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SUPERNOVA NEUTRINO NUCLEOSYNTHESIS OF THE RADIOACTIVE ^{92}Nb OBSERVED IN PRIMITIVE METEORITES

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ABSTRACT

The isotope ^{92}Nb decays to ^{92}Zr with a half-life of 3.47×10^7 yr. Although this isotope does not exist in the current solar system, initial abundance ratios for ^{92}Nb/^{93}Nb at the time of solar system formation have been measured in primitive meteorites. The astrophysical origin of this material, however, has remained unknown. In this Letter, we present new calculations which demonstrate a novel origin for ^{92}Nb via neutrino-induced reactions in core-collapse supernovae (ν-process). Our calculated result shows that the observed ratio of ^{92}Nb/^{93}Nb $\sim 10^{-5}$ can be explained by the ν-process.

Key words: meteorites, meteors, meteoroids – neutrinos – supernovae: general

Online-only material: color figures

1. INTRODUCTION

Short-lived radionuclides (SLRs) with half-lives of 10^5–10^8 yr have been used as nuclear cosmochronometers (Wasserburg et al. 1996) to study the history of the formation of the solar system and to measure the time from the last nucleosynthesis event (such as a supernova (SN) explosion or neutron-capture (*s*-process) synthesis in an asymptotic giant branch (AGB) star) to the time of solar system formation (SSF). The free decay time of 3×10^7–10^8 yr from the last SN event to the time SSF has been estimated (Dauphas 2005) by using several short-lived *r*-process chronometers. One of the major possible sources of SLRs involves a SN as the trigger for the collapse of the pre-solar cloud (Huss et al. 2009). An initial solar abundance of ^{60}Fe has also been reported and a late input, ejecta from a nearby SN into the proto-planetary disk or the molecular cloud after the start of the collapse, was proposed (Ouellette et al. 2007; Takigawa et al. 2008). Recently, however, Tang & Dauphas (2012) showed that the abundance of ^{60}Fe can be explained by the accumulated background of the Galaxy. On the other hand, they suggested that the observed abundance of ^{26}Al requires some sort of local ejecta such as winds from massive stars (Tang & Dauphas 2012). Hence, the detailed history of the pre-solar and early SSF continues to require some sort of late time injection.

Of interest to the present study is the SLR ^{92}Nb. This nuclide decays to the daughter nucleus ^{92}Zr by β decay with a half-life of 3.47×10^7 yr. ^{92}Nb does not exist in the present solar system. However, Harpper (1996) found evidence of its existence in early solar-system material. An isotopic abundance anomaly of ^{92}Zr in primitive meteorites was observed corresponding to an excess of the abundance of ^{92}Zr produced by the in situ β decay of ^{92}Nb after being incorporated into primitive solar system material. Hence, ^{92}Nb has the potential to be used as a nuclear chronometer. There have been, however, two critical unresolved problems regarding this isotope. First, the astrophysical site for the synthesis of ^{92}Nb has remained an unsolved problem (Dauphas et al. 2003; Meyer 2003). To utilize this SLR as a cosmochronometer, therefore, one should first understand the astrophysical origin of ^{92}Nb. Second, the inferred initial abundance ratios for ^{92}Nb/^{93}Nb $\sim 10^{-5}$ (Harpper 1996; Schönbächler et al. 2002, 2005) were measured, but much higher ratios of 10^{-3} were also reported (Yin et al. 2000; Münker et al. 2000; Yin & Jacobsen 2002) although in a recent review (Dauphas & Chaussidon 2011) only the lower value of 10^{-5} was adopted as the currently preferred value.

Figure 1 shows a partial nuclear chart and typical nucleosynthesis reaction flows for isotopes with nuclear masses around $A = 92$. This illustrates why it is so difficult to account for the production of ^{92}Nb. Note, 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) or (ν, ν'n) reactions on ^{93}Nb. In contrast, most other isotopes of Zr, Nb, and Mo are produced by known nucleosynthesis mechanisms, mainly the rapid (r) and slow (s) neutron capture processes.

