states in ^{180}Ta are strongly populated from ^{180}Hf by Gamow-Teller transitions and subsequently decay preferentially to the 1^+ ground state [2, 3]. However, in a high temperature photon bath, the meta-stable isomer is excited from the ground state by (γ, γ') reactions through highly excited states. Moreover, the transition rate between the ground state and the isomer is affected by the changing temperature. Therefore, the final isomeric branching ratio should be evaluated by a time-dependent calculation. In the previous study [4], Hayakawa et al. introduced a new model in which the ground state and the isomer are treated as two different nuclides which are independently thermalized with dependence on environment temperature, and they are weakly linked by (γ, γ') transitions. With experimental values for the transition strengths It was found that the neutrino process reproduces systematically the solar abundances of ^{138}La and ^{180}Ta using a new time-dependent isomer population model with a ν process with electron neutrino temperature of kT = 4 MeV and other neutrino temperature of kT = 6 MeV.

The radioactive isotope ^{92}Nb decays to the daughter nucleus ^{92}Zr by β decay with a half-life of 3.47×10^7 years. ^{92}Nb does not exist in the present solar system. However, Harper et al. [**?**] have found that an isotopic abundance anomaly of ^{92}Zr in primitive meteorites corresponding to an excess of the abundance of ^{92}Zr produced by β decay of ^{92}Nb after being incorporated into primitive solar system material. This indicates that ^{92}Nb exited at the time of the solar system formation (SSF). Radionuclides with half-lives in the range of $10^6 - 10^8$ years can be used as nuclear cosmochronometers [5] to measure the time from the last nucleosynthesis event [such as a supernova (SN) explosion or s-process in an asymptotic giant branch (AGB) star] to the SSF. Thus, ^{92}Nb has the potential to be used as a similar nuclear chronometer. However, there have been two critical unresolved problems. First, there is a controversy in that the inferred initial abundance ratios for ^{92}Nb/^{93}Nb at the time of SSF cluster around two different values: one is near 10^{-3} [**?**, 6, 7]; while the other is near 10^{-5} [8, 9]. Second, the astrophysical origin for the synthesis of ^{92}Nb has remained an unsolved problem [10, 11]. Hayakawa et al. [12] proposed the ν-process origin of ^{92}Nb and presented that the initial ratio of ^{92}Nb/^{93}Nb = 10^{-5} can be explained by the ν-process in a supernova happened $10^6 - 3\times10^7$ years before SSF.

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[†]A footnote may follow.

It should be stressed that ^{92}Nb cannot be synthesized by either β^+ (or electron capture) or β^- decay due to the presence of the stable isobars ^{92}Mo and ^{92}Zr. Thus, ^{92}Nb can only be synthesized by direct nuclear reactions such as the (γ, n) reaction on ^{93}Nb. In contrast, most other isotopes of Zr, Nb, and Mo are produced by known nucleosynthesis mechanisms such as the s-process or r-process. Therefore, whatever stellar process produces ^{92}Nb, it should synthesize ^{92}Nb selectively. Indeed, models have been proposed to account for the measured ^{92}Nb/^{93}Nb in the early solar system. These include photodisintegration reactions in supernovae (the so-called γ process or p process) [10] and the mechanism of alpha-rich freezeout in supernovae [11]. These models, however, cannot explain consistently the observed abundance of ^{92}Nb, without overproducing other nuclides.

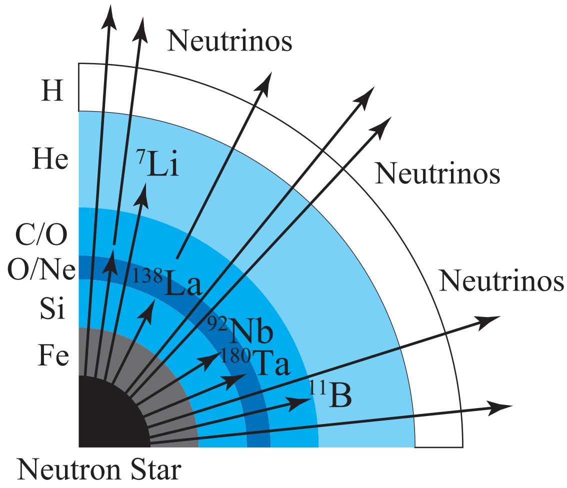

Figure 1: Schematic view of supernova neutrino process. During core-collapse supernovae, a huge number of neutrinos are emitted from the proto-neutron star. A fraction of neutrinos can induce nuclear reactions on pre-existing nuclei in outer layers.

