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AN UNUSUAL PRESOLAR SILICON CARBIDE GRAIN FROM A SUPERNOVA: IMPLICATIONS FOR THE PRODUCTION OF SILICON-29 IN TYPE II SUPERNOVAE

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ABSTRACT

We report the discovery of a presolar SiC grain (KJB2-11-17-1) with unusual Si-isotopic composition. The grain has $^{29}Si/^{28}Si = 1.63 \times$ solar, $^{30}Si/^{28}Si = 0.82 \times$ solar, $^{12}C/^{13}C = 265$ ($= 3 \times$ solar), and evidence for the presence of radiogenic ^{44}Ca from the decay of ^{44}Ti. A comparison of these isotopic signatures with stellar models suggests an origin in a 15 $M_{\odot}$ Type II supernova. It is possible to achieve a very good match between the $^{30}Si/^{28}Si$, $^{12}C/^{13}C$, and inferred $^{44}Ti/^{48}Ti$ ratios in KJB2-11-17-1 and the model predictions if matter from different supernova zones is mixed in appropriate proportions. The $^{29}Si/^{28}Si$ ratio, however, cannot be reproduced and is clearly higher than predicted. It was suggested previously by Travaglio et al. that supernova models underestimate the ^{29}Si yield in the C- and Ne-burning regions by about a factor of 2. Because of its very high $^{29}Si/^{30}Si$ of two times the solar ratio, grain KJB2-11-17-1 provides the opportunity to make a stringent test of this hypothesis. With a twofold enhanced ^{29}Si yield in the C- and Ne-burning zones, we find a perfect match for $^{29}Si/^{28}Si$ between the model predictions and the grain. Nuclear network calculations show that a twofold increase in the ^{29}Si yield in the C- and Ne-burning regions requires roughly a threefold higher $^{26}Mg(\alpha, n)^{29}Si$ reaction rate, the most important reaction for the production of ^{29}Si, in the temperature range 1–3 $\times 10^9$ K than currently used in supernova models. This increase is qualitatively within current uncertainties of this reaction rate.

Key words: circumstellar matter – Galaxy: evolution – nuclear reactions, nucleosynthesis, abundances – supernovae: general

1. INTRODUCTION

Presolar grains are found in small quantities in primitive meteorites, interplanetary dust particles, and cometary matter (Lodders & Amari 2005; McKeegan et al. 2006; Zinner 2007). These grains are characterized by large isotopic anomalies (with respect to average Solar System matter) in the major and minor/trace elements, which requires that the grains formed around evolved stars. They thus represent a sample of stardust that can be analyzed with high precision in the laboratory. Among the identified presolar minerals are diamond, silicon carbide (SiC), graphite, silicon nitride (Si_3N_4), oxides (e.g., Al_2O_3, $MgAl_2O_4$), and silicates. Based on a comparison of isotopic signatures with those predicted from stellar models, most of the grains apparently formed in low-to-intermediate mass asymptotic giant branch (AGB) stars. A small but noticeable fraction appears to come from Type II supernovae (SNII).

Silicon carbide is the best studied presolar mineral phase. Based on its C-, N-, and Si-isotopic compositions, it is divided into several distinct populations. Most of the SiC grains (∼90%) belong to the mainstream group, which most likely represents dust from 1.5–3 $M_{\odot}$ AGB stars of roughly solar metallicity. The so-called X grains represent a small (∼1%) but important subpopulation of presolar SiC grains (e.g., Amari et al. 1992; Hoppe et al. 2000). These grains are characterized by isotopic overabundances in ^{28}Si, ^{12}C (most grains), and ^{15}N. They carry the decay products of large amounts of ^{26}Al (half-life 716,000 yr), ^{44}Ti (half-life 60 yr), and ^{49}V (half-life 330 days). The presence of the latter two radionuclides at the time of grain formation, as well as their Si-isotopic signature, points to an origin in SNII.

