NUCLEOSYNTHESIS OF ZINC AND IRON PEAK ELEMENTS IN POPULATION III TYPE II SUPERNOVAE: COMPARISON WITH ABUNDANCES OF VERY METAL POOR HALO STARS

HIDEYUKI UMEDA AND KEN'ICHI NOMOTO

Research Center for the Early Universe and Department of Astronomy, School of Science, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan; umeda@astron.s.u-tokyo.ac.jp, nomoto@astron.s.u-tokyo.ac.jp

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ABSTRACT

We calculate nucleosynthesis in core collapse explosions of massive Population III stars and compare the results with abundances of metal-poor halo stars to constrain the parameters of Population III supernovae. We focus on iron peak elements, and, in particular, we try to reproduce the large \([\text{Zn/Fe}]\) observed in extremely metal-poor stars. The interesting trends of the observed ratios \([\text{Zn, Co, Mn, Cr, V/Fe}]\) can be related to the variation of the relative mass of the complete and incomplete Si-burning regions in supernova ejecta. We find that \([\text{Zn/Fe}]\) is larger for deeper mass cuts, smaller neutron excess, and larger explosion energies. The large \([\text{Zn/Fe}]\) and \([\text{O/Fe}]\) observed in the very metal-poor halo stars suggest deep mixing of complete Si-burning material and a significant amount of fallback in Type II supernovae. Furthermore, large explosion energies \((E_{51} \gtrsim 2 \, \text{for } M \sim 13 \, M_\odot \text{ and } E_{51} \gtrsim 20 \, \text{for } M \gtrsim 20 \, M_\odot)\) are required to reproduce \([\text{Zn/Fe}] \sim 0.5\). The observed trends of the abundance ratios among the iron peak elements are better explained with this high-energy ("hypernova") model than with the simple "deep" mass cut effect because the overabundance of Ni can be avoided in the hypernova models. We also present the yields of pair instability supernova explosions of \(M \sim 130–300 \, M_\odot\) stars and discuss that the abundance features of very metal-poor stars cannot be explained by pair instability supernovae.

Subject headings: Galaxy: halo — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: Population II — supernovae: general

On-line material: color figures

1. INTRODUCTION

The abundance pattern of metal-poor stars with \([\text{Fe/H}] < -2\) \(([A/B] \equiv \log_{10} (A/B) - \log_{10} (A/B)_\odot)\) provides us with very important information on the formation, evolution, and explosions of massive stars in the early evolution of the galaxy (e.g., Wheeler, Sneden, & Truran 1989; Matteucci 2001). Those metal-poor stars may have been formed just a few generations after the first-generation Population III stars, or they may even represent the second generation (see, e.g., Weiss, Abel, & Hill 2000 for recent reviews). Their abundance patterns may be the result of nucleosynthesis even in one single Type II supernova (SN II) (Audouze & Silk 1995; Ryan, Norris, & Beers 1996; Shigeyama & Tsujimoto 1998; Nakamura et al. 1999). Therefore, comparisons with nucleosynthesis patterns in massive metal-poor stars may help constrain the explosion mechanism of SNe II (which is still quite uncertain), the initial mass function (IMF) of Population III stars, and the mixing of ejected material in the interstellar medium.

With the use of high-resolution spectroscopic devices attached to large telescopes, abundance measurements of extremely metal-poor stars have become possible (e.g., McWilliam et al. 1995; Ryan et al. 1996). The number and quality of the data are expected to increase with new large telescopes such as SUBARU and VLT. The observed abundances of metal-poor halo stars show quite interesting patterns. There are significant differences between the abundance patterns in the iron peak elements below and above \([\text{Fe/H}] \sim -2.5\). For \([\text{Fe/H}] \lesssim -2.5\), the mean values of \([\text{Cr/Fe}]\) and \([\text{Mn/Fe}]\) decrease toward smaller metallicity, while \([\text{Co/Fe}]\) increases.

For Zn, early observations have shown that \([\text{Zn/Fe}] \sim 0\) for \([\text{Fe/H}] \approx -3\) to 0 (Sneden, Gratton, & Crocker 1991). Recently, Primas et al. (2000) have suggested that \([\text{Zn/Fe}]\) increases toward smaller metallicity as seen in Figure 1, and Blake et al. (2001) have one with \([\text{Zn/Fe}] \sim 0.6\) at \([\text{Fe/H}] = -3.3\) (see Ryan 2001).

These trends could be explained with SN II nucleosynthesis, but progenitors and SN explosion models are significantly constrained. In SNe II, stellar material undergoes shock heating and the subsequent explosive nucleosynthesis. Iron peak elements including Cr, Mn, Co, and Zn are produced in two distinct regions, which are characterized by the peak temperature, \(T_{\text{peak}}\), of the shocked material. For \(T_{\text{peak}} > 5 \times 10^9\) K, material undergoes complete Si burning whose products include Co, Zn, V, and some Cr after radioactive decays. For \(4 \times 10^9 < T_{\text{peak}} < 5 \times 10^9\) K, incomplete Si burning takes place and its after decay products include Cr and Mn (e.g., Hashimoto, Nomoto, Shigeyama 1989; Woosley & Weaver 1995, hereafter WW95; Arnett 1996; Thielemann, Nomoto, & Hashimoto 1996).