2. Calculation

2.1 Neutrino-nucleus interactions

Neutrino-nucleus interactions are key physics for understanding the ν-process. However, individual neutrino reaction cross sections depend on the detailed nuclear structure of the nuclei involved [13]. Because the neutrino-induced reaction cross-sections are extremely small, it is almost impossible to measure their cross sections for many nuclei. Therefore, we should calculate the cross sections using nuclear structure models based on experimental data. The previous studies [1, 2, 3] presented that the ν isotopes such as ^{138}La and ^{180}Ta are predominantly produced by two neutrino-induced reactions of the neutral current reaction and the charged current reaction. Thus, ^{92}Nb can also be produced by these reactions. Figure 2 shows a schematic view of the charged current reaction of ^{92}Zr(ν_e, e$^-$)^{92}Nb and the neutral current reaction of ^{93}Nb(ν, ν'n)^{92}Nb. In the neutral current reaction, at first a nucleus ^{93}Nb is excited by a neutrino and subsequently the excited state decays to the ground state or an excited state in the residual nucleus ^{92}Nb by the emission of a neutron when the excitation energy of ^{93}Nb is higher than the neutron separation threshold of ^{93}Nb. The neutral current reaction can be caused by 6 types of neutrinos, ν_e, ν_τ, ν_ν, and their anti-neutrinos. On the other hand, the charged current reaction can be caused by only the electron neutrino and electron anti-neutrino. At first, by the charge exchange reaction on ^{92}Zr, an excited state in ^{92}Nb is populated and subsequently it decays to the ground state of ^{92}Nb. It is known that the Gamow-Teller transition is dominant in the absorption of neutrinos. Thus, 1^+ states are predominantly excited in the case of a 0^+ nucleus. Therefore, the magnetic-dipole (M1) strength (or level density of 1^+ states) is of importance for the estimation of interaction strengths between neutrinos and nuclei with spin and parity of 0^+.

For the present application we have utilized rates for these two reactions calculated using the Quasiparticle Random Phase Approximation (QRPA) with neutron-proton pairing as well as neutron-neutron, and proton-proton pairing correlations [14]. This QRPA method has been successfully applied to describe the relevant neutrino-induced reaction data for ^{12}C [15], ^{138}La, and ^{180}Ta [16]. For the ^{93}Nb(ν, ν'n)^{92}Nb reaction, we generated the ground state and excited states of the odd-even nucleus ^{93}Nb by applying a one quasiparticle creation operator to the even-even nucleus ^{92}Zr which was assumed to be in the BCS ground state. For the neutral current reaction, the cross sections of the ^{92}Zr(ν_e, e$^-$)^{92}Nb reaction are larger than those of the ^{93}Nb(ν, ν'n)^{92}Nb reaction by approximately 2 orders of magnitude. Among the charged current reactions, the synthesis of ^{92}Nb via ^{92}Zr(ν_e, e$^-$)^{92}Nb is the dominant reaction rate, whereas the production rate of ^{92}Nb from the neutral current reactions is less than those of other nuclides. This result shows that the charged current reaction plays a dominant role in the production of ^{92}Nb.

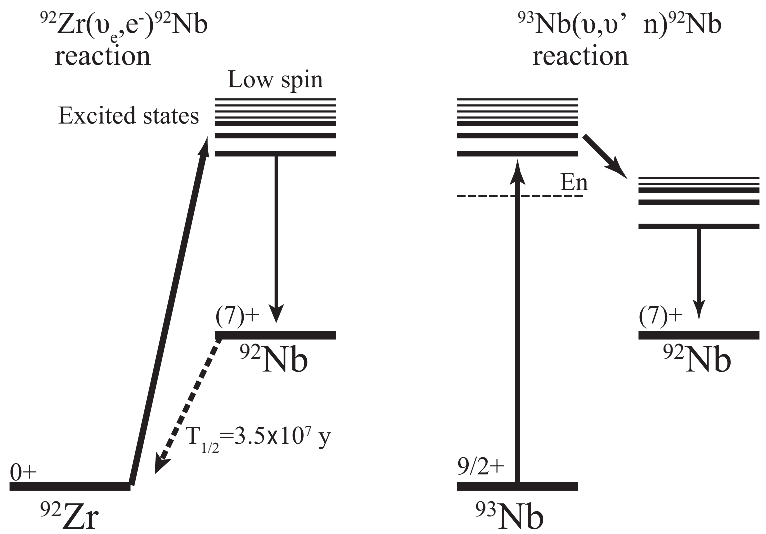

Figure 2: Schematic view of neutrino-induced reactions for ^{92}Nb. ^{92}Nb is predominantly produced by the charged current reaction and the neutral current reaction.