Therefore, whatever stellar mechanism produces ^{92}Nb, it should synthesize ^{92}Nb selectively. Several models have been proposed to account for the measured ^{92}Nb/^{93}Nb in the early solar system. These include photodisintegration reactions in SNe (the so-called γ-process or *p*-process) (Dauphas et al. 2003) and the mechanism of alpha-rich freezeout in SNe (Meyer 2003). However, the γ-process underproduces the observed abundance of ^{92}Nb and the alpha-rich freezeout cannot explain consistently the ^{92}Nb abundance, without overproducing other nuclides. In this Letter, therefore, we propose for the first time that direct neutrino reactions in core collapse SNe (ν-process) can naturally produce the observed abundance of ^{92}Nb. We present the first detailed core-collapse SN calculations of the synthesis of ^{92}Nb by neutrino interactions and show that this model can explain the lower value of the observed meteoritic ^{92}Nb isotopic anomaly.

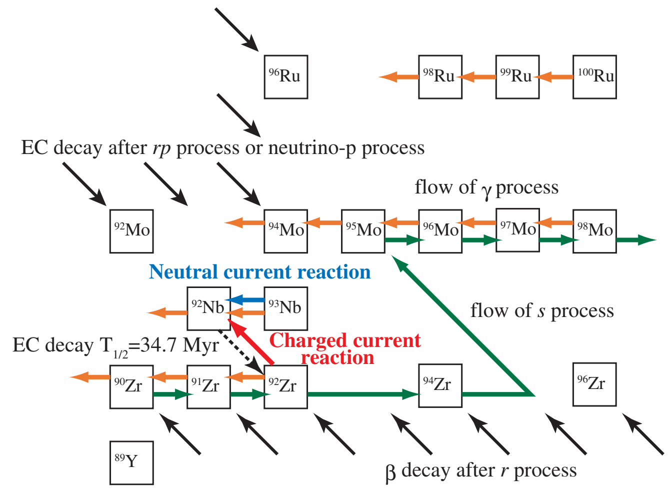

Figure 1. Partial nuclear chart around ^{92}Nb and the relevant nucleosynthesis flows. Most isotopes are produced by the *s*-process and/or beta-decay after the freeze out of the *r*-process. Note that ^{92}Nb cannot be synthesized by either process.

(A color version of this figure is available in the online journal.)

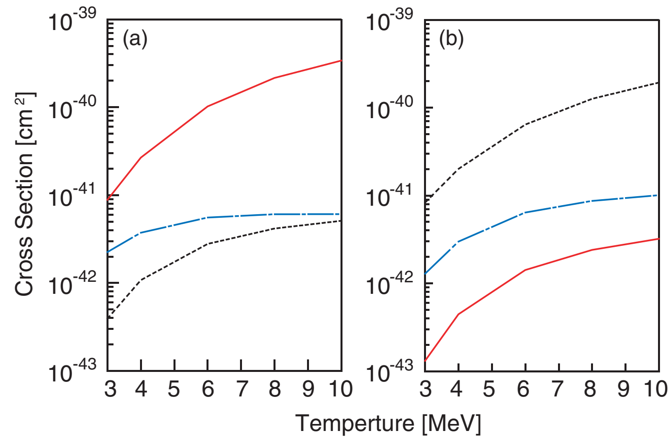

Figure 2. Calculated average temperature-dependent neutrino-induced cross sections for ^{92}Nb Cheoun et al. (2012). (a) The charged current reactions on ^{92}Zr. The solid line is the cross section for the production of ^{92}Nb. The dashed line and dot-dashed line are cross sections for the production of ^{91}Nb and ^{91}Zr, respectively. (b) The neutral current reactions on ^{93}Nb. The solid line shows the cross section for the synthesis of ^{92}Nb. The dashed line and dot-dashed line show cross sections for the production ^{93}Nb and ^{92}Zr, respectively.

(A color version of this figure is available in the online journal.)

2. NEUTRINO–NUCLEUS INTERACTIONS

The ν-process has been suggested (Woosley et al. 1990) as the mechanism for the origin of several other rare isotopes of light-to-heavy elements. Copious amounts of energetic neutrinos are emitted from the proto-neutron star formed during a core-collapse SN. As these neutrinos pass through the star they can induce nuclear reactions on atomic nuclei in the outer layers. Although many nuclides can experience neutrino-induced reactions, the produced abundances are usually negligibly small compared to production by other major nucleosynthesis processes such as the *s* or *r*-process. Hence, other SLRs like ^{26}Al and ^{60}Fe are unaffected. Thus, the ν-process can only play a significant role in the synthesis of rare isotopes which otherwise cannot be produced by the major processes. For example, among the heavy nuclides, only the two isotopes ^{138}La and ^{180}Ta are thought to be synthesized primarily by the ν-process (Woosley et al. 1990; Heger et al. 2005; Byelikov et al. 2007).

