s-Process in Massive Carbon-Enhanced Metal-Poor Stars

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ABSTRACT

Observations suggest that the interstellar medium (ISM) might have been highly enriched in carbon at very early times. We explore the presupernova nucleosynthesis in massive carbon-enhanced metal-poor (CEMP) stars of 12–40$M_\odot$ formed from such an ISM with [Fe/H] $\leq -2$. We find substantial production of elements heavier than Fe, mostly up to Sr, by the weak s-process in stars with initial abundances of [C/H] $\gtrsim -1.5$. Even heavier elements up to Ba can also be produced for [C/H] $\gtrsim -0.5$. The efficiency of this s-process is sensitive to the initial C enhancement and mass of the star, with the yield of heavy elements increasing approximately linearly with the initial Fe abundance. The s-process in CEMP stars of $\gtrsim 20M_\odot$ with initial abundances of [C/H] $\gtrsim -1.5$ can be an important source for heavy elements in the early Galaxy.

1. INTRODUCTION

Chemical abundances of low-mass stars typically represent the composition of the interstellar medium (ISM) from which they formed. Thus, surface abundances of very metal-poor (VMP) stars of $\lesssim 0.8M_\odot$ with [Fe/H] = log(Fe/H) - log(Fe/H)$_\odot$ $\lesssim -2$ can provide a direct window on the composition of the ISM within $\sim 1$ Gyr of the Big Bang. With a large number of observed VMP stars, it has now become clear that there exists a distinct class of carbon-enhanced metal-poor (CEMP) stars with high enhancement of C over Fe relative to the Sun. The nominal criterion for this classification is [C/Fe] $\geq +0.7$ (Aoki et al. 2007). CEMP stars that do not show any enhancement in neutron-capture elements ([Ba/Fe] $\leq 0$), the so-called CEMP-no stars (Beers & Christlieb 2005), constitute $\sim 20\%$, 40%, and 80% of all VMP stars with [Fe/H] $\leq -2$, $-3$, and $-4$, respectively (Yong et al. 2013; Placco et al. 2014). CEMP-no stars are widely thought to have formed from an ISM polluted by only the first or very early core-collapse supernovae (CCSNe) associated with massive VMP stars. Current models for nucleosynthesis and explosion of massive VMP stars can explain the abundances observed in CEMP-no stars reasonably well. These models involve either CCSNe of low to medium explosion energy that preferentially eject C and other light elements relative to the Fe group (Umeda & Nomoto 2005; Nomoto et al. 2005; Heger & Woosley 2010; Tominaga et al. 2014) or winds enriched in CNO from fast-rotating massive stars (Meynet et al. 2006). In either case, the very early ISM became enhanced in C over Fe relative to the Sun. Low-mass stars of $\lesssim 0.8M_\odot$ formed from such an ISM would be observed as CEMP-no stars today. In contrast, massive CEMP stars of $> 10M_\odot$ formed from the same ISM would have exploded as CCSNe within $\sim 10$ Myr of their birth. These massive CEMP stars, however, can have interesting nucleosynthesis due to their C enhancement, thereby potentially providing an important source for chemical enrichment of the early Galaxy.

In this Letter we study the pre-CCSN nucleosynthesis of massive CEMP stars. We show that they can produce heavy elements with mass numbers up to $A \sim 90-140$ by the slow neutron-capture process (s-process) and serve as an effective source for these elements in the early Galaxy. Whereas a similar s-process has been shown to operate in fast-rotating massive VMP stars without C enhancement (Pignatari et al. 2008; Frischknecht et al. 2012, 2016), our study differs in that we focus on non-rotating massive CEMP stars.

2. METHODS

We study the nucleosynthesis in non-rotating CEMP stars of 12–40$M_\odot$ using the 1D hydrodynamical code KEPLER (Weaver et al. 1978; Rauscher et al. 2003).
The results from Big Bang nucleosynthesis are adopted for the initial abundances of H to Li. Scaled solar abundances (Asplund et al. 2009) are assumed for stable isotopes from $^9$Be to $^{70}$Zn, except that $^{12}$C, $^{14}$N, and $^{16}$O are enhanced over the rest. Specifically, we take $[C/H] = -2$ to 0 and $[Fe/H] = -5$ to $-2$ while keeping $[C/Fe] \geq 1$.