2.2 Supernova model

We calculated the production rate in the ν-process using a core-collapse SN model [17]. We used a 15 solar mass progenitor model with an explosion kinetic energy of 10^{51} erg. A huge number of energetic neutrinos are emitted from the proto-neutron star formed during a core-collapse supernova. We assumed that the total energy in emitted neutrinos was 3×10^{53} ergs and the decay constant of the neutrino flux was 5 s. As the initial composition of the progenitor star, the solar abundances were adopted. The mass distribution of heavy seed nuclei in the C and O/Ne shells was affected by the carbon-burning weak s-process. The average temperature of the neutrinos is critical for the ν-process production of elements. In our previous study [4], it was shown that that the solar abundances of the two heavy nuclides ^{138}La and ^{180}Ta based upon the SN calculations of Heger et al. [2] could be best produced by a ν process with an average neutral-current neutrino temperature of kT = 6 MeV and a charged-current neutrino temperature of kT = 4 MeV. The successful nucleosynthesis of r-process elements in the SN neutrino-driven winds required a neutron-rich environment, which was best achieved if the electron neutrino temperature is slightly lower than the anti-electron neutrino temperature [18]. Hence, we used the average energies of kT = 3.2, 4.0, 6.0 MeV for electron neutrino, anti-electron neutrino, and neutral current neutrinos, respectively.

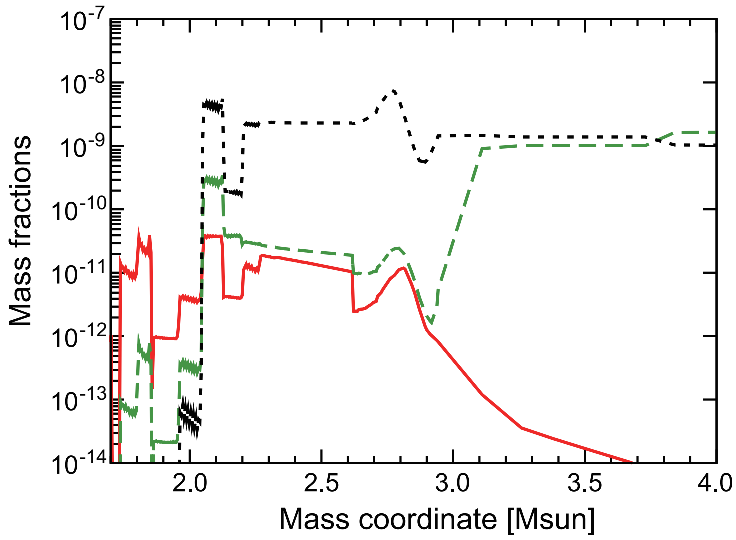

Figure 3: Calculated abundances as a function of interior mass from the supernova ν-process for a 15 solar mass progenitor star with solar metallicity, and an explosion kinetic energy of 10^{51} erg. The solid-line (red) and dashed-line (green) denote the abundances of ^{92}Nb and ^{93}Nb, respectively. The dot (black) line indicates the ^{96}Mo abundance.

3. Result and Discussion

The nucleus ^{92}Nb is synthesized by the ν process in the C- and O/Ne rich layers above the proto-neutron star. At the same time, however, some of the newly synthesized ^{92}Nb and the seed nuclei, ^{93}Nb and ^{92}Zr, are destroyed by (γ, n) reactions as the shock passes. Figure 3 shows residual abundances of the isotopes ^{92,93}Nb, and ^{96}Mo, which is a reference, after these processes. Because ^{96}Mo is shielded against both β^- and β^+ decays by stable isobars, it is predominantly produced by neutron capture in the *s* process. This figure shows that significant synthesis of ^{92}Nb can occur near the bottom of the carbon shell in the mass range of M = 1.9 $-$ 2.9 $M_\odot$ of the exploding star. Synthesized ^{92}Nb inside these layers is predominantly destroyed by (γ, n) reactions because of the high temperature. Because ^{92}Nb is predominantly synthesized in the outer layers in the mass range of M $>$ 1.9, it is likely that all of ^{92}Nb produced by neutrino-induced reactions will be ejected into the interstellar medium (ISM) by the SN explosion. Integrating these layers within the mass range of $1.9 < M < 2.9$ $M_\odot$, we obtain 1.1×10^{-11} $M_\odot$ of ^{92}Nb and 3.7×10^{-11} $M_\odot$ of ^{93}Nb, and hence the ^{92}Nb/^{93}Nb ratio is 3.0×10^{-1}. This ratio is higher than the observed ratios of ^{92}Nb/^{93}Nb = 10^{-5} $\sim 10^{-3}$ by at least two orders of magnitude.

