SILICON ISOTOPIC RATIOS OF PRESOLAR GRAINS FROM SUPERNOVAE. T. Yoshida[1], H. Umeda[2], K. Nomoto[2], [1]*Astronomical Institute, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan, (tyoshida@astr.tohoku.ac.jp),* [2]*Department of Astronomy, School of Science, University of Tokyo, Tokyo 113-0033, Japan.*

Introduction: Silicon carbide type X (SiC X), low density graphite, and some of silicon nitride have been considered to be originating from supernovae (e.g., [1-3]). Their origin is identified using the isotopic signatures such as the excesses of ^{28}Si and an evidence for original presence of short lived nuclei ^{44}Ti [4]. Silicon isotopic ratios have been analyzed in large amount of presolar grains from supernovae (e.g., [5]). The isotopic ratios have been shown on Si three-isotope plot with δ-value notation in units of per mil as shown in Fig. 1. This plot indicates that the Si isotopic ratios of most grains distribute along a line with a slope of ~ 0.7 and the others distribute along a line with a slope of ~ 1.2 (see dashed lines in Fig. 1a). Presolar grains from supernovae are considered to be divided into at least two subtypes [6,7]. We divide the grains into two subtypes as introduced in [7]. The grains having δ^{29}Si/^{28}Si $>$ δ^{30}Si/^{28}Si are classified into subtype X1. The ones having δ^{29}Si/^{28}Si $<$ δ^{30}Si/^{28}Si are classified into subtype X2.

The Si isotopic ratios of these grains have been compared to those of supernova nucleosynthesis and mixing models [5,8,9]. The supernova mixing models reproduced the subtype X2 signature. However, they have not reproduced the subtype X1. We consider that this is because the differences of Si isotopic ratios due to the variety of supernovae have not been investigated enough. In [5,8,9], supernova models of $15 \sim 25$ $M_\odot$ stars were adopted. On the other hand, stars heavier than 12 $M_\odot$ become type II supernovae and ones heavier than 20 $M_\odot$ may become hypernovae [10].

In the present study, we calculate nucleosynthesis of supernova explosions using He star models of 3.3, 4, 6, and 8 $M_\odot$. Then, we evaluate Si isotopic ratios of the supernova mixtures. We investigate the progenitor mass dependence of the Si isotopic ratios in the supernova mixtures. We also investigate conditions favorable to reproduce the Si isotopic signature of subtype X1.

Supernova Nucleosynthesis and Mixing Models: We pursue the stellar evolution from the He burning to the onset of the core collapse and the supernova explosions using the He star models of 3.3, 4, 6, and 8 $M_\odot$ [11,12]. These He star models correspond to 13, 15, 20, and 25 $M_\odot$ zero-age main sequence stars. Then, we calculate detailed nucleosynthesis during these stages. The nuclear reaction network consists of 515 species of nuclei from neutron to Zr [9]. We use the neutrino temperature of $T_{\nu_{\mu,\tau}} = 6$ MeV for $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$, which are the same value as in [13] but smaller than 8 MeV used in [9,14], and 4 MeV for ν_e and $\bar{\nu}_e$.

After the nucleosynthesis calculation, we consider four layer mixing used in [9]. We divide the supernova ejecta into seven layers, i.e., the Ni, Si/S, O/Si, O/Ne, O/C or C/O, He/C, and He/N layers. The compositions of these layers are averaged in each layer. Then, we use the Ni, Si/S, He/C, and He/N layers to make mixtures of supernova ejecta. We mix these layers assuming a C/O ratio and evaluate the Si isotopic ratios of the mixtures.

Results and Discussion: We show Si three-isotope plot for mixtures of 3.3, 4, and 8 $M_\odot$ He star supernova models in Fig. 1. We assume the C/O ratio equal to unity. There are nine lines each of which is drawn assuming a constant value of $r_{\mathrm{Si/S}}$ = r(Si/S)/(r(Si/S)+r(Ni)) where r(Si/S) and r(Ni) are the mixing ratios of the Si/S and Ni layers, respectively. The Si isotopic ratios of SiC X [4,5,7,15] and low density graphite [8] are also shown.

