

## NEUTRINO FLUENCE AFTER $r$ -PROCESS FREEZEOUT AND ABUNDANCES OF Te ISOTOPES IN PRESOLAR DIAMONDS

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### ABSTRACT

Using the data of Richter, Ott, & Begemann on Te isotopes in diamond grains from a meteorite, we derive bounds on the neutrino fluence and the decay timescale of the neutrino flux relevant for the supernova  $r$ -process. Our new bound on the neutrino fluence  $\mathcal{F}$  after freezeout of the  $r$ -process peak at mass number  $A \sim 130$  is more stringent than the previous bound  $\mathcal{F} \lesssim 0.045$  (in units of  $10^{37}$  ergs  $\text{cm}^{-2}$ ) of Qian et al. and Haxton et al., if the neutrino flux decays on a timescale  $\hat{\tau} \gtrsim 0.65$  s. In particular, it requires that a fluence of  $\mathcal{F} = 0.031$  be provided by a neutrino flux with  $\hat{\tau} \lesssim 0.84$  s. Such a fluence may be responsible for the production of the solar  $r$ -process abundances at  $A = 124$ – $126$ . Our results are based on the assumption of Ott that only the stable nuclei implanted into the diamonds are retained, while the radioactive nuclei are lost from the diamonds upon decay after implantation. We consider that the nanodiamonds are condensed in an environment with  $\text{C/O} > 1$  in the expanding supernova debris or from the exterior H envelope. This environment need not have the  $^{13}\text{C}/^{12}\text{C}$  ratio of the bulk diamonds, since the Te- and Xe-containing nanodiamond grains are too rare to affect that ratio. The implantation of nuclei would have occurred  $\sim 10^4$ – $10^6$  s after  $r$ -process freezeout. This time interval may be marginally sufficient to permit adequate cooling upon expansion for the formation of diamond grains. The mechanisms of preferential retention/loss of the implanted nuclei are not well understood.

*Subject headings:* elementary particles — nuclear reactions, nucleosynthesis, abundances — solar system: formation — supernovae: general

### 1. INTRODUCTION

The nature and occurrence of presolar diamonds and the associated isotopic anomalies in several elements have been reported and discussed by various authors (see, e.g., Fraundorf et al. 1989; Russell, Arden, & Pillinger 1991; Anders & Zinner 1993; Huss & Lewis 1995). It has been shown that macroscopic samples of these diamond crystals ( $\sim 1$  nm in size) contain xenon with major excesses of  $^{124}\text{Xe}$ ,  $^{126}\text{Xe}$ ,  $^{134}\text{Xe}$ , and  $^{136}\text{Xe}$ . This xenon has a characteristic abundance pattern that is called Xe-HL. These excesses appear to be correlated and have been attributed to a variety of causes ranging from superheavy element fission (Anders et al. 1975) to some special combination of  $r$ -process and  $p$ -process. It is evident that this widespread anomalous Xe (see, e.g., Huss & Lewis 1995) cannot be attributed to a single nuclear process and could represent a mixture of two or more distinctive nucleosynthetic sources that were subsequently mixed. The separation of Xe-H (with excesses in  $^{134}\text{Xe}$  and  $^{136}\text{Xe}$  of a likely  $r$ -process origin) from Xe-L (with excesses in  $^{124}\text{Xe}$  and  $^{126}\text{Xe}$  of a likely  $p$ -process origin) appears to have been accomplished in an elegant experiment by Meshik, Pravdivtseva, & Hohenberg (1998). This demonstrates that Xe-H is a distinct component.

Recently, Richter, Ott, & Begemann (1998) have shown that tellurium found in diamond-rich residues from a meteorite is comprised of a mixture of isotopically normal Te (e.g., terrestrial composition) and a pure  $r$ -process component of  $^{128}\text{Te}$  and  $^{130}\text{Te}$ . However,  $^{125}\text{Te}$  and  $^{126}\text{Te}$  with substantial  $r$ -process contributions are essentially absent in the component containing  $^{128}\text{Te}$  and  $^{130}\text{Te}$ . Based on the Xe data and the fact that stable isotopes are produced through  $\beta$  decays after  $r$ -process freezeout, Ott (1996) earlier proposed that the isotopic composition of the pure  $r$ -process component in presolar diamonds reflects the lifetimes of precursors for individual isotopes. He also calculated a period of  $\sim 7.5 \times 10^3$  s between  $r$ -process freezeout and implantation of  $r$ -process products into the diamonds, assuming that only the stable isotopes present at the time of implantation will be retained. The study by Richter et al. (1998) strongly supports his proposal, as the virtual absence of pure  $r$ -process  $^{125}\text{Te}$  and  $^{126}\text{Te}$  in the diamonds can be attributed to the long half-lives of their corresponding precursors  $^{125}\text{Sb}$  (2.76 yr) and  $^{126}\text{Sn}$  ( $\sim 10^5$  yr). In the model of Ott (1996), it is required that radioactive nuclei will be lost almost completely from the diamonds upon decay after implantation.