We have discussed, using the progenitor models for solar metallicity (Nomoto & Hashimoto 1988), that the decreasing trend of Mn and Cr and the increasing trend of Co toward the lower metallicity can be explained simultaneously if the mass cut that divides the ejecta and the compact remnant tends to be deeper for more massive core collapse SNe (Nakamura et al. 1999). This is because Mn and Cr are produced mainly in the incomplete explosive Si-burning region, while Co is produced in the deeper complete explosive Si-burning region. The mass cut is typically located somewhere close to the border of complete and incomplete Si-burning regions. Therefore, the deeper mass cut leads to larger Co/Mn.

As for Zn, its main production site has not been clearly identified. If it is mainly produced by s-processes, the abundance ratio \([\text{Zn/Fe}]\) should decrease with \([\text{Fe/H}]\). This is not consistent with the observations of \([\text{Zn/Fe}] \sim 0\) for...
[Fe/H] ≃ −2.5 to 0 and the increase in [Zn/Fe] toward lower metallicity for [Fe/H] ≲ −2.5. Another possible site of Zn production is explosive burning in SNe II. However, previous nucleosynthesis calculations in SNe II appear to predict too small Zn/Fe ratio (WW95; Thielemann et al. 1996).

In the application to the Galactic chemical evolution model, it has been known that the Fe yield of the WW95 model was too large, and thus only the Fe yield (not Zn, etc.) has been reduced by a factor of 3 to better fit the observations (Timmes, Woosley, & Weaver 1995; Goswami & Prantzos 2000). This makes the [Zn/Fe] ratio larger, but still [Zn/Fe] ≲ 0. In addition, this procedure is not justified if Zn and Fe are produced in the same site. Hoffman et al. (1996) proposed another site for Zn, i.e., the neutrino-driven neutron star wind following the delayed explosion of a core collapse SN. Such a site has been considered for an r-process site (e.g., Woosley et al. 1994), and the Zn synthesis was found to be very sensitive to the wind condition such as neutron excess.

Understanding the origin of the variation in [Zn/Fe] is very important especially for studying the abundance of damped Lyα (DLA) systems because [Zn/Fe] = 0 is usually assumed, after the work by Sneden et al. (1991), to determine their abundance pattern. In DLA systems supersolar [Zn/Fe] ratios have often been observed, but they have been explained by assuming that dust depletion is larger for Fe than for Zn (e.g., Lu et al. 1996; Pettini et al. 1999; Prochaska & Wolfe 1999; Molaro et al. 2000; Hou, Boissier, & Prantzos 2001). However, recent observations (Primas et al. 2000; Blake et al. 2001) suggest that the assumption [Zn/Fe] = 0 may not always be correct.

In this paper, using recently calculated pre-SN models (§ 2; H. Umeda & K. Nomoto 2002, in preparation; Umeda, Nomoto, & Nakamura 2000), we study the nucleosynthesis pattern of iron peak elements, focusing on Zn, in massive Population III stars. We show that, depending on stellar masses, mass cuts, and explosion energies, large Zn/Fe can be achieved in the explosive nucleosynthesis yields of our SN II models of Population III stars (§§ 3 and 4). Since Zn and Co are mainly produced in the same region, their enhancement, the reduction of Mn and Cr, and the near constancy of Ni can be understood simultaneously with the same mechanism (§§ 4 and 5). We also discuss the reasons why previous models (Hashimoto et al. 1989; WW95; Thielemann et al. 1996; Nomoto et al. 1997) underproduce Zn (§ 4). Finally, we present the yields of the pair instability supernova (PISN) explosions of $M \approx 130$–300 $M_\odot$ stars and discuss that the abundance features of very metal-poor stars cannot be explained by PISNe (§ 5; Appendix).

2. EVOLUTION OF POPULATION III MASSIVE STARS

The elemental abundances in metal-poor halo stars may preserve nucleosynthesis patterns of the SN explosions of Population III stars for the following reasons. First, the IMF of very metal-poor stars ($Z \lesssim 10^{-2}$ to $10^{-3} Z_\odot$) can be similar to Population III stars, since the dominant cooling mechanism for interstellar matter is almost the same (Böhringer & Hensler 1989). Second, the nucleosynthesis patterns in the explosions of very metal-poor Population II stars ($Z < 10^{-2} Z_\odot$) are similar to those of Population III SNe (Umeda et al. 2000). In addition, a single SN event is likely to induce star formation for metallicity [Fe/H] ≃ −4 to −2, so that the observed metal-poor stars can be the second or very early generation (Ryan et al. 1996; Shigeyama & Tsujimoto 1998; Nakamura et al. 1999).