Although some authors (Deneault et al. 2003) argue that molecular mixing occurs too slowly in SN ejecta to take place prior to grain condensation, mixing models of SN ejecta can account for isotopic signatures in SiC X grains and in many presolar graphite grains (Travaglio et al. 1999; Hoppe et al. 2000; Yoshida et al. 2005). The mixing calculations by Hoppe et al. (2000) for X grains used the isotope yields of the 15 and 25 $M_{\odot}$ SN models of Woosley & Weaver (1995) and mixed matter from eight discrete zones (rich in Ni, Si/S, O/Si, O/Ne, O/C, He/C, He/N, and H, respectively) (Meyer et al. 1995) in various proportions, using the average isotope abundances in each zone. The layers experienced different stages of nuclear burning: an α-rich freezeout from nuclear statistical equilibrium (Ni), O burning (Si/S), Ne and partial O burning (O/Si), C burning (O/Ne), He burning (O/C), H and partial He burning (He/C), H burning (He/N), and partial H burning (H). It was shown that the 15 $M_{\odot}$ SNII model generally gives the best match with the isotope data of X grains. Nevertheless, several unsolved problems are evident, e.g., too low $^{26}Al/^{27}Al$ and $^{15}N/^{14}N$ ratios predicted from the mixing models. Also, although the ^{28}Si enrichments of X grains can be qualitatively explained, the mixing models show lower $^{29}Si/^{30}Si$ ratios than observed in most of the X grains.

The problem of apparent ^{29}Si deficits from SNII has been addressed by several authors in the past. Galactic chemical evolution (GCE) models fail to reproduce the solar Si isotope abundances; specifically ^{29}Si comes out too low (Timmes & Clayton 1996). It was pointed out by these authors that the abundances of the Si isotopes in the interstellar medium (ISM) are largely determined from SNII ejecta, and that the key nuclear reaction rates affecting the abundances of ^{29}Si and ^{30}Si in

SNII might have systematic errors. Timmes & Clayton (1996) suggested to multiply the $^{29}Si/^{30}Si$ ratio in SNII ejecta by 1.5, which would reproduce the solar Si-isotopic ratios in their GCE model. Similarly, Lugaro et al. (1999) followed this approach to get the best match between the Si-isotopic composition of SiC mainstream grains and predictions from a model of incomplete mixing of SN ejecta in the ISM. Travaglio et al. (1998) proposed a twofold enhanced ^{29}Si yield in the C- and Ne-burning zones (O/Ne and O/Si) of SNII, which would reproduce the Si-isotopic ratios of many low density and SiC X grains in SN mixing calculations fairly well. Yoshida et al. (2005), on the other hand, argued that the ^{29}Si excesses (relative to ^{30}Si) in presolar SN grains are the signature of large contributions from the Ni zone in the ejecta. However, this would result in very high $^{44}Ti/^{48}Ti$ ratios (higher than observed in most grains) and high Ti/Si at the condensation site in the ejecta. Since the Ti/Si ratio is roughly preserved during condensation (Hoppe et al. 2001; Lodders & Fegley 1995), one would expect to find Ti concentrations of higher than 10% in SN grains, which is not observed.

Here, we report on the discovery of a presolar SiC grain (KJB2-11-17-1) from the Murchison CM2 meteorite with an unusual Si-isotopic composition: strong enrichment in ^{29}Si and depletion in ^{30}Si. This grain has the highest $^{29}Si/^{30}Si$ ratio found in presolar grains so far and, as we will discuss below, likely originates from a SNII. Because of its very high $^{29}Si/^{30}Si$ ratio, it provides a stringent test for the proposed adjustment of ^{29}Si yields in specific SNII zones. We will explore the effect of changing the $^{26}Mg(\alpha, n)^{29}Si$ rate, which is the most important reaction with respect to the production of ^{29}Si, on the yield of ^{29}Si in the C- and Ne-burning zones, the overall yield of ^{29}Si in SNII ejecta, and on the GCE of Si isotope ratios.