Next, we considered a scenario in which a fraction of the newly synthesized Nb isotopes in the ejecta of the last nearby SN is well mixed with the proto-solar material. ^{92}Nb decays out before the time of SSF. With the assumption that ejected material is well mixed with the preexisting material in the proto-solar cloud, then the abundance ratio is [19]

$$\frac{^{92}\mathrm{Nb}}{^{93}\mathrm{Nb}} = \frac{fN(^{92}\mathrm{Nb})_{SN}e^{-\Delta/\tau}}{N(^{93}\mathrm{Nb})_\odot + fN(^{93}\mathrm{Nb})_{SN}} \quad , \tag{3.1}$$

where $N(^{92}\mathrm{Nb})_{SN}$ and $N(^{93}\mathrm{Nb})_{SN}$ are the abundances in the SN ejecta and f is the dilution fraction, i.e. the fraction of the material that mixes with the proto-solar cloud of 1 $M_\odot$. Values of the dilution fraction f based upon other short-lived radioisotopes [20, 21, 19] vary from $\sim 7 \times 10^{-5}$ to $\sim 2 \times 10^{-3}$. Thus, we used $f = 3\times10^{-3}$ as reasonable values for the late input scenario. This mixing is consistent with $f = 1.9\times10^{-3}$ with the 20 $M_\odot$ SN model invoked [19] to explain other radioisotopes, ^{26}Al, ^{41}Ca, ^{53}Mn, and ^{60}Fe, in meteoritic material. The quantity $N(^{93}\mathrm{Nb})_\odot$ is the initial number of ^{93}Nb in the collapsing cloud. The quantity Δ is the duration between the SN event and the mixing with the proto-solar cloud. The timescales have been previously estimated [22] from several short-lived r-process chronometers, for example ^{129}I, ^{107}Pd, and ^{182}Hf with half-lives within 10^6–10^8 years. The evaluated time scale falls within the range of 3×10^7 - 10^8 years [22]. We used $\Delta = 3 \times 10^7$ or 10^6 years for this calculation.

We obtained the ratios of 8.2×10^{-6} and 1.5×10^{-5} for $\Delta = 3 \times 10^7$ and 10^6 years, respectively. The measured ^{92}Nb/^{93}Nb ratio of 10^{-5} can be explained by a mixing factor of $f = 3 \times 10^{-3}$ and $\Delta = 3 \times 10^7$ or 10^6 years. However, the higher observed value of 10^{-3} can be reproduced if the 1 $M_\odot$ proto-solar cloud contains > 0.2 $M_\odot$ of material from the SN ejecta. A required mass of 0.2 $M_\odot$ is much larger than the 10^{-4} $M_\odot$ typically expected [20, 21, 19]. Therefore, this calculated result is only consistent with the lower value of 10^{-5}.

The previous study [2] presented that the abundances of the ν-isotopes are sensitive to energies of neutrinos. In this calculation, the ν-process model with average energies of kT = 3.2, 4.0, 6.0 MeV for electron neutrino, anti-electron neutrino, and neutral current neutrinos, respectively, were used. However, because the observed initial abundance of ^{92}Nb has a large uncertainty and the dilution fraction also has a large uncertainty, it is almost impossible to determine the ^{92}Nb abundance with dependence on the neutrino temperature at present. When the initial abundance of ^{92}Nb will be precisely measured and the dilution fraction will be constrained after the study of various nuclear cosmochronometers, the neutrino temperatures for the last SN will be determined.

4. Conclusion

The astrophysical origin of a short-lived radioactivity ^{92}Nb has been an open question. We have proposed a single last SN ν-process provided ^{92}Nb to the proto solar materials and calculated the abundance using a detailed SN simulation. The observed ratio of 10^{-5} can be explained by mixing of 3×10^{-3} $M_\odot$ of the SN ejecta with the 1 $M_\odot$ proto-solar material.

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