For these reasons, we use our Population III (metal-free) models to compare their explosive nucleosynthesis with the observed abundances of very low metal stars. We calculate the evolution of massive Population III stars for a mass range of $M = 13$–$30 M_\odot$ from pre–main-sequence to SN II explosions. Stellar evolution is calculated with a Henyey-type stellar evolution code (Umeda et al. 2000), which runs a large nuclear reaction network with 240 isotopes to calculate detailed nucleosynthesis and nuclear energy generation. For the Population III models we assumed no mass loss. SN explosions are simulated with a piecewise parabolic method code. The detailed nucleosynthesis during the explosion is calculated by postprocessing as in Nakamura et al. (2001), using a code of Hix & Thielemann (1996).

In the metal-free star evolution, CNO elements are absent during the early stage of hydrogen burning. Therefore, the CNO cycle does not operate initially, and the star contracts until the central temperature rises sufficiently high for the $3\alpha$ reaction to produce $^{12}$C with mass fraction $\sim 10^{-10}$ K. Then Population III stars undergo the CNO cycle at a much higher central temperature ($T_\mathrm{c} \sim 1.5 \times 10^8$ K) than metal-poor Population II stars (e.g., Ezer & Cameron 1971; Castellani, Chieffi, & Tornambè 1983). On the other hand, the late core evolution and the resultant Fe core masses of Population III stars are not significantly different from Population II stars (e.g., WW95; Limongi, Chieffi, & Straniero 1998; Umeda et al. 2000). In Table 1 we show the “Fe” core masses of our model defined as a region with the

Here $Y_e = \Sigma Z_i X_i / A_i$, is the electron mole number; $Z_i$, $X_i$, and $A_i$ are, respectively, the atomic number, mass fraction, and mass number for each species. With $Y_e$, neutron excess is defined as $\eta = 1 - 2Y_e$. 

Fig. 1.—Observed abundance ratios of [Zn/Fe]. These data are taken from Primas et al. (2000) (filled circles), Blake et al. (2001) (filled square), and Sneden et al. (1991) (open symbols).
TABLE 1
"Fe" Core Masses in $M_\odot$ Defined as a Region with $Y_e \leq 0.49$ for the Progenitor Models with $Z = 0, 10^{-4},$ and 0.02

| $Z$   | 13  | 15  | 20  | 25  | 30  |
|-------|-----|-----|-----|-----|-----|
| 0.....| 1.29| 1.38| 1.52| 1.70| 1.77|
| $10^{-4}$| 1.32| ... | 1.51| ... | ... |
| 0.02..| 1.27| 1.34| 1.52| 1.67| ... |

One of the major uncertainties in the calculations of stellar evolution is the treatment of convection. Here we use the models calculated with relatively slow convective mixing ($f_k = 0.05$ in the parameter described in Umeda et al. 2000). Larger $f_k$ leads to stronger mixing of nuclear fuel, thus resulting in stronger convective shell burning, which leads to smaller mass core and smaller mass compact remnants.

Fig. 2.—Distribution of neutron excess $\eta \equiv 1 - 2Y_e$ in the inner core at the beginning of collapse ($\rho_r \sim 3 \times 10^{10}$ g cm$^{-3}$) of the Population III pre-SN progenitor models with 13–25 $M_\odot$. 
3. SYNTHESIS OF ZINC IN POPULATION III SUPERNOVAE

We briefly summarize general nucleosynthesis of Population III SNe obtained in Umeda et al. (2000). The mass fraction ratio of odd- and even-Z elements (e.g., Al/Mg) and the inverse ratio of α-elements and their isotopes (e.g., 13C/12C) decrease for lower metallicity. However, the former ratios almost saturate for low metallicity (Z ≤ 10⁻³), and the latter ones are difficult to observe. Therefore, the differences in the nucleosynthesis pattern between the very metal-poor Population II and Population III stars are difficult to observe. The abundance ratios among the even-Z elements are almost independent of the metallicity. Dependencies on the mass and explosion energy are more important. These results suggest that in discussing the abundance pattern of very metal-poor stars, effects other than the metallicity are likely to be more important.

In the following subsections we discuss the dependence of the production of Zn and other iron peak elements on the progenitor mass, mass cut, and explosion energy separately. In order to clarify the site of Zn synthesis in our models, we first show in Figure 3 the ratio of the integrated pre-SN yield divided by the postexplosion yield in our 20 M☉ Population III model $\left[E_{51} = E_{\text{exp}}/(10^{51} \text{ ergs})\right]$. This indicates how much of each element is made by s-processes before explosion or explosive Si burning. This figure shows that elements heavier than Si are mostly synthesized in the explosion. In particular, Zn is almost entirely produced by explosive Si burning.