In this paper we discuss the connection between the isotopic composition of presolar diamonds and the supernova  $r$ -process. In particular, we consider the effects of a neutrino flux on the distribution of Te isotopes after  $r$ -process

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freezeout. The high abundance of  $^{128}\text{Sn}$ , the precursor for  $^{128}\text{Te}$ , could facilitate appreciable production of  $^{126}\text{Te}$  because of interactions with neutrinos. By using the data of Richter et al. (1998), we can derive a bound on the neutrino fluence to which nuclei were subject subsequent to the freezeout of the  $r$ -process in a supernova environment. This bound is presented in § 2. We recognize that the mechanism of implantation and retention/loss of volatile elements like Te and Xe in the very fine diamond crystallites is still enigmatic. These and other general issues will be discussed later in § 3. For simplicity, we assume the following time sequence and environment illustrated in Figure 1.

At time  $t_{\text{ej}}$ , some material is ejected from the neutron star produced by the core collapse and the subsequent supernova explosion. Within the moving material, the  $r$ -process starts at  $t_0$  and continues to  $t_{\text{FO}}$ , the time of freezeout. By definition, the  $r$ -process involves rapid neutron capture onto seed nuclei (with  $\beta$  decays and possibly also  $\nu_e$  capture reactions playing important roles; see, e.g., Kratz et al. 1993; Fuller & Meyer 1995; McLaughlin & Fuller 1996, 1997; Qian et al. 1997; Haxton et al. 1997; Qian, Vogel, & Wasserburg 1998). At  $t_{\text{FO}}$ , which is taken to coincide with the time  $t = 0$ , all the neutrons are exhausted and the population of nuclei is assumed to reach the  $r$ -process peak at the magic neutron number  $N = 82$ . Subsequent to freezeout (i.e., at  $t > 0$ ), these nuclei are subject to modification by further neutrino interactions (for  $\sim 10$  s, the so-called postprocessing) and  $\beta$  decays and to implantation into the preexisting diamond grains (with retention of only the stable nuclei). The freezeout abundances of all nuclear species in the  $N = 82$  peak would correspond to the normal solar  $r$ -process yields at mass number  $A \sim 130$  after the postprocessing, and all of the  $\beta$  decays are completed.

Diamond grains are assumed to be formed at the time  $t_{\text{DF}}$  after freezeout, and nuclei can be implanted into them anytime afterward. At  $t_{\text{ret}}$  (about a few hours), the grains are

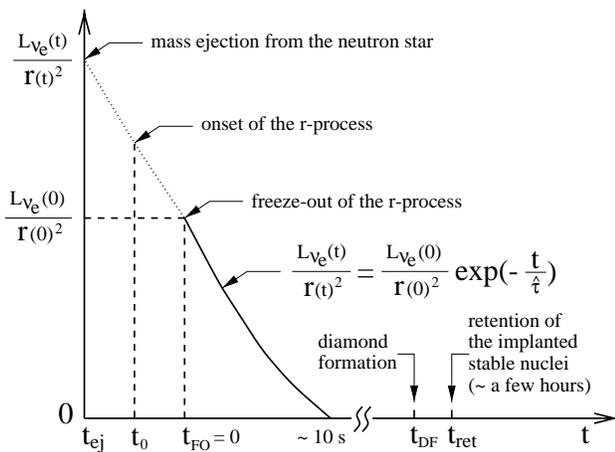


FIG. 1.—Time sequence of events relevant for the origin of  $r$ -process Te and Xe isotopes in presolar diamonds. The  $r$ -process is considered to take place in the material ejected from the neutron star produced in a supernova. This material experiences a neutrino flux that decreases with time. After  $r$ -process freezeout, the neutrino flux is assumed to decay exponentially on a characteristic timescale  $\hat{\tau}$ . A few hours after freezeout, the  $r$ -process material catches up with the previously ejected supernova material, implanting  $r$ -process nuclei into the earlier formed diamonds. However, only the implanted stable nuclei will be retained indefinitely when the diamond grains become sufficiently cool.

sufficiently cool so that the implanted stable nuclei will be retained indefinitely. However, radioactive nuclei will, by recoil or lattice site damage, be lost from the microcrystals upon decay after implantation (Ott 1996). We now address the effects of neutrino-nucleus interactions immediately after  $t_{\text{FO}}$  that can significantly alter the abundances of stable Te isotopes at  $t_{\text{ret}}$ , and we derive a bound on the neutrino fluence after  $r$ -process freezeout.