We follow the nucleosynthesis from the birth of a star until its death in a CCSN using a large adaptive post-processing network with the same reaction rates as in Rauscher et al. (2002). In particular, we use the rate of $^{22}$Ne during core. Then all of the $^{14}$N is converted to $^{14}$N during core He burning. By the time the He core becomes convective, almost all of the initial CNO have been effectively converted to $^{22}$Ne, which can provide a neutron source through $^{22}$Ne to produce a neutron source through $^{22}$Ne to produce $^{25}$Mg during the subsequent evolution. The efficiency of the s-process, however, depends on the neutron density, which is determined by the competition between production by the neutron source and capture by neutron poisons. For a normal star, the effects of neutron poisons render the weak s-process inefficient unless the initial metallicity of the star is $[Fe/H] \gtrsim -1$. In contrast, the enhanced initial abundances of CNO facilitate an efficient s-process in a CEMP star with $[Fe/H] \lesssim -2$ and $[C/Fe] \gtrsim 1$. Below we present the results from our studies of the s-process in such CEMP stars of 12–40$M_\odot$.

The reaction $^{22}$Ne($\alpha$, $n$)$^{25}$Mg is sensitive to temperature. For most part of the core He burning, the temperature remains $\lesssim 2.3 \times 10^8$ K, which is too low to activate this reaction. It is activated only when the $^4$He mass fraction drops to $\lesssim 0.1$ during the late stage of core He burning. Its sensitivity to temperature directly affects the efficiency of the s-process during this phase. The temperature is higher for stars of higher masses. For example, when the central $^4$He mass fraction drops to 0.01, the central temperature is $\sim 2.4 \times 10^8$ and $\sim 2.8 \times 10^8$ K for 12$M_\odot$ and 25$M_\odot$ models, respectively. This seemingly minor temperature difference corresponds to a difference in the $^{22}$Ne($\alpha$, $n$)$^{25}$Mg rate by a factor of $\sim 50$. Consequently, in more massive stars, a larger fraction of $^{22}$Ne is burned to produce neutrons, which leads to a more efficient s-process during the late stage of core He burning.

Regardless of its mass, the star runs out of $^4$He before $^{22}$Ne is consumed. In fact, most of the $^{22}$Ne survives at the end of core He burning in stars of $\gtrsim 15M_\odot$ and a considerable fraction survives in those of higher masses. The remaining $^{22}$Ne can be used for further neutron production when $\alpha$-particles are provided through $^{12}$C($^{12}$C, $\alpha$)$^{20}$Ne during the subsequent evolution. The resulting additional s-process acts on the products left behind by the s-process during core He burning. Unfortunately, only a small fraction of this material can be ejected during the CCSN whereas most of it becomes part of the Fe core that collapses into a neutron star or black hole. Nevertheless, the additional s-process does occur in some material left behind by core He burning that lies outside the region eventually forming the Fe core. This process occurs during shell C burning associated with core O burning and during shell He burning when the temperature at the base of the He shell increases above $\sim 2.5 \times 10^8$ K as the star contracts during core C and O burning. We find that the s-process mainly occurs during shell He burning for stars of $\gtrsim 15M_\odot$ and during core He burning for those of higher masses.

3. RESULTS

It is well known that the weak s-process occurs during the pre-CCSN evolution of massive stars (Peters 1968; Couch et al. 1974; Lamb et al. 1977; Raiteri et al. 1991; Pignatari et al. 2010). The initial $^{12}$C and $^{16}$O in a star are first converted to $^{14}$N during core burning. Then all of the $^{14}$N is converted to $^{22}$Ne via $^{14}$N($\alpha$, $\gamma$)$^{18}$F(e$^+$, $\nu_e$)$^{18}$O($\alpha$, $\gamma$)$^{22}$Ne at the start of core He burning. By the time the He core becomes convective, almost all of the initial CNO have been effectively converted to $^{22}$Ne, which can provide a neutron source through $^{22}$Ne($\alpha$, $n$)$^{25}$Mg during the subsequent evolution. The efficiency of the s-process, however, depends on the neutron density, which is determined by the competition between production by the neutron source and capture by neutron poisons. For a normal star, the effects of neutron poisons render the weak s-process inefficient unless the initial metallicity of the star is $[Fe/H] \gtrsim -1$. In contrast, the enhanced initial abundances of CNO facilitate an efficient s-process in a CEMP star with $[Fe/H] \lesssim -2$ and $[C/Fe] \gtrsim 1$. Below we present the results from our studies of the s-process in such CEMP stars of 12–40$M_\odot$.