One of the key inputs for ν-process nucleosynthesis is a set of neutrino-induced nuclear reaction cross sections. Experimental measurements of neutrino–nucleus interactions for heavy nuclei are almost impossible because the associated weak reaction cross-sections are extremely small. Thus, one must rely on calculated cross sections. However, individual neutrino reaction cross sections depend on the detailed nuclear structure of the nuclei involved (Langanke et al. 2004). Thus, it is necessary to calculate the relevant cross-sections using detailed nuclear structure models. Previous studies for ^{138}La and ^{180}Ta (Woosley et al. 1990; Heger et al. 2005; Byelikov et al. 2007) have shown that the ν nuclei are predominantly synthesized by charged current (CC) and neutral current (NC) reactions. In the CC reaction, ^{92}Zr(ν_e, e$^-$)^{92}Nb, excited states with low spin in ^{92}Nb are the most important because those states are strongly populated by Gamow–Teller transitions from the 0$^+$ ground state of the ^{92}Zr seed nucleus. For the NC reaction, ^{93}Nb(ν, ν'n)^{92}Nb reaction, low spin states in ^{93}Nb are initially populated and subsequently decay to ^{92}Nb through the emission of a neutron. Thus, excited states in ^{93}Nb should be calculated using detailed nuclear structure models.

For the present application we have utilized rates for these two reactions calculated (Cheoun et al. 2012) using the quasiparticle random phase approximation (QRPA) with neutron–proton pairing as well as neutron–neutron, and proton–proton pairing correlations. This QRPA method has been successfully applied to describe the relevant neutrino-induced reaction data for ^{12}C (Cheoun et al. 2010b), as well as the heavy nuclides ^{138}La, and ^{180}Ta (Cheoun et al. 2010a). 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 that was assumed to be in the Bardeen–Cooper–Schrieffer ground state. Figure 2 summarizes all relevant calculated reaction rates on ^{93}Nb and ^{92}Zr. Among the possible CC 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 NC reactions is less than that for other nuclides. 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 about two orders of magnitude. This result shows that the CC reaction plays a dominant role in the production of ^{92}Nb. This trend is similar to that of ^{138}La and ^{180}Ta (Heger et al. 2005; Byelikov et al. 2007).

3. SUPERNOVA NEUTRINO PROCESS CALCULATION

We have calculated ν-process production rates using the core-collapse SN model of Rauscher et al. (2002). We use a 15 solar mass progenitor model with an explosion kinetic energy of 10^{51} erg. Solar abundances were adopted for the initial composition of the progenitor star. We then calculated a weak carbon-burning *s*-process, and used the resultant mass distribution of heavy isotopes as seed nuclei in the C and O/Ne shells after the weak *s*-process. The average temperature of the neutrinos is critical for the ν-process production of elements. In our previous study (Hayakawa et al. 2010), it was shown (based on the SN calculations of Heger et al. 2005) that the solar abundances of the two heavy nuclides ^{138}La and ^{180}Ta can be best produced in the correct relative abundances by a ν-process with an average ν_μ and ν_τ neutrino temperature of $kT = 6$ MeV and an averaged electron and anti-electron neutrino temperature of $kT = 4$ MeV. Similarly, the successful nucleosynthesis of *r*-process elements requires a neutron-rich environment in the

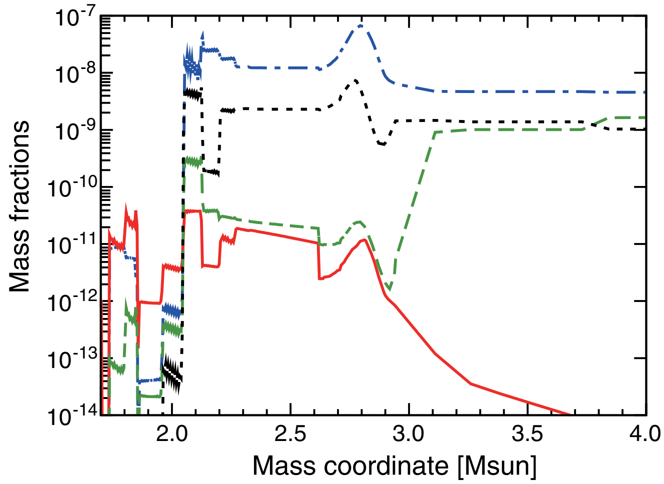

Figure 3. Calculated abundances as a function of interior mass from the supernova ν-process for a 15 solar mass progenitor star with solar metallicity, and an explosion kinetic energy of 10^{51} erg. The solid-line (red) and dashed-line (green) denote the abundances of ^{92}Nb and ^{93}Nb, respectively.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

(A color version of this figure is available in the online journal.)