2. EXPERIMENTAL DETAILS

Thousands of submicrometer-sized presolar SiC grains from the Murchison separate KJB (typical size 0.25–0.45 μm; Amari et al. 1994) were dispersed on an ultraclean Au foil using an isopropanol suspension. Carbon- and Si-isotope measurements were done by a fully automated ion imaging procedure developed for the NanoSIMS at Max-Planck-Institute for Chemistry (Gröner & Hoppe 2006). The ion imaging consists of three steps: (1) acquisition of simultaneous ion images of $^{12}C^-$, $^{13}C^-$, $^{28}Si^-$, $^{29}Si^-$, and $^{30}Si^-$ by rastering a focused Cs^+ ion beam ($\sim$1 pA, 100 nm) over areas 30 $\times$ 30 μm^2 in size (integration time of $\sim$15 minutes); (2) automated particle recognition and C- and Si-isotope measurements in square areas with a lateral length of 2 $\times$ the grain diameter (defined at 10% of the maximum ^{28}Si intensity) around each grain, with integration times of 60 s; and (3) moving the sample stage to the adjacent 30 $\times$ 30 μm^2-sized analysis area and continuation with step (1). Application to 1 μm-sized synthetic SiC grains gave grain-to-grain reproducibilities (1σ) of <10‰ for $^{13}C/^{12}C$, $^{29}Si/^{28}Si$, and $^{30}Si/^{28}Si$. Subsequent to the C- and Si-isotope analysis, grain KJB2-11-17-1 was analyzed for its Ca–Ti-isotopic composition. These measurements were done with O^- primary ions ($\sim$15 pA, 300 nm) and a raster of 2 $\times$ 2 μm^2. Positive secondary ions of ^{28}Si, ^{40}Ca, ^{42}Ca, ^{44}Ca, and ^{48}Ti were measured in multicollection. Calcium-rich grains on the KJB sample mount were used as Ca isotope standards. The relative Ti^+/Ca^+ sensitivity factor (0.5), required to calculate $^{44}Ti/^{48}Ti$ from excesses in ^{44}Ca, was taken from Besmehn & Hoppe (2003).

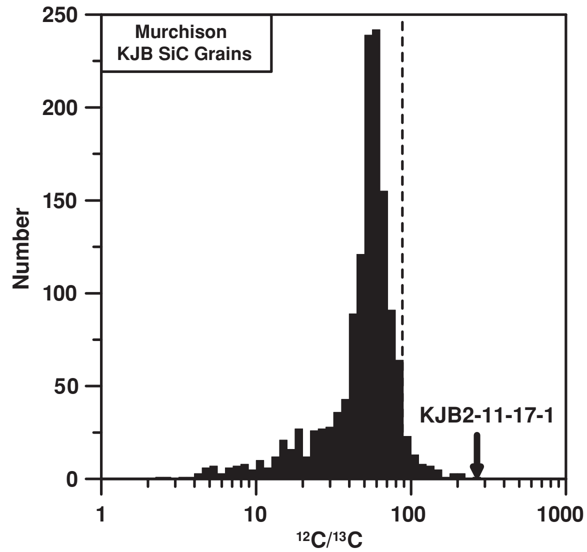

Figure 1. Histogram of $^{12}C/^{13}C$ ratios of presolar SiC grains from Murchison separate KJB (0.25–0.45 μm). The solar ratio is indicated by the dashed line. Most grains plot in the range $^{12}C/^{13}C$ = 30–100. Grain KJB2-11-17-1 has the highest $^{12}C/^{13}C$ ratio of all grains from this study.

3. RESULTS AND DISCUSSION

About 1300 individual presolar SiC grains were identified in our ion imaging survey (Hoppe et al. 2008). The C- and Si-isotopic data are displayed in Figures 1 and 2. The distribution of $^{12}C/^{13}C$ ratios in the KJB grains of this study (Figure 1) is similar to what has been observed in previous studies for micrometer-sized grains (Hoppe et al. 1994; Hoppe et al. 1996; Nittler & Alexander 2003). In the Si-three-isotope representation (Figure 2) most grains plot along the SiC mainstream line ($\delta^{29}Si = 1.37 \times \delta^{30}Si - 20$; Zinner et al. 2007). Exceptions are the rare Y and Z grains (Amari et al. 2001b; Hoppe et al. 1997), which plot to the ^{30}Si-rich side of this line, and the X grains, which exhibit enrichments in ^{28}Si. Like the mainstream grains, the Y and Z grains are likely to be from AGB stars, but from those with subsolar metallicities. Grain KJB2-11-17-1 clearly stands out in the Si isotope plot. It has $\delta^{29}Si = 634 \pm 20$‰ and $\delta^{30}Si = -177 \pm 18$‰. Its $^{29}Si/^{30}Si$ ratio of 3.0 is about 2 $\times$ the solar ratio, the highest $^{29}Si/^{30}Si$ ratio found in presolar grains so far. Among the measured KJB grains, it also has the highest $^{12}C/^{13}C$ ratio (265 $\pm$ 14; see Figure 1). Calcium isotope ratios are close to normal (solar) with $\delta^{42}Ca = -14 \pm 16$‰ and $\delta^{44}Ca = 40 \pm 19$‰. In the context of a SNII origin of grain KJB2-11-17-1 (see below), the small but noticeable excess in ^{44}Ca is likely due to the decay of radioactive ^{44}Ti. The inferred initial $^{44}Ti/^{48}Ti$ ratio is 0.018 $\pm$ 0.009.