## 2. BOUND ON NEUTRINO FLUENCE AFTER $r$ -PROCESS FREEZEOUT

The Te isotopic abundance ratios are  $^{125}\text{Te} : ^{126}\text{Te} : ^{128}\text{Te} : ^{130}\text{Te} = 0.0006 \pm 0.0018 : 0.0001 \pm 0.0037 : 1.008 \pm 0.018 : 1$  for the pure  $r$ -process component in presolar diamonds (Richter et al. 1998), compared with 0.159:0.307:0.923:1 for the solar  $r$ -process component (Käppeler, Beer, & Wisshak 1989). This striking difference can be explained by the hypothesis of Ott (1996) that the diamonds sample only the  $r$ -process yields carried by stable isotopes a few hours after freezeout. With a generic precursor abundance pattern at freezeout, the solar  $r$ -process abundances of Te isotopes would be produced after all  $\beta$  decays are completed. The rather close agreement between the  $^{128}\text{Te}/^{130}\text{Te}$  ratio in the diamonds and that in the solar system indicates that  $^{128}\text{Te}$  and  $^{130}\text{Te}$  are essentially carrying their full  $r$ -process yields a few hours after freezeout, since their precursors have half-lives of  $\lesssim 1$  hr. On the other hand, the virtual absence of  $^{125}\text{Te}$  and  $^{126}\text{Te}$  in the diamonds appears to be due to the extremely slow  $\beta$  decays of their corresponding precursors  $^{125}\text{Sb}$  and  $^{126}\text{Sn}$ .

Although essentially no production of  $^{126}\text{Te}$  occurs through the  $\beta$  decay of  $^{126}\text{Sn}$  on a timescale of a few hours,  $^{126}\text{Te}$  can be produced on a much shorter timescale via neutrino reactions after the  $r$ -process freezes out in a supernova environment. These reactions are as follows:  $^{128}\text{Sn}(\nu_e, e^-2n)^{126}\text{Sb}$ ,  $^{127}\text{Sn}(\nu_e, e^-n)^{126}\text{Sb}$ , and  $^{126}\text{Sn}(\nu_e, e^-)^{126}\text{Sb}$ , where, for example,  $^{128}\text{Sn}(\nu_e, e^-2n)^{126}\text{Sb}$  is a shorthand for  $\nu_e$  capture on  $^{128}\text{Sn}$  producing  $^{126}\text{Sb}$ , one electron and two neutrons. Reactions with emission of more than two neutrons are insignificant because of energetic requirements. The above reactions of concern produce  $^{126}\text{Sb}$  mainly in its isomeric state, which has a half-life of 19.15 minutes, and 86% of the time have  $\beta$  decays to  $^{126}\text{Te}$ . (The ground state of  $^{126}\text{Sb}$  has spin 8 and is unlikely to be populated directly by neutrino interactions due to angular momentum selection rules.) Therefore, a bound on the neutrino fluence after  $r$ -process freezeout can be obtained by restricting neutrino-induced production of  $^{126}\text{Te}$ . However, no similar bound can be obtained by considering  $^{125}\text{Te}$ . While  $\nu_e$  capture reactions on Sb isotopes can bypass the slow  $\beta$  decay of  $^{125}\text{Sb}$  (which holds up the  $^{125}\text{Te}$  production), no neutrino flux would be available to induce such reactions. This is because the  $\beta$  decays only reach the relevant Sb isotopes more than 1 minute after  $r$ -process freezeout, while the entire supernova neutrino emission only lasts for  $\sim 10$  s. In addition, although  $^{125}\text{Sb}$  can be produced within  $\sim 10$  s after  $r$ -process freezeout through the reactions  $^{127}\text{Sn}(\nu_e, e^-2n)^{125}\text{Sb}$ ,  $^{126}\text{Sn}(\nu_e, e^-n)^{125}\text{Sb}$ , and  $^{125}\text{Sn}(\nu_e, e^-)^{125}\text{Sb}$ , there are no isomeric states in  $^{125}\text{Sb}$  that can  $\beta$  decay to  $^{125}\text{Te}$  on a timescale shorter than a few hours.