SN neutrino-driven winds. This neutron-rich environment is best achieved if the electron neutrino temperature is slightly lower than the anti-electron neutrino temperature (Yoshida & Hashimoto 2004). Hence, we here take 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. The total energy in emitted neutrinos is set to 3×10^{53} erg and the neutrino flux is taken to exponentially decay with a time constant of 5 s. The results, however, are not particularly sensitive to these assumptions.

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, ^{92}Zr, and ^{96}Mo after these processes. 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. Deeper inside the star any synthesized ^{92}Nb is destroyed by photodisintegration reactions because of the high temperature. Since ^{92}Nb is synthesized in the outer layers it is likely that all of the ^{92}Nb produced there will be ejected into the interstellar medium (ISM) by the SN explosion. Integrating the layers within the mass range of $1.9M_\odot < \mathrm{M} < 2.9\ M_\odot$, we obtain masses of $1.1\times10^{-11}\ M_\odot$ for ^{92}Nb and $3.7\times10^{-11}\ M_\odot$ for ^{93}Nb. Hence, the ^{92}Nb/^{93}Nb ratio in the $1.0\ M_\odot$ shell is 3.0×10^{-1}. This ratio is much higher than the observed ratios of ^{92}Nb/^{93}Nb $= 10^{-5} \sim 10^{-3}$. However, to compare to the observed ratio, one should consider mixture with the protosolar cloud and the effects of the galactic chemical evolution.

3.1. *ISM Abundance*

We adopt a galactic chemical evolution calculation in the closed-box instantaneous recycling approximation with a slowly varying star formation rate function. We consider that both the *s*-process to produce ^{93}Nb and the ν-process to produce ^{92}Nb are secondary processes requiring the existence or prior heavy element seed material in the progenitor star. It is then straightforward (Huss et al. 2009) to show that the ratio of the mass fractions of radioactive ^{92}Nb to stable ^{93}Nb is:

$$\frac{Z_{92\mathrm{Nb}}}{Z_{93\mathrm{Nb}}} = \frac{2P_{92}}{P_{93}}\frac{\tau_{92}}{T}, \tag{1}$$

where the quantity $\tau_{92} = 50.1$ Myr is the mean lifetime of ^{92}Nb and $T = 10$ Gyr is the timescale for nucleosynthesis in the Galaxy prior to SSF. A similar result derives from the more general star formation and infall rates in analytic chemical evolution models (Huss et al. 2009).

For secondary nuclei requiring the existence of preexisting seed nuclei, the production factors are proportional to metallicity $Z(t)$, i.e.,

$$P_i = \int_{m_l}^{m_h} \epsilon_i Z(t)(m - m_r)\phi(m)dm \approx \epsilon_i Z(t)R_i \tag{2}$$

where ϵ_i is the efficiency for producing new species i from material of initial metallicity Z in the progenitor star. The quantities m_l and m_h denote the mass range of stars that produce nuclide i, m_r is the remnant mass for stars of progenitor mass m, $\phi(m) \sim m^{-2.3}$ is the initial mass function, and R_i is the returned fraction of material defined:

$$R_i = \int_{m_l}^{m_h} (m - m_r)\phi(m)dm, \tag{3}$$

In the above, the usual normalization $\int m\phi(m)dm = 1$ is employed.

For the production of ν-process ^{92}Nb, we take the range of SNe to be $m_l = 10$ to $m_h = 25$, and $m_r = 1.4$. This gives $R_{\mathrm{SN}} \approx 0.05$. For the *s*-process production of ^{93}Nb we note that this nuclide is thought to be dominantly produced by the main *s*-process in thermally pulsing AGB stars, we take the usual range of thermally pulsing stars with degenerate C-O cores to be $m_l = 1$ to $m_h = 7$, while $m_r = 0.15m + 0.38$ (Iben & Renzini 1983). This gives a returned fraction of $R_{\mathrm{AGB}} = 0.10$ We can estimate the production efficiency ϵ_{92} directly from our SN model with an initial metallicity of $Z_\odot = 0.02$. For ^{92}Nb we have

$$\epsilon_{92}Z_\odot = \frac{1.1\times10^{-11}M_\odot}{11M_\odot} \approx 1.0\times10^{-12}. \tag{4}$$