3.1. Dependence on $[C/H]$, stellar mass, and $[Fe/H]$

Because the $^{22}$Ne providing the neutron source is produced by burning the initial CNO, the initial $[C/H]$ representing the CNO abundances is critical to the weak s-process in massive CEMP stars. There is very little s-processing for $[C/H] \leq -2$. As $[C/H]$ increases from $-2$ to 0, the efficiency of the s-process increases dramatically (see Fig. 1 and Table 1). For example, for 25$M_\odot$ models with $[Fe/H] = -3$, the Sr yield increases by a factor of $\sim 600$ ($4 \times 10^4$) when $[C/H]$ increases from $-2$ to $-1.5$ ($-1$). For $[C/H] > -1$, the $^{22}$Ne abundance becomes so high that a significant
amount of $^{25,26}\text{Mg}$ is produced by $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ and $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$. Whereas these secondary neutron poisons become important, their effects are more than compensated by the increased neutron production due to the high $^{22}\text{Ne}$ abundance. Consequently, the Sr yield further increases by a factor of $\sim 100$ when $[C/H]$ increases from $-1$ to $0$ (see Fig. 1 and Table 1).

![Figure 1](image1.png)

Figure 1. Post-CCSN number yields of heavy elements for $25\text{M}_\odot$ models with a fixed $[\text{Fe}/\text{H}] = -3$ but varying values of $[C/H] = -2$ (dotted black), $-1.5$ (dotted blue), $-1.2$ (dotted magenta), $-1$ (dashed red), $-0.5$ (dashed blue), $-0.2$ (dashed magenta), and $0$ (dashed black).

The mass of a CEMP star also plays a vital role in its $s$-process. Because $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ is very sensitive to temperature, neutron production is more efficient in more massive stars that burn He at higher temperature. In addition, a more massive star has a larger He core, which allows more material to undergo $s$-processing. The above two effects cause the efficiency of the $s$-process to increase with the stellar mass. This trend is particularly strong in comparing models of $\sim 12\text{M}_\odot$ to those of $\gtrsim 20\text{M}_\odot$ (see Fig. 2 and Table 1). For example, for models with $[\text{Fe}/\text{H}] = -3$ and $[C/H] = -1$, the Sr yield of a $12\text{M}_\odot$ star is $\sim 800$ times lower than that of a $25\text{M}_\odot$ star. The trend is less dramatic but still substantial for stars of $\gtrsim 20\text{M}_\odot$. For example, the Sr yield of a $25\text{M}_\odot$ star is $\sim 10$ times lower than that of a $35\text{M}_\odot$ star for models with $[\text{Fe}/\text{H}] = -3$ and $[C/H] = -1$ (see Fig. 2 and Table 1).

As can be seen from the above discussion, the initial $[C/H]$ and the mass of a CEMP star are the two key factors governing neutron production for its $s$-process. As discussed below, the main neutron poisons are the primary $^{16}\text{O}$ produced by He burning and the secondary $^{25,26}\text{Mg}$ produced by $^{22}\text{Ne}$ burning. Because neither the neutron source nor the main poisons depend on the initial $[\text{Fe}/\text{H}]$, this parameter has little impact on the efficiency of the $s$-process. Its role in this process is almost solely to provide the seeds for neutron capture. Table 2 shows the yields of heavy elements for $25\text{M}_\odot$ models with a fixed $[C/H] = -1$ but varying values of $[\text{Fe}/\text{H}] = -5$ to $-2$. These yields scale almost linearly with the number abundance ($\text{Fe}/\text{H}$) as $[\text{Fe}/\text{H}]$ increases from $-5$ to $-3$. The increases in the yields of Sr, Y, and Zr from $[\text{Fe}/\text{H}] = -3$ to $-2$ still follow this linear scaling within a factor of $\sim 2$.

![Figure 2](image2.png)

Figure 2. (a) Post-CCSN number yields of heavy elements for models with fixed $[\text{Fe}/\text{H}] = -3$ and $[C/H] = -1$ but varying masses of 12 (dotted black), 15 (dotted blue), 20 (dotted magenta), 25 (dashed red), 30 (dashed blue), 35 (dashed magenta), and 40$\text{M}_\odot$ (dashed black). (b) Same as (a), but for models with $[C/H] = 0$.