Compared with  $^{126}\text{Sn}$  and  $^{127}\text{Sn}$ ,  $^{128}\text{Sn}$  is more abundant and is reached earlier when the neutrino flux is also higher after  $r$ -process freezeout. Therefore, while the cross sections for neutrino reactions on  $^{126}\text{Sn}$ ,  $^{127}\text{Sn}$ , and  $^{128}\text{Sn}$  are

similar, the reaction on  $^{128}\text{Sn}$  is the most important one for the production of  $^{126}\text{Te}$ . In what follows, we specifically consider the reaction  $^{128}\text{Sn}(v_e, e^{-2n})^{126}\text{Sb}$  to derive a bound on the neutrino fluence after freezeout. We separate the process of neutrino-induced production of  $^{126}\text{Te}$  into three steps: (1) the production of  $^{128}\text{Sn}$  through  $\beta$  decays after  $r$ -process freezeout, (2) the production of  $^{126}\text{Sb}$  by  $^{128}\text{Sn}(v_e, e^{-2n})^{126}\text{Sb}$ , and (3) the production of  $^{126}\text{Te}$  through the  $\beta$  decay of  $^{126}\text{Sb}$ . These three steps are illustrated in Figure 2.

The production of  $^{128}\text{Sn}$  is essentially through a chain of  $\beta$  decays starting from  $^{128}\text{Pd}$  (with  $N = 82$ ) at  $r$ -process freezeout. For simplicity, we do not consider neutrino reactions at this stage, although adding them would speed up the production of  $^{128}\text{Sn}$  somewhat and might give a more stringent bound on the neutrino fluence. The half-life of  $^{128}\text{Sn}$  is 59.07 minutes, and it can be taken as stable over a period of  $\sim 10$  s relevant for neutrino-induced production of  $^{126}\text{Sb}$ . The other half-lives in the decay chain are 0.125, 0.0922, 0.34, and 0.84 s for  $^{128}\text{Pd}$ ,  $^{128}\text{Ag}$ ,  $^{128}\text{Cd}$ , and  $^{128}\text{In}$ , respectively. The first two half-lives are taken from Möller, Nix, & Kratz (1997), and the other two are from Firestone et al. (1996).

The  $v_e$  capture on  $^{128}\text{Sn}$  mainly proceeds through Fermi and Gamow-Teller (GT) transitions. The Fermi strength is carried by the isobaric analog state (IAS) in  $^{128}\text{Sb}$ , which lies below the two-neutron-emission threshold. Guided by experimental data on  $^{128}\text{Te}$  and  $^{130}\text{Te}$  (Madey et al. 1989), we put 85% of the GT strength in the giant resonance (GTGR) states and the rest in the low-lying states. The cross section for  $^{128}\text{Sn}(v_e, e^{-2n})^{126}\text{Sb}$  is essentially determined by transitions to the GTGR states between the thresholds for emission of two and three neutrons. The spectrum-averaged cross section for this reaction is  $\langle\sigma_{v_e,2n}\rangle = 1.65 \times 10^{-41}$

$\text{cm}^2$ , where the  $v_e$  spectrum is taken to be  $f_{v_e}(E_{v_e}) \propto E_{v_e}^2 / [\exp(E_{v_e}/T_{v_e} - 3) + 1]$ , with an average energy  $\langle E_{v_e} \rangle = 3.99 T_{v_e} = 11$  MeV (see, e.g., Janka & Hillebrandt 1989; Qian et al. 1997). The corresponding reaction rate is

$$\lambda_{v_e,2n}(t) = \frac{L_{v_e}(t)}{4\pi r(t)^2} \frac{\langle\sigma_{v_e,2n}\rangle}{\langle E_{v_e} \rangle} = 0.744 \frac{L_{v_e,51}(t)}{r_7(t)^2} \text{ s}^{-1}, \quad (1)$$

where  $L_{v_e,51}$  is the  $v_e$  luminosity  $L_{v_e}$  in units of  $10^{51}$  ergs $^{-1}$ , and  $r_7$  is the distance  $r$  of the  $r$ -process material from the neutron star in units of  $10^7$  cm. After  $r$ -process freezeout (i.e., at  $t > 0$ ), we assume that

$$\frac{L_{v_e,51}(t)}{r_7(t)^2} = \frac{L_{v_e,51}(0)}{r_7(0)^2} \exp\left(-\frac{t}{\hat{\tau}}\right), \quad (2)$$

where  $\hat{\tau}$  is the characteristic decay timescale of the neutrino flux.