Figure 1a shows Si three-isotope plot for mixtures of 3.3 $M_\odot$ He star supernova model. We see that the mixing lines overlap with symbols of subtype X1 grains: the mixtures show subtype X1 signature rather than subtype X2. In the case of $r_{\mathrm{Si/S}} = 1 \times 10^{-4}$, the slope of the mixing line is close to 0.7. When we consider the variation of $r_{\mathrm{Si/S}}$, the region of the Si isotopic ratios on this plot forms a triangle, of which vertexes correspond to the values in the Ni, Si/S, and He/N layers. In the Ni layer the Si isotopic ratios are δ^{30}Si/^{28}Si=-670 and δ^{29}Si/^{28}Si=-64. The Si composition in the Si/S layer indicates the excesses of ^{28}Si and that in the He/N layer is almost equal to the solar composition. Therefore, the Ni layer contributes to show the subtype X1 signature of the mixtures.

Figure 1b shows the Si isotopic ratios of mixtures of 4 $M_\odot$ model. We also see the Si isotopic signature of subtype X1 in the mixtures. Lines with different $r_{\mathrm{Si/S}}$ values overlap with circles of the subtype X1 grains except very ^{30}Si deficient ones. On the other hand, the X2 signature is not reproduced by this model. The Ni layer indicates ^{29}Si rich profile; δ^{29}Si/^{28}S=840 and δ^{30}Si/^{28}Si=430.

Figure 1c shows the Si isotopic ratios of mixtures of 8 $M_\odot$ model. The Si isotopic ratios indicate only subtype X2 signature. The X1 signature is not reproduced by the mixtures of this model. The Si isotopic ratios in the Ni layer are δ^{29}Si/^{28}Si=1570 and δ^{30}Si/^{28}Si=9100. The Ni layer is extremely ^{30}Si rich contrary to the cases of 3.3 $M_\odot$ and 4 $M_\odot$ models. The mixtures of 6 $M_\odot$ model produce a Si isotopic signature similar to the 8 $M_\odot$ model.

We note that the Si isotopic ratios of the mixtures of the 4 $M_\odot$ He star model indicate the subtype X1 signature whereas those of 15 $M_\odot$ model [8] and 4 $M_\odot$ He star model [9] indicate the X2 signature. In the present study, we use the neutrino temperature of $T_{\nu_{\mu,\tau}} = 6$ MeV, which is smaller than 8 MeV adopted in the previous study. In the Ni layer, ^{29}Si and ^{30}Si are produced through ^{28}Si$(p,\gamma)^{29}$P$(\beta^+)^{29}$Si and ^{29}Si$(p,\gamma)^{30}$P$(\beta^+)^{30}$Si. Larger neutrino temperature provides ^{30}Si rich composition because more protons are produced through neutrino spallation reactions (the ν-process).

For the Si isotopic ratios, the contribution of the Ni layer is not small. The Si isotopic ratios of the Ni layer depend on the progenitor mass. Both of the isotopic ratios increase with the progenitor mass. The increment degree of δ^{30}Si/^{28}Si is much larger than that of δ^{29}Si/^{28}Si. On the other hand, numerical simulations indicate that the time scale of the temperature decrease during the supernova explosions also depends on the progenitor mass. The time scale becomes longer with increase in the progenitor mass. Thus, we investigate the dependence of the Si isotopic ratios on the temperature decrease time scale. We calculate nucleosynthesis using a simple explosion model of which temperature decreases from 5.6×10^9 K in accordance with $t^{-\alpha}$ from a finite time. Large value of α corresponds to rapid temperature decrease and small progenitor mass. Within the range of $0.45 \leq \alpha \leq 0.85$, the δ^{30}Si/^{28}Si ratio decreases with increasing in α. The Si isotopic ratios of the subtype X1 signature is shown in the case of $\alpha \geq 0.6$. Therefore, rapid temperature decrease, corresponding to small progenitor mass, provides the subtype X1 signature shown in most of the grains from supernovae. Details will be discussed in [16].