3.2. Neutron poisons

Although the $s$-process in massive CEMP stars is similar to the well-known weak $s$-process at higher metallicities, there are some important differences, the most crucial of which has to do with neutron poisons. As
mentioned above, the s-process in CEMP stars occurs mainly during shell He burning for stars of \( M \lesssim 15M_\odot \) and during the late stage of core He burning for those of higher masses. The main neutron poisons during these phases are the primary \(^{16}\text{O}\) produced by He burning and the secondary \(^{25,26}\text{Mg}\) produced by \(^{22}\text{Ne}\) burning. The primary nature of the former comes from the independence of the initial metallicity for its production, whereas the secondary nature of the latter is due to the dependence on the initial CNO abundances for the supply of \(^{22}\text{Ne}\). Because of this difference, \(^{16}\text{O}\) is the dominant poison for stars with initial abundances of \([\text{C}/\text{H}] \lesssim -1\) and \(^{25,26}\text{Mg}\) take over for \([\text{C}/\text{H}] > -1\).

The above discussion of neutron poisons largely holds for normal massive stars as well. Without any C enhancement, however, the initial abundances of CNO for these stars are commensurate with those of other metals, some of which, such as \(^{20}\text{Ne}\), \(^{24}\text{Mg}\), and \(^{28}\text{Si}\), are also neutron poisons. The end result is that the weak s-process becomes efficient in normal stars only when their initial metallicities are \([\text{Fe}/\text{H}] \gtrsim -1\). The dominant neutron poisons in this case are \(^{25,26}\text{Mg}\).

When the s-process occurs during shell He burning or the late stage of core He burning in our models, the primary \(^{16}\text{O}\) is the predominant isotope with a mass fraction of \( \gtrsim 0.8\). This large abundance enables \(^{16}\text{O}\) to be the dominant poison for stars with initial abundances of \([\text{C}/\text{H}] \lesssim -1\). For stars with \([\text{C}/\text{H}] > -1\), however, \(^{25,26}\text{Mg}\) become the dominant poisons because the neutron-capture cross section for \(^{16}\text{O}\) is much smaller than those for \(^{25,26}\text{Mg}\). In addition, the effectiveness of \(^{16}\text{O}\) as a neutron poison is greatly reduced at He-burning temperatures due to neutron regeneration through \(^{17}\text{O}(\alpha, n)^{20}\text{Ne}\) following \(^{16}\text{O}(n, \gamma)^{17}\text{O}\). Specifically, for the neutron density achieved during the s-process, the rate of \(^{16}\text{O}(n, \gamma)^{17}\text{O}\) is orders of magnitude slower than that of \(^{17}\text{O}(\alpha, n)^{20}\text{Ne}\). The latter is also a factor of \(\kappa \sim 13\)–15 higher than the rate of \(^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}\) at temperatures of \(\sim (2.5\)–3\() \times 10^8\) K relevant for the s-process. As a result, the effective rate of neutron capture by \(^{16}\text{O}\) is reduced by a factor of \(\sim \kappa\).

The value of \(\kappa \sim 13\)–15 relevant for the s-process corresponds to the rates of Caughlan & Fowler (1988) for \(^{17}\text{O}(\alpha, n)^{20}\text{Ne}\) and \(^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}\), which are the default rates for these two reactions used in our study. Descouvemont (1993) gave a \(\kappa\) three orders of magnitude larger. Such a large \(\kappa\) would drastically increase the efficiency of the s-process in stars with initial abundances of \([\text{C}/\text{H}] \lesssim -1\), for which \(^{16}\text{O}\) is the dominant neutron poison. Recent measurements of \(^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}\) and \(^{17}\text{O}(\alpha, n)^{20}\text{Ne}\) by Best et al. (2011, 2013), however, gave a \(\kappa\) within \(\sim 10\%\) of that from Caughlan & Fowler (1988). We note that recent studies of the s-process in fast-rotating “spinstars” by Frischknecht et al. (2016) and Choplin et al. (2017) explored the effects of a lower rate for \(^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}\) citing unpublished measurements. To explore such a possibility as well, we reduce the rate of \(^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}\) from its default value by a factor of 3 and 10, respectively, for \(25M_\odot\) models with \([\text{Fe}/\text{H}] = -3\) and varying values of \([\text{C}/\text{H}]\) from -2 to 0. As expected, the reduced rate has a strong effect on the s-process for models with \([\text{C}/\text{H}] \lesssim -1\), but has a rather small impact for \([\text{C}/\text{H}] = 0\), in which case \(^{25,26}\text{Mg}\) are the dominant neutron poisons (see Table 3). For example, when the rate is reduced by a factor of 3, the Sr yield increases by a factor of 475, 13, and 1.3 for models with \([\text{C}/\text{H}] = -2, -1,\) and 0, respectively. The reduced rate has an even stronger effect on the s-process flow beyond \(^{88}\text{Sr}\). For example, when the rate is reduced by a factor of 10, the Zr yield increases by six and two orders of magnitude for models with \([\text{C}/\text{H}] = -2\) and -1, respectively.