In the following, we discuss why a SNII is the most likely stellar source of KJB2-11-17-1 and why other potential sources of presolar SiC grains (AGB stars, SNIa, novae) are less likely. (1) There is a large body of evidence that the majority of SiC grains (mainstream) formed in AGB stars. The Si isotope data of these grains plot along the SiC mainstream line (see Figure 2) which is believed to represent essentially the starting compositions of a large number of parent stars (e.g., Zinner et al. 2006). Grain KJB2-11-17-1 plots far off the mainstream line; hence, it is hard to envision that it originates from an AGB star with a Si starting composition far off the trend obvious for all other AGB stars that apparently contributed to the presolar SiC population. (2) Models of SNIa can account for many isotopic

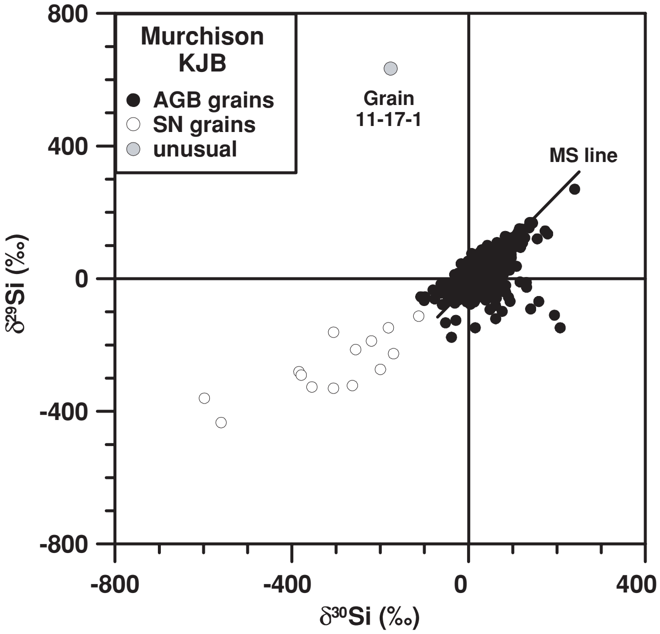

Figure 2. Silicon-isotopic ratios of presolar SiC grains from Murchison separate KJB (0.25–0.45 μm), given as permil deviation from the solar ratios. $\delta^i\mathrm{Si} = \{(^i\mathrm{Si}/^{28}\mathrm{Si})_{\mathrm{Grain}}/(^i\mathrm{Si}/^{28}\mathrm{Si})_\odot - 1\} \times 1000$. AGB (mainstream, Y, and Z) and SN (X) grains as well as the unusual grain KJB2-11-17-1 are indicated by the different symbols. The SiC mainstream (MS) line is shown for reference. Only grains with error of <20‰ (1σ) in δ^{30}Si are displayed.

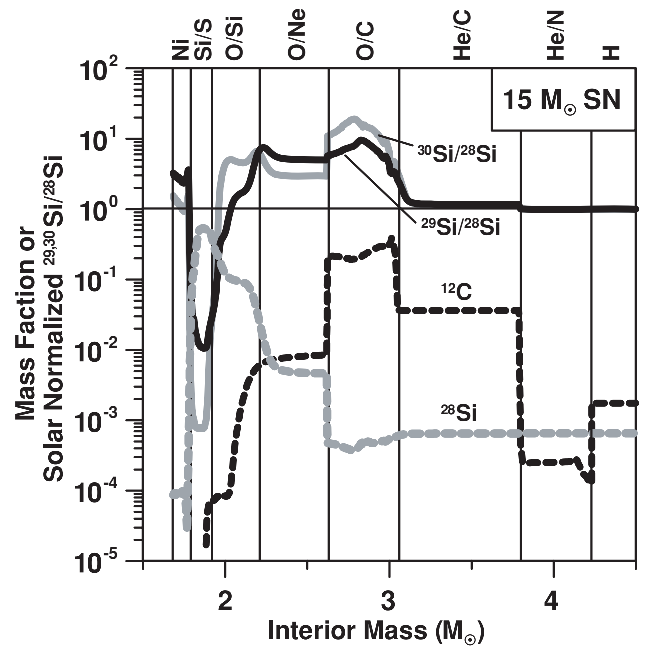

Figure 3. Profiles of mass fractions of ^{12}C and ^{28}Si and of solar-normalized $^{29,30}\mathrm{Si}/^{28}\mathrm{Si}$ ratios in the interior of a 15 $M_\odot$ SNII (Rauscher et al. 2002). Following the concept of Meyer et al. (1995), the SN is divided into eight distinct zones which are named according to the most abundant elements.