As mentioned earlier, the reaction  $^{128}\text{Sn}(v_e, e^{-2n})^{126}\text{Sb}$  produces  $^{126}\text{Sb}$  mainly in its isomeric state, which directly  $\beta$  decays to  $^{126}\text{Te}$  86% of the time. We do not consider neutrino reactions on  $^{126}\text{Sb}$  in the production of  $^{126}\text{Te}$ , since their effects are of the second order in the neutrino fluence.

In order to illuminate the underlying physics, we first derive a bound on the neutrino fluence after  $r$ -process freezeout using a perturbative approach and assuming that all of the four  $\beta$  decays leading to  $^{128}\text{Sn}$  have the same rate of  $\bar{\lambda}_\beta = 1.98$  s $^{-1}$ . This rate corresponds to a lifetime that equals a quarter of the sum of lifetimes in the original decay chain. Without any neutrino effects, the abundance of  $^{128}\text{Sn}$  after freezeout is

$$Y_{128\text{Sn}}(t) = 1 - \sum_{n=0}^3 \frac{(\bar{\lambda}_\beta t)^n}{n!} \exp(-\bar{\lambda}_\beta t), \quad (3)$$

where we have set the abundance of  $^{128}\text{Pd}$  at freezeout ( $t = 0$ ) to unity without loss of generality. The neutrino-induced production of  $^{126}\text{Sb}$  over a period of  $\sim 10$  s after freezeout can be evaluated by the first order perturbation theory as

$$(\Delta Y)_{126\text{Sb}} = \int_0^\infty \lambda_{v_e,2n}(t) Y_{128\text{Sn}}(t) dt = \frac{0.744 \mathcal{F}}{[1 + (\bar{\lambda}_\beta \hat{\tau})^{-1}]^4}, \quad (4)$$

where

$$\mathcal{F} = \int_0^\infty \frac{L_{v_e,51}(t)}{r_7(t)^2} dt = \frac{L_{v_e,51}(0)}{r_7(0)^2} \hat{\tau} \quad (5)$$

is the neutrino fluence after freezeout in units of  $10^{37}$  ergs  $\text{cm}^{-2}$ . For practical purpose, we have taken  $\sim 10$  s as infinity in equation (4).

A few hours after  $r$ -process freezeout, 86% of the  $^{126}\text{Sb}$  produced by neutrino reactions has decayed to  $^{126}\text{Te}$ . At the same time, the bulk of the initial  $^{128}\text{Pd}$  has decayed to  $^{128}\text{Te}$ . From the abundance ratio  $^{126}\text{Te}/^{128}\text{Te} < 3.67 \times 10^{-3}$  in presolar diamonds, we obtain

$$\begin{aligned} \mathcal{F} &< \frac{3.67 \times 10^{-3}}{0.744 \times 0.86} \left(1 + \frac{1}{\bar{\lambda}_\beta \hat{\tau}}\right)^4 \\ &= 5.74 \times 10^{-3} \left[1 + \left(\frac{0.505 \text{ s}}{\hat{\tau}}\right)\right]^4. \end{aligned} \quad (6)$$

The bound given in equation (6) is shown as the dot-dashed line in Figure 3.