3.3. Production of elements beyond Sr

The s-process flow slows down greatly when it encounters \(^{88}\text{Sr}\) with the magic neutron number \(N = 50\), which usually marks the effective end point for the weak s-process. This feature can be clearly seen from Fig. 1, which shows steeply decreasing yields of elements beyond Sr with negligible Ba production for models with \([\text{C}/\text{H}] \lesssim -1\). For the most C-rich models with \([\text{C}/\text{H}] = 0\), however, substantial s-process flow proceeds beyond \(^{88}\text{Sr}\) for stars of \(\gtrsim 20M_\odot\) with comparable yields of Sr and Zr (see Table 1). For stars of \(\gtrsim 30M_\odot\), the s-process is even able to produce substantial amounts of Ba with \([\text{Sr}/\text{Ba}]\) as low as \(\sim 0.3\). As can be seen from Table 3, decreasing the \(^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}\) rate also results in considerable increase in the yields of elements beyond Sr, especially for models with \([\text{C}/\text{H}] \lesssim -1\).

4. DISCUSSION AND CONCLUSIONS

We have studied pre-CCSN nucleosynthesis in CEMP stars of \(12\)–\(40M_\odot\) with initial abundances of \([\text{Fe}/\text{H}] \leq -2\) and \([\text{C}/\text{H}] = -2\) to 0. We find that the enhanced initial CNO abundances of such a star enable a weak s-process whose efficiency is determined by the \([\text{C}/\text{H}]\) and the mass of the star and whose yields scale approximately linearly with the \([\text{Fe}/\text{H}]\) of the star. The s-process is especially efficient in stars of \(\gtrsim 20M_\odot\) with \([\text{C}/\text{H}] \gtrsim -1.5\), producing mainly elements up to Zr (\(A \sim 90\)) with \([\text{Sr}/\text{Zr}] \sim -0.3\) to 1.6. For the most C-rich (\([\text{C}/\text{H}] = 0\)) stars studied here, comparable amounts of Sr and Zr (\([\text{Sr}/\text{Zr}] \sim -0.2\)) are produced in stars of \(\gtrsim 30M_\odot\), along with substantial amounts of Ba.
(\([\text{Sr/Ba}] \sim 0.3\text{–}0.8\)). We also have explored the effects of reducing the \(^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}\) rate from the default value given by Caughlan & Fowler (1988) and found dramatically increased s-process yields. Our main results, however, are based on the default rate, which is in agreement with the published measurement of Best et al. (2011).

As noted in the introduction, the s-process in massive CEMP stars is very similar to that in spinstars, which are fast-rotating massive VMP stars with normal initial CNO abundances (Pignatari et al. 2008; Frischknecht et al. 2016). The main difference between these two s-process models is in the production of the \(^{22}\text{Ne}\) that provides the neutron source. In CEMP stars the \(^{22}\text{Ne}\) is produced by burning the initial CNO, whereas in spinstars it is made by burning the primary \(^{14}\text{N}\) whose production is facilitated by rotation-induced mixing. It is difficult to assess the frequency of occurrences for spinstars in the early Galaxy. In contrast, observations show that CEMP-no stars constitute \(\sim 20\%\) of the low-mass VMP stars (Yong et al. 2013; Placco et al. 2014). As CEMP-no stars are thought to reflect the composition of the ISM polluted by the first or very early massive stars, formation of massive CEMP stars from the same ISM must also be relatively common. In a recent compilation of 125 CEMP-no stars by Yoon et al. (2016), 24 (\(\sim 19\%\)) have \([\text{C/H}] > -1.5\) with corrections for depletion during evolution (Placco et al. 2014). Furthermore, 12 (\(\sim 10\%\)) such stars have \([\text{C/H}] > -1\) and 5 (4\%) have \([\text{C/H}] > -0.5\). If this distribution of \([\text{C/H}]\) extends to massive CEMP stars, a significant fraction of them would have had an efficient s-process, and therefore, made important contributions of heavy elements to the early Galaxy.