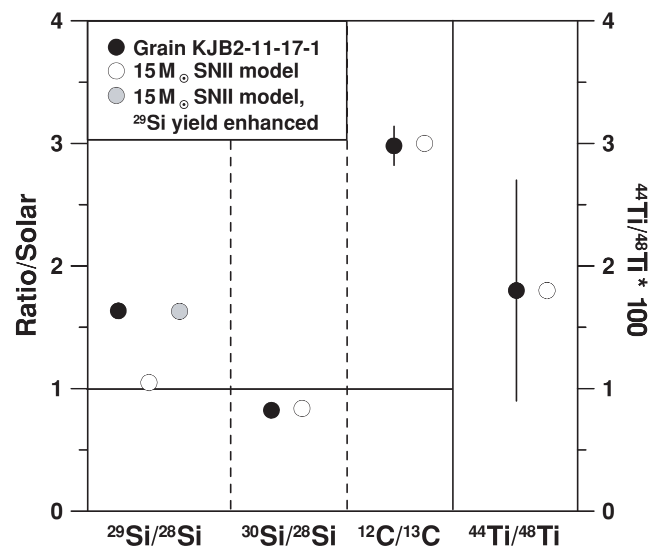

Figure 4. Solar-normalized $^{29}\mathrm{Si}/^{28}\mathrm{Si}$, $^{30}\mathrm{Si}/^{28}\mathrm{Si}$, and $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios, and inferred $^{44}\mathrm{Ti}/^{48}\mathrm{Ti}$ ratio of SiC grain KJB2-11-17-1 (black circles) along with predictions from a 15 $M_\odot$ SNII mixing model with "normal" ^{29}Si yield (white circles) and with enhanced (2x) ^{29}Si yield (grey circles) in the O/Ne zone. Errors are 1σ.

signatures of X grains (Clayton et al. 1997), although the best match with the X grain data is achieved for O > C in the ejecta (Amari et al. 1998). SNIa models, however, fail to account for higher than solar $^{29}\mathrm{Si}/^{28}\mathrm{Si}$ ratios. All zones in the SNIa model of Clayton et al. (1997) show deficits in ^{29}Si and ^{30}Si and we therefore rule out the possibility that KJB2-11-17-1 originates from a SNIa. (3) Presolar grains with likely nova origin show low $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios of < 10 and lower than solar $^{29}\mathrm{Si}/^{30}\mathrm{Si}$ (Amari et al. 2001a). This is in accord with nova model predictions (José et al. 2004) and we thus exclude a nova origin for grain KJB2-11-17-1. (4) The different zones in SNII do show very different isotope ratios. This permits to produce isotope ratios over a large range, depending on the specific mixing conditions, in SNII ejecta. Of particular importance is the fact that SNII models predict higher than solar $^{29}\mathrm{Si}/^{30}\mathrm{Si}$ in the intermediate O/Ne zone (Rauscher et al. 2002; see Figure 3). A SNII is thus the most promising source for grain KJB2-11-17-1.

In order to reproduce the isotopic signatures of grain KJB2-11-17-1, we have explored the 15, 19, and 25 $M_\odot$ SNII models of Rauscher et al. (2002). In particular, we have used the models s15a28c, s19a28g, and s25a34d on www.nucleosynthesis.org. The 15 $M_\odot$ model is the most promising one, because it exhibits the highest $^{29}\mathrm{Si}/^{30}\mathrm{Si}$ ratio in the O/Ne zone. Also, the best match between the 19 and 25 $M_\odot$ models and the grain data is for C/O $\leqslant$ 0.3 in the ejecta, which is not favorable for SiC formation. The best match between the 15 $M_\odot$ model and the grain data is obtained when matter from the Si/S, O/Ne, He/C, He/N, and H zones is mixed in a ratio 0.19% : 2.3% : 37.3% : 22.0% : 38.2%. More than 97% of the matter comes from the outer He/C, He/N, and H zones and contributions of only 2.5% are needed from the interior zones. This mixing scenario results in C/O ~ 1, $^{12}\mathrm{C}/^{13}\mathrm{C} = 267$, $\delta^{29}\mathrm{Si} = 49‰$, $\delta^{30}\mathrm{Si} = -162‰$, and $^{44}\mathrm{Ti}/^{48}\mathrm{Ti} = 0.018$. This is an excellent agreement between the model and the grain data, except that the ^{29}Si enrichment falls far short of the observed value (Figure 4). Following the suggestion by Travaglio et al. (1998) in doubling the ^{29}Si yield in the C- and Ne-burning regions (i.e., in the O/Si and O/Ne zones), we obtain with the same mixing conditions as given above $\delta^{29}\mathrm{Si} = 630‰$ which is a perfect match with the grain data (Figure 4).