3.1. Dependence on Mass Cut ($M_{\text{cut}}$)

Here we discuss the dependence of yields on the mass cut, $M_r = M_{\text{cut}}$. The explosion energy is assumed to be $E_{51} = 1$. The abundance distribution for select species after explosion for 13 and 15 M☉ models is shown in Figure 4. Also indicated in this figure are the regions for the complete and incomplete Si burnings. The upper bounds of the complete Si-burning region and the incomplete Si-burning region are defined by $X(^{56}\text{Ni}) = 10^{-3}$ and $X(^{28}\text{Si}) = 10^{-4}$, respectively. The labeled elements V, Cr, Mn, Co, and Zn are the decay products of unstable $^{51}\text{Mn}$, $^{52}\text{Fe}$, $^{55}\text{Co}$, $^{59}\text{Cu}$, and $^{64}\text{Ge}$, respectively.

In the ejecta, the mass fraction of the complete Si-burning products is larger if the mass cut is deeper (i.e., $M_{\text{cut}}$ is smaller). Mn and Cr are produced mainly in the incomplete explosive Si-burning region, while Co and Zn are mainly produced in the deeper complete explosive Si-burning region. Therefore, if the mass cut is deeper, the abundance ratios Co/Fe and Zn/Fe increase, while the ratios Mn/Fe and Cr/Fe decrease as seen in Figure 5.

Figure 5 shows that larger [Zn, Co/Fe] and smaller [Cr, Mn/Fe] can be achieved simultaneously for a smaller $M_{\text{cut}}$. In the 13 M☉ model for for example, [Zn/Fe] is large enough to be consistent with the observed
ratio $[\text{Zn/Fe}] \approx 0.1$ for stars with $[\text{Fe/H}] \gtrsim -2$. More massive stars can also yield $[\text{Zn/Fe}] > 0$ if the mass cut is deep enough. The observed large ratio $[\text{Zn/Fe}] \approx 0.5$ in very metal-poor stars can only be achieved with the combination of deep mass cut and large explosion energy ($\S\,3.4$).

Another effect of the mass cut on the yield is the $^{56}\text{Ni}$ mass in the ejecta $M(^{56}\text{Ni})$, which is larger for smaller $M_{\text{cut}}$ as shown in Figure 5. Ejection of the large amount of radioactive $^{56}\text{Ni}$ has actually been seen in such bright SNe as SN 1997ef and SN 1998bw (e.g., Nomoto et al. 2000). We note that for $M \gtrsim 15 M_\odot$, the $M(^{56}\text{Ni})$ required to get $[\text{Zn/Fe}] \sim 0.5$ appears to be too large to be compatible with observations of $[\text{O/Fe}] \sim 0$–0.5 in metal-poor stars. However, if fallback of a large enough amount of iron peak
elements occur after mixing, \( M^{(56)\text{Ni}} \) can be smaller without changing the \([\text{Zn}/\text{Fe}]\) ratio, as will be discussed in § 3.5.

### 3.2. Dependence on Stellar Mass

Figure 5 shows that the relation between \([X/\text{Fe}]\) and \( M^{(56)\text{Ni}} \) is sensitive to the progenitor mass. To understand this behavior, we summarize in Table 2 the location of the incomplete Si-burning region \( M_\ast \) and \( M^{(56)\text{Ni}} \) contained in this region for several models. The thickness in mass of the incomplete Si-burning region \( [\text{and thus } M^{(56)\text{Ni}} \text{ there}] \) is larger for larger progenitor masses. Suppose that all SNe II eject the same amount of \( 56\text{Ni} \). Then the fraction of complete Si-burning products is larger for less massive stars because the incomplete Si-burning region is thinner. This is why the 13 \( M_\odot \) model yields larger \([\text{Zn}, \text{Co}/\text{Fe}]\) than more massive models if, for example, \( M^{(56)\text{Ni}} = 0.07 M_\odot \) (Fig. 5). Models heavier than 15 \( M_\odot \) are consistent with very metal-poor star data if \( M_{\text{cut}} \) is small \([\text{i.e., } M^{(56)\text{Ni}} \text{ is large}]\).

The maximum values of \([X/\text{Fe}]\) as a function of \( M_{\text{cut}} \) also depend on the stellar mass because of the different density-temperature histories and \( Y_e \) distribution of the progenitors. There is a tendency that the maximum \([\text{Zn}, \text{Co}/\text{Fe}]\) decreases with increasing stellar mass. One of the reasons for this trend is that more massive stars have a thicker incomplete Si-burning region, and thus deeper material must be ejected to make \([\text{Zn}, \text{Co}/\text{Fe}]\) large. As discussed in the next subsection, in the deeper regions \( Y_e \) is typically smaller, which leads also to smaller \text{Zn} and \text{Co} mass fractions. On the other hand, there is no clear mass dependence for \([\text{Mn}, \text{Cr}/\text{Fe}]\).