A recent study by Hansen et al. (2016) found that among the low-mass CEMP stars enhanced in heavy elements of the s-process origin, the so-called CEMP-s stars (Beers & Christlieb 2005), \(\sim 10\text{–}30\%\) could be single stars. The surface abundances of these stars would reflect the composition of their birth ISM instead of pollution by binary companions as for the rest of the CEMP-s stars. The origin of the heavy elements in single CEMP-s stars was investigated by Banerjee et al. (2017). The C abundances of \([\text{C/H}] \sim -0.5\) in some of these stars (Spite et al. 2013) reinforce the indication from CEMP-no stars that some early ISM was highly enriched in C. Massive CEMP stars formed from such ISM would produce significant amounts of Ba by the s-process discussed here and contribute Ba and associated heavy elements to stars of the subsequent generation.

The ejecta from a typical CCSN would be mixed with \(\sim 10^3\text{–}10^4M_{\odot}\) of ISM. Massive CEMP stars of \(\gtrsim 25M_{\odot}\) with initial abundances of \([\text{C/H}] = -1\) and \([\text{Fe/H}] = -3\) would enrich the ISM with log \(\epsilon(\text{Sr})\) \(\sim -1.6\) to 0.6, which is in agreement with the range observed in many VMP stars with \([\text{Fe/H}] \gtrsim -3\). Scaling the Sr yield with \([\text{Fe/H}]\), we obtain the enrichment by similar CEMP stars but with \([\text{Fe/H}] = -4\) to be log \(\epsilon(\text{Sr})\) \(\sim -2.6\) to \(-0.4\), which is in agreement with the typical Sr abundances of VMP stars with \(-4 \lesssim [\text{Fe/H}] \lesssim -3\) (Suda et al. 2008). Likewise, CEMP stars of \(\gtrsim 25M_{\odot}\) with initial abundances of \([\text{C/H}] = 0\) and \([\text{Fe/H}] = -3\) would provide \(-1.5 \lesssim \log \epsilon(\text{Ba}) \lesssim 0.8\) along with \(0.4 \lesssim \log \epsilon(\text{Sr}) \lesssim 1.8\), and these results can be scaled to estimate the enrichment by similar stars but with different \([\text{Fe/H}]\). In conclusion, the s-process in massive CEMP stars have rather interesting implications for chemical evolution of the early Galaxy.

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Table 1. Post-CCSN yields (in $M_{\odot}$) of Sr, Y, Zr, Ba, and Pb. Models are labelled as (mass/$M_{\odot}$, [Fe/H], [C/H]) and $X(Y) \equiv X \times 10^{Y}$.