Hence, $\epsilon_{92} \approx 5\times10^{-11}$. To estimate the production efficiency of the *s*-process nucleus ^{93}Nb, it is adequate for our purposes to assume a constant star formation, so that the metallicity grows linearly in time, i.e., $Z = Z_\odot \cdot t/T$. We find that $\psi_0 = 0.33$ 1/Gyr for a present gas fraction of 10% in the Solar neighborhood. In non-constant analytic models (Huss et al. 2009), the equivalent normalization is 0.4 ± 0.2, depending upon the infall parameter and star formation rate. The mass fraction of ^{93}Nb then grows quadratically,

$$Z_{93\mathrm{Nb}} = R_{\mathrm{AGB}}\int P_{93}\psi(t)dt = \epsilon_{93}\frac{Z_\odot}{T}R_{\mathrm{AGB}}\psi_0\frac{t^2}{2}. \tag{5}$$

For a solar mass fraction of 2.2×10^{-9} for ^{93}Nb (Lodders 2003) when $t = T$, this gives $\epsilon_{93} = 0.7\times10^{-7}$.

Hence, at the time of SSF we have,

$$\begin{aligned}\frac{Z_{92\mathrm{Nb}}}{Z_{93\mathrm{Nb}}} &= \frac{2P_{92}}{P_{93}}\frac{\tau_{92}}{T},\\ &= \frac{2\epsilon_{92}R_{\mathrm{SN}}}{\epsilon_{93}R_{\mathrm{AGB}}}\frac{\tau_{92}}{T} \sim 4\times10^{-7}\end{aligned} \tag{6}$$

Table 1
The Fraction of ^{92}Nb is the Value Calculated by the Current Study, f is the Assumed Dilution Fraction, i.e., the Fraction of the Material That Mixes with the Protosolar Cloud of 1 $M_\odot$

The Fraction of ^{92}Nb	f	Δ	$[^{92}\mathrm{Nb}/^{93}\mathrm{Nb}]_{\mathrm{SSF}}$
1.1×10^{-11}	10^{-4}	3×10^{7}	2.8×10^{-7}
1.1×10^{-11}	10^{-4}	10^{6}	4.9×10^{-7}
1.1×10^{-11}	3×10^{-3}	3×10^{7}	8.2×10^{-6}
1.1×10^{-11}	3×10^{-3}	10^{6}	1.5×10^{-5}

Notes. Δ is the time interval from the last SN event to the time of SSF. $[^{92}\mathrm{Nb}/^{93}\mathrm{Nb}]_{\mathrm{SSF}}$ is the abundance ratio at SSF after a decay time Δ.

This ratio is more than an order of magnitude below the lower observed ratio of 10^{-5}. We therefore conclude that another mechanism to account for even the lower observed abundance is required.

4. LATE INPUT SCENARIO

We consider a scenario in which a significant contribution to the observed ^{92}Nb is produced by the single injection of material from a nearby SN before the SSF or at early stages of SSF. The material ejected from the last SN will be diluted and then mixed with the collapsing protosolar cloud. Assuming that the ejected material is well mixed with the pre-existing material in the protosolar cloud, the abundance ratio will be (Takigawa et al. 2008)

$$\left[\frac{^{92}\mathrm{Nb}}{^{93}\mathrm{Nb}}\right]_{\mathrm{SSF}} = \frac{f N(^{92}\mathrm{Nb})_{\mathrm{SN}} e^{-\Delta/\tau 92}}{N(^{93}\mathrm{Nb})_\odot + f N(^{93}\mathrm{Nb})_{\mathrm{SN}}}, \qquad (7)$$

where $N(^{92}\mathrm{Nb})_{\mathrm{SN}}$ and $N(^{93}\mathrm{Nb})_{\mathrm{SN}}$ are the abundances in the SN ejecta and f is the dilution fraction, i.e., the fraction of the material that mixes with the protosolar cloud of 1 $M_\odot$. The quantity $N(^{93}\mathrm{Nb})_\odot$ is the number of initial ^{93}Nb nuclei in the collapsing cloud. The quantity Δ is the time from the SN event until the mixing with the protosolar cloud. The timescales have been previously estimated (Dauphas 2005) from several short-lived r-process chronometers, for example ^{129}I, ^{107}Pd, and ^{182}Hf, with half-lives within 10^6–10^8 yr. The evaluated time scale falls within the range of 3×10^7–10^8 yr (Dauphas 2005). We take $\Delta = 3 \times 10^7$ yr and $\Delta = 10^6$ yr for this late input scenario.