### 3.3. Dependence on \( Y_e \)

In order to see the dependence on \( Y_e \), we compare the postexplosive abundance distribution of the 25 \( M_\odot \) \( (E_{\text{e1}} = 1) \) models in Figure 6. The top panel shows the original model, whose \( Y_e \) distribution is enlarged in Figure 7. In the bottom panel \( Y_e \) is modified to be 0.5 at \( M \leq 2.5 M_\odot \). As shown in these figures, \text{Zn} and \text{Co} abundances are very sensitive to \( Y_e \). If \( Y_e \) decreases below \( Y_e \approx 0.4998 \), the \text{Zn} abundance becomes significantly smaller because \text{Zn} is the decay product of the symmetric species \( ^{64}\text{Ge} \). The dependence of the \text{Co} abundance on \( Y_e \) is not monotonic but rather complicated, although the \text{Co} abundance is larger in the \( Y_e = 0.5 \) model of this example. \([X(\text{Co}) \text{ is relatively large for } Y_e = 0.5. \text{ With lowering } Y_e, \text{ it decreases once but increases again toward } Y_e \approx 0.49. \text{ Previous progenitor models in Nomoto & Hashimoto (1988) have much lower } Y_e \text{ than our current models in the complete Si-burning region because of the different initial metallicity and treatment of convection, and this is the main reason why those models significantly underproduce Zn even for the 13 } M_\odot \text{ model.}

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**TABLE 2**

**Mass Coordinates in \( M_\odot \) of the Incomplete Si-burning Regions for Models with Several Initial Masses and Explosion Energies**

| \( M_\ast \) \( (M, E_{\text{e1}}) \) | \( M_{\text{Ni}} \) (Incomplete Si Burning) | \( M^{(56)\text{Ni}} \) |
|---|---|---|
| (13, 1) | 1.60–1.67 | 0.022 |
| (15, 1) | 1.87–2.06 | 0.052 |
| (20, 1) | 2.38–2.88 | 0.14 |
| (20, 5) | 2.82–3.38 | 0.15 |
| (25, 1) | 2.47–3.00 | 0.12 |
| (25, 10) | 3.13–3.87 | 0.18 |
| (30, 1) | 2.70–3.67 | 0.35 |
| (30, 20) | 4.28–5.58 | 0.36 |
| (30, 30) | 4.64–6.32 | 0.45 |

**Note.** The upper and lower bounds of the regions are defined by \( X^{(56)\text{Ni}} = 10^{-3} \) and \( X^{(54)\text{Si}} = 10^{-4} \), respectively. The \( ^{56}\text{Ni} \) mass values in \( M_\odot \) in these regions, \( \Delta M^{(56)\text{Ni}} \), are also shown.

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**Fig. 6.**—Abundance distribution after SN explosions of Population III 25 \( M_\odot \) stars with \( E_{\text{e1}} = 1 \). The top panel is the original model. In the bottom panel \( Y_e \) is modified to be 0.5 below \( M \leq 2.5 M_\odot \).
In our present progenitor models (as well as in Nomoto & Hashimoto 1988), we have applied electron capture rates by Fuller, Fowler, & Newman (1980, 1982). The use of the recent rates by Langanke & Martinez-Pinedo (2000), which are lower than those of Fuller et al. (1980, 1982), would lead to larger $Y_e$ (Heger et al. 2001). Mezzacappa et al. (2001) and Rampf & Janka (2000) have recently performed simulations of SNe II with full Boltzmann neutrino transports, and they have shown that $Y_e$ in the deep layers may be enhanced up to $\sim 0.5$ by neutrino processes.

In this case, Zn production may be significantly enhanced over what has been calculated in previous models. We should note that $X(Zn)$ can be large even if $Y_e \lesssim 0.4995$ for energetic explosion as will be discussed in the next subsection.

3.4. Dependence on Explosion Energy

Recent observations suggest that at least some core collapse SNe explode with large explosion energies, which may be called “hypernovae” (e.g., Galama et al. 1998; Iwamoto et al. 1998, 2000; Nomoto et al. 2000). These SNe likely originate from relatively massive SNe ($M \gtrsim 25 M_\odot$).

In Figure 8 we show nucleosynthesis in the $25 M_\odot$ star with the explosion energy of $10^{52}$ ergs. By comparing with Figure 6, we find that for larger explosion energies, the boundaries of both the complete and incomplete Si-burning regions move outward in mass coordinates. We also find that for a larger explosion energy the complete Si-burning region is thicker in mass, thus containing a larger amount of $^{56}$Ni (Table 2).

Thus, we may expect that hypernova explosions, which eject a large amount of complete Si-burning products, also produce a larger amount of $^{56}$Ni than ordinary SNe II, unless significant fallback takes place after mixing (see § 3.5). This is seen in Figure 9, which shows that $[Zn/Fe]$ only for $M(^{56}$Ni) $\gtrsim 0.7 M_\odot$ (i.e., very bright SNe).