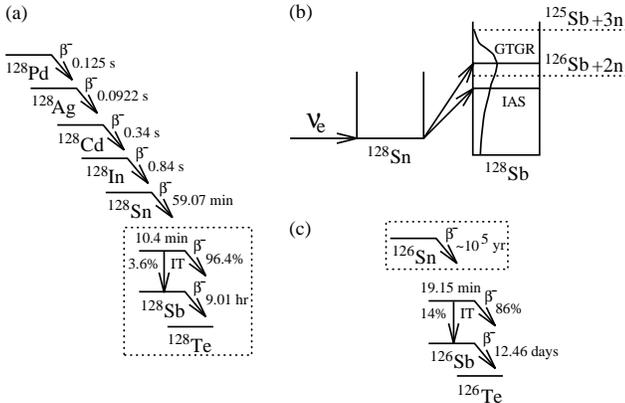


FIG. 2.—Three steps involved in neutrino-induced production of  $^{126}\text{Te}$ . (a) Production of  $^{128}\text{Sn}$  through  $\beta$  decays after  $r$ -process freezeout is shown with the relevant half-lives. Over the period ( $\sim 10$  s) of concern to (b),  $^{128}\text{Sn}$  can be taken as stable. It decays predominantly to the short-lived isomeric state of  $^{128}\text{Sb}$ , which in turn decays to  $^{128}\text{Te}$  (shown in the dotted box). (b) Production of  $^{126}\text{Sb}$  by  $v_e$  capture on  $^{128}\text{Sn}$  is shown. It essentially proceeds through transitions to the GTGR states in  $^{128}\text{Sb}$  that lie between the thresholds for emission of two and three neutrons (dotted lines). Due to angular momentum selection rules,  $^{126}\text{Sb}$  is produced mainly in its isomeric state rather than its high-spin ground state. (c) Production of  $^{126}\text{Te}$  through the  $\beta$  decay of  $^{126}\text{Sb}$  is shown. The  $\beta$  decay from the isomeric state dominates the production; see (b). For comparison, the production of  $^{126}\text{Te}$  through the  $\beta$  decay of  $^{128}\text{Sn}$  on a much longer timescale is shown in the dotted box. Note that the nuclear energy levels in Fig. 1 are for illustrative purpose only and are not to scale.

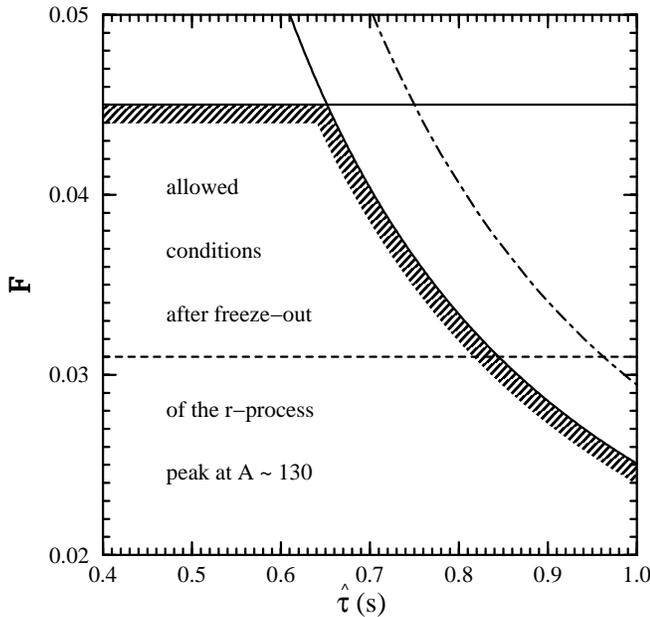


FIG. 3.—Bounds on the neutrino fluence  $\mathcal{F}$  and the characteristic decay timescale  $\hat{\tau}$  of the neutrino flux after freezeout of the  $r$ -process peak at  $A \sim 130$ . The dot-dashed line shows the approximate bound (eq. [6]) derived from the data of Richter et al. (1998) on Te isotopes in presolar diamonds. The solid line nearly parallel to it is from a more accurate calculation. The horizontal solid line is from Qian et al. (1997) and Haxton et al. (1997). The dashed line shows the neutrino fluence that may be responsible for the production of the solar  $r$ -process abundances at  $A = 124$ – $126$ . The Te data in presolar diamonds require that such a fluence be provided by a neutrino flux with  $\hat{\tau} \lesssim 0.84$  s.

Using the actual  $\beta$  decay rates for the production of  $^{128}\text{Sn}$  and taking into account its destruction by  $\nu_e$  capture with all neutron emission channels and by inelastic neutral-current scatterings of  $\nu_\mu$ ,  $\bar{\nu}_\mu$ ,  $\nu_\tau$ , and  $\bar{\nu}_\tau$  (see, e.g., Qian et al. 1997 for discussions of these reactions in supernovae), we have solved the system of equations for the production of  $^{126}\text{Te}$ . The bound on the neutrino fluence obtained from this more accurate nonperturbative approach is shown as the solid line nearly parallel to the dot-dashed line in Figure 3. It is more stringent than the approximate bound in equation (6), because equation (3) underestimates the production of  $^{128}\text{Sn}$  at earlier times when the neutrino flux is higher.

Previously, Qian et al. (1997) and Haxton et al. (1997) have derived bounds on the neutrino fluence by considering neutrino-induced neutron spallation off the  $r$ -process peak nuclei at  $A \sim 130$  and 195 after freezeout. They found that the final abundances at  $A = 124$ – $126$  and 182–187 are extremely sensitive to the neutrino fluence. By requiring that the nuclei at  $A = 124$ – $126$  not be overproduced by neutrino reactions, they put an upper bound of  $\mathcal{F} \lesssim 0.045$  on the neutrino fluence after freezeout. This bound is shown as the horizontal solid line in Figure 3. In addition, Qian et al. (1997) and Haxton et al. (1997) found that for  $\mathcal{F} = 0.031$ , the solar  $r$ -process abundances at  $A = 124$ – $126$  can be produced entirely by neutrino reactions after freezeout. This neutrino fluence is shown as the dashed line in Figure 3.