Thornton et al. (1998) estimated a dilution fraction of $f = 10^{-4}$ based upon SN remnant evolution if the source of some SLRs is the SN that triggered the proto-stellar collapse and the SN products are well mixed within the proto-solar material. Values of the dilution factor f based upon other SLRs (Meyer & Clayton 2000; Wasserburg et al. 2006; Takigawa et al. 2008) vary from $\sim 7 \times 10^{-5}$ to $\sim 2 \times 10^{-3}$. Based upon this we take $f = 10^{-4}$ and 3×10^{-3} as reasonable values for the late input scenario.

Table 1 summarizes the calculated ^{92}Nb/^{93}Nb ratio at SSF based on these illustrative mixing fractions and delay times. We note that the larger value of the dilution factor is consistent with $f = 1.9 \times 10^{-3}$ with the 20 $M_\odot$ SN model invoked (Takigawa et al. 2008) to explain other SLRs, ^{26}Al, ^{41}Ca, ^{53}Mn, and ^{60}Fe, in meteoritic material.

From Table 1 we infer that a ^{92}Nb/^{93}Nb ratio of 10^{-5} can be explained by a mixing factor of $f = 3 \times 10^{-3}$. However, the higher observed value of 10^{-3} cannot be reproduced if the SN ejecta is mixed and can only approach that value if the 1 $M_\odot$ proto-solar cloud contains $>0.2\ M_\odot$ of material from the SN. A required mass of 0.2 $M_\odot$ is much larger than the $10^{-4}\ M_\odot$ typically expected (Meyer & Clayton 2000; Wasserburg et al. 2006; Takigawa et al. 2008). Therefore, the present calculated result is at best only consistent with the lower value of 10^{-5}.

Thus, although the observed ratio ^{92}Nb/^{93}Nb clusters around the two values of 10^{-5} and 10^{-3}, the present study suggests that the ν-process can only explain the smaller value of 10^{-5}. The three ν-process isotopes ^{138}La, ^{180}Ta, and ^{92}Nb have common features in that they are all odd-odd nuclei and are shielded from β decays by stable isobars. For ^{138}La and ^{180}Ta, all proposed models except the ν-process can only underproduce their solar abundances, whereas the ν-process naturally reproduces or even overestimates their abundances. This suggests that no known nucleosynthesis model can reproduce the larger value of 10^{-3} for the $[^{92}\mathrm{Nb}/^{93}\mathrm{Nb}]_{\mathrm{SSF}}$ ratio if these three nuclides are predominantly produced by the same nucleosynthesis process.

In general, this ν-process chronometer has some advantages over other r-process chronometers. First, the ν-isotope ^{92}Nb is synthesized only by direct nuclear reactions. Therefore, the estimated abundance at freezeout is more robust for the ν-process than for the r-process chronometers which have possible contributions from many nucleosynthesis paths. Second, the astrophysical site of the ν-process is clear, whereas the origin of the r-process has not yet been firmly established; e.g., both SNe and neutron star mergers along with other scenarios have been suggested (Mathews & Cowan 1990) as the astrophysical site. Thus, once the ratio of ^{92}Nb/^{93}Nb at SSF has been determined to high accuracy from an analysis of primitive meteorites, one can evaluate an exact timescale from the last SN to SSF. We suggest that if the timescale evaluated from an r-process chronometer is identical with the time obtained by ^{92}Nb, this can be taken as evidence that the astrophysical origin of the r-isotope is indeed a core-collapse SN.

5. CONCLUSION

The short-lived radioactivity (SLR) ^{92}Nb has the potential to be a new nuclear cosmochronometer. However, the origin of ^{92}Nb has been an open question. We have proposed a single last SN ν-process origin and calculated the abundance using a detailed SN simulation. The observed ratio of 10^{-5} cannot be explained by a galactic chemical evolution model and could be explained by a scenario in which a nearby SN produce ^{92}Nb to proto-solar materials. The ratio 10^{-5} can be reproduced by mixing of $3 \times 10^{-3}\ M_\odot$ of the SN ejecta with the 1 $M_\odot$ proto-solar material.

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