The explosion energy also affects the local mass fraction of elements. For more energetic explosions, the temperature during the explosion is higher for the same density (Nakamura et al. 2001). Figures 6 and 8 show that for a higher energy $X(Co)$ and $X(Zn)$ are enhanced in complete Si burning and $X(Mn)$ is reduced in incomplete Si burning. $X(Cr)$ in incomplete Si burning is almost unchanged.

In order to show the parameter dependences of $X(Zn)$, we plot in Figure 10 the density-temperature track during explosive complete Si burning for four representative cases following the maximum temperature (open circles). The parameters of the four models and the mass fractions of $^{56}$Ni and Zn are summarized in Table 3. Cases B and D produce large $X(Zn)$, while cases A and C are the cases with smaller $X(Zn)$. Case C is the same as case C except for the modifications of $Y_e$. The general trend is that $X(Zn)$ is larger if $Y_e$ is closer to 0.5 and an explosion is more energetic to produce larger specific radiation entropy $(4a/3)(T^3/\rho)$, where $a$ denotes the radiation constant. Cases A and C have low $X(Zn)$ because of relatively low $Y_e$. Case C has the same density-temperature history as case C, but it yields larger $X(Zn)$ as a result of larger $Y_e$. Case D has the same $Y_e$ as case C, but it yields larger $X(Zn)$ as a result of larger $T^3/\rho$. Case B yields large $X(Zn)$ because of the relatively large $Y_e$ and $T^3/\rho$. In Figures 11 and 12 we show the time evolution of density, temperature, $T^3/\rho$, and mass fraction ratios of some elements that are relevant to Zn synthesis for cases C (C')

TABLE 3

| Case | $(M/M_\odot, E_{kin}, M/M_\odot)$ | $Y_e$ | $X(^{56}$Ni) | $X(Zn)$ |
|------|----------------------------------|------|--------------|---------|
| A    | (13, 1, 1.52)                    | 0.4996 | 7.65E-01     | 6.04E-04 |
| B    | (13, 1, 1.57)                    | 0.4999 | 7.61E-01     | 3.46E-03 |
| C    | (25, 1, 2.2)                     | 0.4998 | 8.48E-01     | 8.89E-04 |
| C    | (25, 1, 2.2)                     | 0.5000 | 8.55E-01     | 2.01E-03 |
| D    | (25, 10, 2.2)                    | 0.4998 | 7.12E-01     | 3.36E-03 |
and D. These figures show that for larger $T^3/\rho$ the mass fraction of $^4\text{He}$ is larger and thus the $\alpha$-rich freezeout is enhanced. Then the larger fractions of $^{56}\text{Ni}$ and $^{60}\text{Zn}$ are converted to $^{64}\text{Ge}$, which enhances the Zn mass fraction.

We note that the trend that large $E$ gives high $T^3/\rho$ during an $\alpha$-rich freezeout can be further enhanced in nonspherical explosions. This is because the shock in the jet direction is stronger than the shock in the spherical model with the same $E$ (e.g., Maeda et al. 2002; Nagataki et al. 1997).

3.5. Mixing and Fallback

We have shown that large [Zn, Co/Fe] and small [Mn, Cr/Fe] can be obtained simultaneously if $M_{\text{cut}}$ is sufficiently
small. However, the ejected $^{56}\text{Ni}$ mass is larger for smaller $M_{\text{cut}}$, and $M_{\text{cut}}(^{56}\text{Ni})$ required to get $[\text{Zn}/\text{Fe}] \approx 0.5$ appears to be too large to be compatible with observations $[\text{O}/\text{Fe}] \sim 0-0.5$.

Here we consider a possible process that realizes effectively smaller mass cuts without changing the $^{56}\text{Ni}$ mass. In SNe II, when the rapidly expanding core hits the H and He envelopes, a reverse shock forms and decelerates core expansion. The deceleration induces Rayleigh-Taylor instabilities at the composition interfaces of H/He, He/C + O, and O/Si as has been found in SN 1987A (e.g., Ebisuzaki, Shigeyama, & Nomoto 1989; Arnett et al. 1989). Therefore, mixing can take place between the complete and incomplete Si-burning regions according to the recent two-dimensional numerical simulations (Kifonidis et al. 2000; Kifonidis & Nomoto 1989). The reverse shock can further induce matter fallback onto the compact remnant (e.g., Chevalier 1989).

Based on these earlier findings, we propose that the following “mixing fallback” process takes place in most SNe II:

1. Burned material is uniformly mixed between the “initial” mass cut $M_{\text{cut}}(i)$ and the top of the incomplete Si-burning region at $M_* = M_{\text{Si}}$. Then $[\text{Zn}/\text{Fe}]$ in the mixed region becomes as large as $\sim 0.5$.