We showed that the mixtures of supernova ejecta from $13 \sim 15\ M_\odot$ progenitors would provide the subtype X1 signature found in most of presolar grains from supernovae. On the other hand, the subtype X2 signature found in less abundant grains is reproduced by the mixtures of heavier supernovae. From the viewpoint of initial mass function, the generation rate of less massive stars is larger than that of heavier stars. The fact that the population of subtype X1 grains is larger than that of subtype X2 grains is consistent with the initial mass function and the production of subtype X1 grains from less massive supernovae.

Summary: We calculated nucleosynthesis during the stellar evolution and the supernova explosions of 3.3, 4, 6, and 8 $M_\odot$ He star models. Then, we investigated Si isotopic ratios of mixtures of the supernova ejecta considering four layer mixing of the Ni, Si/S, He/C, and He/N layers. The subtype X1 Si isotopic signature is reproduced by the mixtures of supernova ejecta of 3.3 and 4 $M_\odot$ He star supernova models. The subtype X2 signature is reproduced by the mixtures of 6 and 8 $M_\odot$ models. Thus, supernova explosions of less massive stars would be a favorable site for most of presolar grains from supernovae having the subtype X1 signature.

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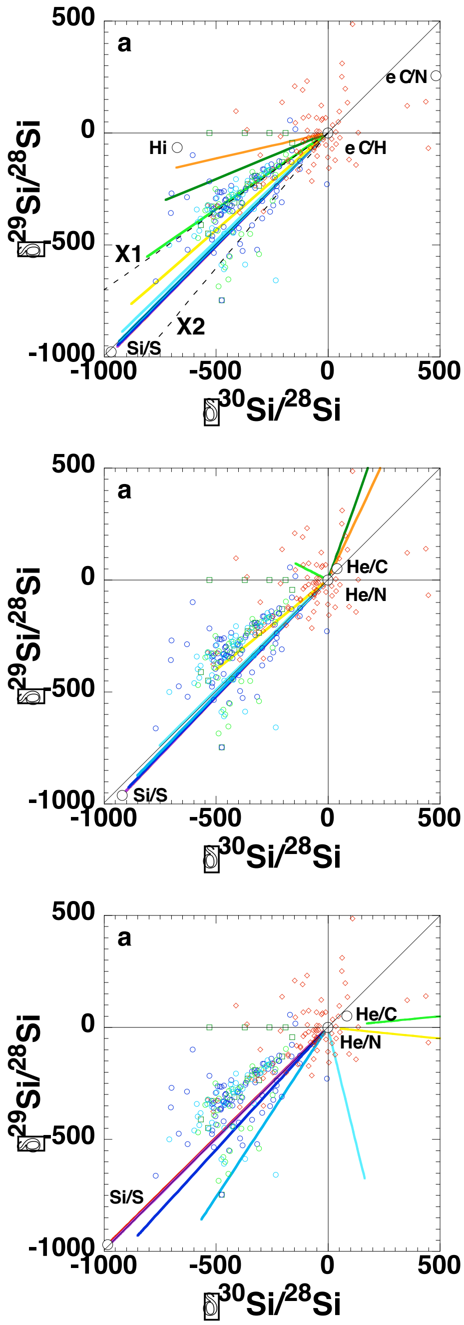

Figure 1: Si three-isotope plot for the mixtures of 3.3 $M_\odot$ (panel (a)), 4 $M_\odot$ (panel (b)), and 8 $M_\odot$ (panel (c)) He star supernova models. Color sold lines indicate the Si isotopic ratios of the mixtures varying the mixing ratios. The value of $r_{\rm Si/S}$ is fixed in each line from 0.9 (red line) to 1×10^{-5} (orange line). Large circles correspond to the averaged values in the Ni, Si/S, He/C, and He/N layers. The Si isotopic ratios of SiC X and low density graphite are denoted by green squares [4], blue circles [5], yellow-green circles [7], red diamonds [8], and sky-blue circles [15]. Dashed lines with the slope of 0.7 (X1) and 1.2 (X2) are presented in panel (a).