### 3. DISCUSSION AND CONCLUSIONS

Using the Te data in presolar diamonds, we have derived a new bound on the neutrino fluence and the decay timescale of the neutrino flux relevant for the supernova  $r$ -process. This bound and the previous one of Qian et al.

(1997) and Haxton et al. (1997) define an allowed region shown in Figure 3 for the neutrino fluence  $\mathcal{F}$  and the characteristic decay timescale  $\hat{\tau}$  of the neutrino flux after freezeout of the  $r$ -process peak at  $A \sim 130$ . In particular, if a neutrino fluence of  $\mathcal{F} = 0.031$  is indeed responsible for the production of the solar  $r$ -process abundances at  $A = 124$ – $126$  (Qian et al. 1997; Haxton et al. 1997), then the corresponding decay timescale of the neutrino flux is required to be  $\hat{\tau} \lesssim 0.84$  s.

The present results depend on a model for retention of only the stable isotopes after implantation of supernova  $r$ -process products into the microdiamonds. The association of supernovae with the diamond-rich residues found in several meteorites was first based on the presence of isotopically anomalous Xe (Xe-HL) that has been attributed to some aspects of the  $r$ -process (see the review by Anders & Zinner 1993; Clayton 1989). As shown by Richter et al. (1998), the Te associated with the diamonds has a clear  $r$ -process signature and strengthens the possible connection with supernovae. In order to account for the rather close agreement between the  $^{128}\text{Te}/^{130}\text{Te}$  ratio in the diamonds and the ratio in the solar system, the radioactive precursors of  $^{128}\text{Te}$  would have to decay nearly completely before implantation. As noted by Richter et al. (1998), the decay of  $^{128}\text{Sn}$  (with a half-life of  $\tau_{1/2} = 59.07$  minutes) produces  $^{128}\text{Sb}$  predominantly in the short-lived isomeric state ( $\tau_{1/2} = 10.4$  minutes) rather than the ground state ( $\tau_{1/2} = 9.01$  hr). It follows that the timescale for retention of the stable isotopes necessary to produce the observed  $^{128}\text{Te}/^{130}\text{Te}$  ratio in the diamonds must be at least a few hours after  $r$ -process freezeout; i.e.,  $t_{\text{ret}} \gtrsim 10^4$  s. In addition, the observed bound  $^{125}\text{Te}/^{130}\text{Te} < 0.0024$  limits the decay of  $^{125}\text{Sb}$  before implantation. Using the lifetime of  $^{125}\text{Sb}$ ,  $\tau(^{125}\text{Sb}) = 3.98$  yr, we obtain  $t_{\text{ret}} < (0.0024/0.159)\tau(^{125}\text{Sb}) = 1.9 \times 10^6$  s. This assumes that the initial  $r$ -process yields of the nuclei at  $A = 125$  and 130 correspond to  $^{125}\text{Te}/^{130}\text{Te} = 0.159$ , the ratio of the relevant solar  $r$ -process abundances. Thus we obtain  $10^4 \lesssim t_{\text{ret}} < 1.9 \times 10^6$  s. These bounds on  $t_{\text{ret}}$  are reasonably consistent with the retention timescale ( $\sim 7.5 \times 10^3$  s) calculated by Ott (1996) from the Xe-H data.

There are several problems that require attention. The first class of issues is related to the carbon in the diamonds. One of them is that the  $^{13}\text{C}/^{12}\text{C}$  ratio in the diamonds is very close to the solar value. While some variations have been observed (Russell et al. 1991), they are at the level of  $\sim 1\%$ . In addition, one has to explain how carbon phases (e.g., diamonds, graphite, SiC) could condense out of debris from a supernova when the bulk C/O ratio is less than 1. This is particularly problematic since the  $^{13}\text{C}/^{12}\text{C}$  ratio in the diamonds in no way reflects the very low  $^{13}\text{C}/^{12}\text{C}$  ratios associated with supernova zones having C/O  $> 1$ . The second class of issues is related to the mechanisms of selective trapping/retention of stable nuclei as compared with almost complete loss of radioactive species and the conditions under which this may take place relative to the timescales presented here. Many of these issues have previously attracted the attention of other workers. In particular, Clayton (1989) and Clayton et al. (1995) have proposed models to account for the conditions of formation of the diamonds, their carbon and nitrogen isotopic composition, and the implanted Xe. The model of Clayton et al. (1995) for diamond formation requires a timescale of  $\sim 1$  yr and assumes that the essentially solar  $^{13}\text{C}/^{12}\text{C}$  ratio is made of a

mixture from extremely  $^{12}\text{C}$ - and  $^{13}\text{C}$ -rich supernova zones. The rapid neutron burst model of Clayton (1989) for the origin of Xe-HL has been shown to conflict with the Te data by Richter et al. (1998).