This perfect match clearly supports the approach of Travaglio et al. (1998) of doubling the ^{29}Si yield in the C- and Ne-burning regions of SNII. An important question to answer is whether this can be justified in view of uncertainties of reaction rates relevant for the production of ^{29}Si in the O/Si and O/Ne zones. We have explored the impact of various reaction rates on the ^{29}Si abundance in these zones using a computer code built on the nuclear reaction toolkit libnucnet (Meyer & Adams 2007). The ^{29}Si abundance in these zones is most sensitive to changes in the ^{26}Mg(α, n)^{29}Si and, to a lesser extent, ^{29}Si(n, γ)^{30}Si reaction rates. The SNII models of Rauscher et al. (2002) use the reaction rates of Fowler et al. (1975) (model series "S") and NACRE (Angulo et al. 1999) (model series "N") for ^{26}Mg(α, n)^{29}Si. The latter rate is about a factor of 1.2 higher for $T_9 =$ 1–3. However, upper limits on the NACRE rate are higher by factors of 1.4–3.5 in this temperature range than the rates given by Fowler et al. (1975). In order to estimate how changes in the ^{26}Mg(α, n)^{29}Si reaction rate affect the ^{29}Si yield in the O/Si and O/Ne zones, we performed a full network reaction calculation involving a reaction network appropriate for explosive carbon and oxygen burning. For the starting composition, we took the composition of the region where ^{29}Si is most abundant. The calculations used a starting temperature of $T_9 = 2.25$, a density of 2.27×10^5 g cm^{-3}, and an expansion timescale of 0.9257 (Meyer 2005). For ^{29}Si(n, γ)^{30}Si, we took the Bao et al. (2000) rate (extended to $T_9 = 2.25$ using appropriate fit parameters). It was found that if the ^{26}Mg(α, n)^{29}Si rate of Fowler et al. (1975) is increased by a factor of 3 over the whole temperature range, then the ^{29}Si/^{30}Si ratio increases by a factor of 1.8, with the ^{30}Si abundance largely unchanged. This is roughly what is needed to account for the Si-isotopic signature of grain KJB2-11-17-1 and underlines the need for a re-measurement of the ^{26}Mg(α, n)^{29}Si rate. A recent re-measurement of the ^{29}Si(n, γ)^{30}Si rate for $T_9 < 0.6$ by Guber et al. (2003) has confirmed the rate determined by Bao et al. (2000) within experimental uncertainties, although the rates for (n, γ) reactions on ^{28}Si and especially ^{30}Si turned out to be lower than determined by Bao et al. (2000).

SNII are the most important supplier of ^{29}Si to the ISM (>80%; Timmes & Clayton 1996). Since the O/Si and O/Ne zones contribute some 90% of the ejected ^{29}Si, changes in the ^{29}Si yield in these zones will heavily influence the Galactic ^{29}Si inventory. It is beyond the scope of this Letter to perform a detailed calculation of the abundance evolution of ^{29}Si in our Galaxy with a revised ^{29}Si yield. Instead, we investigate how ^{29}Si/^{28}Si ratios will change in the ejecta of 15, 19, and 25 $M_\odot$ SNII (Rauscher et al. 2002) if the ^{29}Si yield in the O/Si and O/Ne zones is increased by a factor of 2. If we mix the ejecta from these SNII (considering relative abundances expected from the IMF), we obtain δ^{29}Si $= -475$‰ at the time and place of the formation of the Solar System, qualitatively in agreement with the predictions by Timmes & Clayton (1996) from their GCE model. If we increase the ^{29}Si yield in the O/Si and O/Ne zones by a factor of 2, we obtain δ^{29}Si $= +5$‰, i.e., a value very close to solar. It is hoped that future nuclear experiments will provide a more precise determination of the ^{26}Mg(α, n)^{29}Si reaction rate to be included in SN models. It will then be of interest to re-evaluate predictions for the ^{29}Si/^{28}Si ratio using detailed GCE models.

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