| Model   | Sr      | Y       | Zr     | Ba     | Pb      | [Sr/Y] | [Sr/Zr] | [Sr/Ba] |
|---------|---------|---------|--------|--------|---------|--------|---------|---------|
| (40, -3, -2) | 3.00(-11) | 1.09(-12) | 4.05(-13) | 0      | 0       | 0.74   | 1.53    |         |
| (40, -3, -1.5) | 4.81(-9)  | 3.97(-10) | 1.71(-10) | 0      | 0       | 0.38   | 1.11    |         |
| (40, -3, -1)  | 2.91(-7)  | 3.79(-8)  | 2.80(-8)  | 5.16(-12) | 0       | 0.18   | 0.68    | 4.45    |
| (40, -3, -0.5) | 2.89(-6)  | 6.53(-7)  | 9.81(-7)  | 1.44(-8) | 3.15(-12) | -0.06  | 0.13    | 1.80    |
| (40, -3, 0)   | 4.31(-6)  | 1.39(-6)  | 3.61(-6)  | 5.94(-7) | 1.63(-9) | -0.22  | -0.26   | 0.36    |
| (35, -3, -2)  | 9.30(-12) | 2.22(-13) | 6.85(-14) | 0      | 0       | 0.92   | 1.79    |         |
| (35, -3, -1.5) | 2.66(-9)  | 1.50(-10) | 7.42(-11) | 0      | 0       | 0.54   | 1.21    |         |
| (35, -3, -1)  | 1.51(-7)  | 1.43(-8)  | 1.26(-8)  | 1.34(-12) | 0       | 0.32   | 0.74    | 4.55    |
| (35, -3, -0.5) | 2.04(-6)  | 3.49(-7)  | 6.46(-7)  | 6.21(-9) | 3.00(-13) | 0.06   | 0.16    | 2.01    |
| (35, -3, 0)   | 3.69(-6)  | 8.75(-7)  | 3.01(-6)  | 3.35(-7) | 5.36(-10) | -0.08  | -0.25   | 0.54    |
| (30, -3, -2)  | 2.21(-12) | 4.94(-14) | 1.50(-14) | 0      | 0       | 0.95   | 1.83    |         |
| (30, -3, -1.5) | 1.01(-9)  | 4.89(-11) | 1.91(-11) | 0      | 0       | 0.61   | 1.38    |         |
| (30, -3, -1)  | 6.87(-8)  | 5.89(-9)  | 4.89(-9)  | 2.35(-13) | 0       | 0.36   | 0.81    | 4.96    |
| (30, -3, -0.5) | 1.29(-6)  | 1.83(-7)  | 3.50(-7)  | 2.20(-9) | 4.67(-14) | 0.14   | 0.23    | 2.26    |
| (30, -3, 0)   | 2.65(-6)  | 4.73(-7)  | 1.93(-6)  | 1.34(-7) | 1.46(-10) | 0.04   | -0.20   | 0.79    |
| (25, -3, -2)  | 4.17(-13) | 9.01(-15) | 3.30(-15) | 0      | 0       | 0.96   | 1.76    |         |
| (25, -3, -1.5) | 2.49(-10) | 9.77(-12) | 3.01(-12) | 0      | 0       | 0.70   | 1.58    |         |
| (25, -3, -1)  | 3.53(-9)  | 2.35(-10) | 1.27(-10) | 2.41(-18) | 0       | 0.47   | 1.10    | 8.66    |
| (25, -3, -0.5) | 1.57(-8)  | 1.25(-9)  | 8.79(-10) | 7.61(-15) | 0       | 0.40   | 0.91    | 5.81    |
| (25, -3, -0.2) | 5.15(-7)  | 6.68(-8)  | 9.87(-8)  | 2.19(-10) | 5.79(-16) | 0.18   | 0.38    | 2.87    |
| (25, -3, 0)   | 1.21(-6)  | 2.09(-7)  | 4.67(-7)  | 6.65(-9) | 6.40(-13) | 0.06   | 0.08    | 1.76    |
| (20, -3, -2)  | 2.58(-13) | 2.43(-14) | 8.29(-14) | 0      | 0       | 0.32   | 0.15    |         |
| (20, -3, -1.5) | 3.72(-11) | 4.19(-12) | 1.13(-11) | 0      | 0       | 0.24   | 0.18    |         |
| (20, -3, -1)  | 1.99(-9)  | 2.97(-10) | 5.84(-10) | 2.26(-17) | 0.00    | 0.12   | 0.19    | 7.44    |
| (20, -3, -0.5) | 8.83(-8)  | 1.15(-8)  | 2.21(-8)  | 7.11(-12) | 1.55(-17) | 0.18   | 0.26    | 3.59    |
| (20, -3, 0)   | 3.38(-7)  | 9.07(-8)  | 1.62(-7)  | 1.64(-9) | 7.64(-13) | -0.13  | -0.02   | 1.81    |
| (15, -3, -2)  | 2.24(-14) | 1.31(-16) | 1.32(-16) | 0      | 0       | 1.53   | 1.89    |         |
| (15, -3, -1.5) | 4.25(-13) | 9.22(-15) | 1.76(-13) | 0      | 0       | 0.96   | 0.04    |         |
| (15, -3, -1)  | 7.72(-11) | 5.34(-12) | 3.07(-11) | 1.91(-19) | 0       | 0.46   | 0.06    | 8.10    |
| (15, -3, -0.5) | 3.63(-9)  | 5.18(-10) | 9.31(-10) | 1.89(-13) | 0       | 0.14   | 0.25    | 3.78    |
| (15, -3, 0)   | 3.88(-8)  | 6.60(-9)  | 7.35(-9)  | 2.19(-11) | 1.59(-16) | 0.06   | 0.38    | 2.74    |
| (12, -3, -2)  | 6.14(-15) | 3.43(-17) | 2.63(-17) | 0      | 0       | 1.55   | 2.02    |         |
| (12, -3, -1.5) | 5.46(-14) | 7.01(-16) | 1.42(-16) | 0      | 0       | 1.19   | 2.24    |         |
| (12, -3, -1)  | 1.91(-11) | 1.17(-12) | 5.15(-13) | 0      | 0       | 0.51   | 1.23    |         |
| (12, -3, -0.5) | 1.12(-9)  | 1.58(-10) | 1.46(-10) | 4.10(-14) | 0       | 0.15   | 0.55    | 3.93    |
| (12, -3, 0)   | 1.41(-8)  | 3.02(-9)  | 4.65(-9)  | 8.81(-11) | 5.37(-14) | -0.04  | 0.14    | 1.70    |
Table 2. Post-CCSN yields (in $M_\odot$) of Sr, Y, Zr, Ba, and Pb for $25 M_\odot$ models with $[\text{C/H}] = -1$ but varying values of $[\text{Fe/H}] = -5$ to $-2$. Notations are the same as for Table 1.