2. Afterward the mixed materials below $M_{\text{cut}}(f)$ [greater than $M_{\text{cut}}(i)$] fall back onto the compact remnant, and $M_{\text{cut}}(f)$ becomes the final mass cut. Then $M(^{56}\text{Ni})$ becomes smaller while the mass ratios (Zn, Co, Mn)/Fe remain the same compared with the values determined by $M_{\text{cut}}(i)$ in Figures 5 and 9.

We emphasize that the mixing has to take place across the $M_{\text{cut}}(f)$ in order to enhance the fractions of complete Si-burning products. Otherwise, Zn and Co are under-

![Fig. 10.—Density-temperature tracks during explosive Si burning for representative cases. Here the parameters of cases A, B, C, C', and D are summarized in Table 3.](image1)

![Fig. 11.—Density and temperature evolution for the cases C, C', (E_{51} = 1), and D (E_{51} = 10) in Fig. 10. Here T_{9} = T/10^9 (K), and \(\rho\) in g cm\(^{-3}\).](image2)

**TABLE 4**

| $M$ (M\(_{\odot}\)) | $E_{51}$ | $M_{\text{cut}}(i)$ | $M_{\text{Si}}$ | $M_{\text{cut}}(f)$ | $M(^{56}\text{Ni})$ | $M(^{44}\text{Ti})$ | $[\text{O}/\text{Fe}]$ | $[\text{Zn}/\text{Fe}]$ |
|-------------|--------|------------------|----------------|------------------|-----------------|-----------------|-----------------|-----------------|
| (13, 1)     |        | 1.54             | 1.67           | 1.54             | 0.070           | 5.6E-5          | -0.54           | 0.16            |
| (15, 1)     |        | 1.76             | 2.06           | 2.02             | 0.070           | 5.6E-5          | -0.08           | 0.09            |
| (20, 1)     |        | 2.10             | 2.88           | 2.73 (2.50)      | 0.070           | 4.4E-5 (1.2E-4) | 0.43 (0.0)      | 0.02            |
| (20, 5)     |        | 2.10             | 3.38           | 3.27 (3.13)      | 0.070           | 6.9E-5 (1.4E-4) | 0.31 (0.0)      | 0.24            |
| (25, 1)     |        | 2.20             | 5.00           | 5.00 (2.00)      | 0.089           | 7.1E-5 (1.7E-4) | 0.50 (0.0)      | -0.13           |
| (25, 10)    |        | 2.20             | 2.86           | 3.74 (2.25)      | 0.070           | 8.7E-5 (2.3E-4) | 0.45 (0.0)      | 0.30            |
| (25, 30)    |        | 2.50             | 4.52           | 4.39 (4.27)      | 0.070           | 1.6E-4 (2.5E-4) | 0.28 (0.0)      | 0.43            |
| (30, 1)     |        | 2.26             | 3.66           | 3.29 (2.57)      | 0.20 (0.58)     | 1.5E-4 (4.4E-4) | 0.50 (0.0)      | -0.18           |
| (30, 20)    |        | 2.49             | 3.58           | 6.36 (6.35)      | 0.12 (0.39)     | 1.6E-7 (5.3E-4) | 0.50 (0.0)      | 0.32            |
| (30, 30)    |        | 2.83             | 6.01           | 5.81 (5.36)      | 0.011           | 1.7E-4 (5.4E-4) | 0.50 (0.0)      | 0.34            |
| (30, 50)    |        | 3.15             | 6.92           | 6.74 (6.35)      | 0.087           | 1.7E-4 (5.1E-4) | 0.50 (0.0)      | 0.43            |

**Note:** In these models, the matter is first uniformly mixed between $M_* = M_{\text{cut}}(i)$ and top of the incomplete Si-burning region $M_* = M_{\text{Si}}$, and then the matter below $M_* = M_{\text{cut}}(f)$ falls back. For the models with $M \geq 20 M_{\odot}$ two choices of $M_{\text{cut}}(f)$ are shown that give relatively large $[\text{O}/\text{Fe}] \sim 0.3$–0.5 and small $[\text{O}/\text{Fe}] \sim 0$ ratios. Here $M_{\text{cut}}(f)$ is chosen to eject no less than 0.07 $M_{\odot}$ of $^{56}\text{Ni}$. 
produced, or too much $^{56}\text{Ni}$ is ejected as also seen in previous works such as Nakamura et al. (1999) and WW95.

The adopted model parameters of SNe II [$M, E, M_{\text{cut}}(i)$, $M_{\text{Si}}$, and the resultant [O/Fe] and [Zn/Fe] are summarized in Table 4. Here the initial mass cuts $M_{\text{cut}}(i)$ are chosen to give maximum [Zn/Fe]. For $M_{\text{cut}}(f)$ we consider two cases that give [O/Fe] $\sim$ 0.3–0.5 and 0.0, respectively (for $M \geq 20 M_\odot$). Here $M_{\text{cut}}(f)$ is chosen to eject no less than 0.07 $M_\odot$ of $^{56}\text{Ni}$. Note that the ratio [Zn/Fe] is independent of $M_{\text{cut}}(f)$. Note also that larger $E$ leads to larger [Zn/Fe] as discussed in § 3.4. Metallicity dependence of $M_{\text{cut}}(f)$ will be discussed elsewhere, but $M_{\text{cut}}(f)$ tends to be smaller for $Z = 0.02$, being consistent with the observed neutron star masses.