Concerning the issue of the  $^{13}\text{C}/^{12}\text{C}$  ratio, Clayton et al. (1995) recognized that the experimentally analyzed bulk nanodiamond separates may represent mixtures of very different components from many different supernova contributions. These workers considered that the individual nanodiamonds would have  $^{13}\text{C}/^{12}\text{C}$  ratios changing from their centers to their surfaces. Interestingly, with differential thermal and chemical treatments it has been demonstrated that there are large variations ( $\sim 50\%$ ) in the  $^{15}\text{N}/^{14}\text{N}$  ratio of the bulk diamond separates (Russell et al. 1991; Verchovsky et al. 1994). In addition, the  $r$ -process Te and Xe isotopes discussed in this paper correspond to only one atom in  $\sim 10^7$  nanodiamond crystals. The separation of Xe-H from the bulk Xe-HL by Meshick et al. (1998) is particularly pertinent for the present discussion. If the  $r$ -process Te and Xe isotopes are contained in only a small subset of the diamonds, then these carriers may have an arbitrary  $^{13}\text{C}/^{12}\text{C}$  ratio that is unrelated to the bulk value. In this case, the Te and Xe-H carrier grains associated with the diamonds could be pure  $^{12}\text{C}$  and thus represent ejecta from the supernova He/C shell. This would leave the question of what the bulk diamond separates represent. Conceivably, they could be produced in the solar system, thereby explaining their observed essentially solar  $^{13}\text{C}/^{12}\text{C}$  ratio.

Taking into account some of the issues considered by the previous workers, we propose the following scenario, which may tie together the observations and try to relate it to plausible supernova processes. We consider either that a supernova has  $\text{C}/\text{O} \gtrsim 1$  in its evolved massive H envelope, or that the ejected mass from an interior supernova (He/C) zone provides material with  $\text{C}/\text{O} \gtrsim 1$ . Upon expansion and cooling after the supernova explosion, carbon and carbides can be condensed from the material in the H envelope or the ejected mass, as in the case of AGB stars (see, e.g., Sharp & Wasserburg 1995; Bernatowicz et al. 1996). The diamonds or other polymorphs formed in this way are then

dominated by the chemistry and isotopic characteristics of either the H envelope or the ejected material from the interior supernova zones.

In addition, we consider that the material involved in the  $r$ -process deep inside the supernova is blasted out at high velocities. It catches up with and penetrates the previously ejected material, which implants the  $r$ -process products into the earlier-formed diamond grains (see, e.g., Clayton 1989). We consider that both the stable and the radioactive nuclei will be implanted. To explain the absence of  $^{125}\text{Te}$  and  $^{126}\text{Te}$ , we must assume that recoil and crystallite damage by decay would cause the later loss of essentially all radioactive species as suggested by Ott (1996). The conditions under which any of the implanted stable nuclei (particularly the volatile elements) would be retained suggest a grain temperature for retention of less than about 800–1000 K. At expansion velocities of  $\sim 10^4 \text{ km s}^{-1}$ , the required cooling could possibly be achieved for the ejected material within  $\sim 10^4 \text{ s}$ , our lower bound on the retention timescale from the Te data (i.e., over an expansion distance of  $\sim 1 \text{ AU}$ . See Lattimer, Schramm, & Grossman 1978). Our upper bound of  $\sim 10^6 \text{ s}$  would allow much more room for cooling, but it would cause a conflict with the Xe data (Ott 1996). As the size of the diamond crystals is very small ( $\sim 1 \text{ nm}$ ), it is possible to achieve grain growth over a period of  $\sim 10^4 \text{ s}$  for plausible gas densities and with carbon sticking probabilities of the order of unity. Loss of radioactive species due to recoil or lattice damage by decay would take place on a much longer timescale. The typical recoil energy of the daughter nuclei is  $\sim 0.3\text{--}1 \text{ eV}$ . This may be enough to eject them from the diamonds. However, the essentially complete loss of the implanted radioactive nuclei as compared with retention of the implanted stable nuclei cannot be put on a sufficiently quantitative basis yet.

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