| Model         | Sr    | Y     | Zr     | Ba     | Pb    | [Sr/Y] | [Sr/Zr] | [Sr/Ba] |
|---------------|-------|-------|--------|--------|-------|--------|---------|---------|
| (25, −5, −1) | 2.16  | 1.77  | 1.31   | 1.59   | 0     | 0.38   | 0.88    | 5.63    |
| (25, −4, −1) | 1.96  | 1.59  | 1.15   | 1.59   | 0     | 0.39   | 0.89    | 5.59    |
| (25, −3, −1) | 1.57  | 1.25  | 8.79   | 7.61   | 0     | 0.40   | 0.91    | 5.81    |
| (25, −2, −1) | 9.50  | 7.11  | 1.23   | 4.76   | 0     | 0.42   | 0.95    | 6.38    |

Table 3. Post-CCSN yields (in $M_\odot$) of Sr, Y, Zr, Ba, and Pb for $25 M_\odot$ models with $[\text{Fe/H}] = -3$ and varying values of $[\text{C/H}] = -2$ to 0 assuming different rates for $^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}$. Notations are the same as for Table 1.

| Model         | $^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}$ | Sr    | Y     | Zr     | Ba     | Pb    | [Sr/Y] | [Sr/Zr] | [Sr/Ba] |
|---------------|--------------------------------------|-------|-------|--------|--------|-------|--------|---------|---------|
| (25, −3, −2)  | CF88                                 | 4.17  | 9.01  | 3.30   | 0      | 0     | 0.96   | 1.76    |         |
| (25, −3, −2)  | CF88/3                               | 1.98  | 4.08  | 3.99   | 3.14   | 0     | −0.02  | 0.36    | 5.29    |
| (25, −3, −2)  | CF88/10                              | 5.64  | 1.33  | 1.79   | 1.96   | 0     | −0.08  | 0.16    | 2.95    |
| (25, −3, −1)  | CF88                                 | 1.57  | 1.25  | 8.79   | 7.61   | 0     | 0.40   | 0.91    | 5.81    |
| (25, −3, −1)  | CF88/3                               | 2.11  | 2.31  | 2.26   | 1.04   | 0     | 0.26   | 0.64    | 3.80    |
| (25, −3, −1)  | CF88/10                              | 6.95  | 9.77  | 1.22   | 3.44   | 1.80  | 0.15   | 0.42    | 2.80    |
| (25, −3, 0)   | CF88                                 | 1.58  | 3.13  | 8.78   | 3.10   | 1.28  | 0      | −0.09   | 1.20    |
| (25, −3, 0)   | CF88/3                               | 2.09  | 4.70  | 1.54   | 1.60   | 2.49  | −0.06  | −0.21   | 0.61    |
| (25, −3, 0)   | CF88/10                              | 2.16  | 4.93  | 1.79   | 2.86   | 8.50  | −0.06  | −0.26   | 0.37    |