We note that the occurrence of the mixing has been demonstrated by the multidimensional simulations of SN1987A and SNe Ib (e.g., Arnett et al. 1989; Hachisu et al. 1990, 1991; Kifonidis et al. 2000), but the fallback simulations have been done only in one dimension (WW95). Therefore, we need multidimensional simulations of fallback to confirm the occurrence of the “mixing and fallback” process and the resulting modification of the ejecta composition, which has not been done. Only when the mixing takes place across the “final mass cut” are the SN yields modified by the mixing, which has not been taken into account in previous SN yields.

This “mixing and fallback” effect may also be effectively realized in nonspherical explosions accompanying energetic jets (e.g., Maeda et al. 2002; Khokhlov et al. 1999; Nagataki et al. 1997). Compared with the spherical model with the same $M_{\text{cut}}(i)$ and $E$, the shock is stronger (weaker) and thus temperatures are higher (lower) in the jet (equatorial) direction. As a result, a larger amount of complete Si-burning products are ejected in the jet direction, while only incomplete Si-burning products are ejected in the equatorial direction. In total, complete Si-burning elements can be enhanced (Maeda 2001; Nomoto et al. 2001).

4. CONCLUSIONS

We have calculated nucleosynthesis in massive Population III stars using our recent metal-free progenitor models and compared the results with the abundances of metal-poor halo stars to constrain the explosion models of Population III stars. In particular, we have found through
the following parameter study that the explosion has to be
energetic, and explosively synthesized matter needs to be
mixed across the final mass cut unless the explosion is
highly anisotropic.

4.1. Parameter Dependence

In the present work we have focused on iron peak ele-
ments and, in particular, explored the parameter ranges
$[M_{\text{cut}(i)}]$, $Y_e$, $M$, and $E$ to reproduce $[\text{Zn}/\text{Fe}] \sim 0.5$ observed
in extremely metal-poor stars. Our main results are sum-
morized as follows:

1. The interesting trends of the observed ratios $[(\text{Zn}, \text{Co},$
$\text{Mn}, \text{Cr})/\text{Fe}]$ can be understood in terms of the variation of
the mass ratio between the complete Si-burning region and
the incomplete Si-burning region. The large Zn and Co
abundances observed in very metal-poor stars are obtained
in our models if the mass cut is deep enough [i.e., if $M_{\text{cut}(i)}$
small enough in Figs. 5 and 9], or equivalently if deep
material from the complete Si-burning region is ejected by
mixing or aspherical effects ($\S$ 3.1). Vanadium also appears
to be abundant at low $[\text{Fe/H}]$ (e.g., Goswami & Prantzos
2000). Since V is also produced mainly in the complete
Si-burning region (Figs. 6 and 8), this trend can be
explained in the same way as those of Zn and Co.

2. The mass of the incomplete Si-burning region is sensi-
tive to the progenitor mass $M$, being smaller for smaller
$M$. Thus, $[\text{Zn}/\text{Fe}]$ tends to be larger for less massive stars for
the same $E$ ($\S$ 3.2).

3. The production of Zn and Co is sensitive to the value
of $Y_e$, being larger as $Y_e$ is closer to 0.5, especially for the
case of a normal explosion energy ($E_{51} \sim 1$) ($\S$ 3.3).

4. A large explosion energy $E$ results in the enhancement
of the local mass fractions of Zn and Co, while Cr and Mn
are not enhanced (Fig. 9). This is because larger $E$ produces
larger entropy and thus a stronger $\alpha$-rich freezeout ($\S$ 3.4).

5. To be consistent with the observed $[\text{O}/\text{Fe}] \sim 0$–0.5 as
well as with $[\text{Zn}/\text{Fe}] \sim 0.5$ in metal-poor stars, we propose
that the “mixing and fallback” process or aspherical effects
are significant in the explosion of relatively massive stars
($\S$ 3.5).

4.2. Hypernova Scenario

The dependence of $[\text{Zn}/\text{Fe}]$ on $M$ and $E$ is summarized
in Figures 13 and 14 as follows:

1. In Figure 13 we compare the $[\text{Zn}/\text{Fe}]$ ratios in our
$E_{51} = 1$ models with previous models for various progeni-
tor masses $M$. The $[\text{Zn}/\text{Fe}]$ ratio depends also on $M_{\text{cut}(i)}$
and our values in Figure 13 correspond to the maximum
values for the same $E$. The difference in $Y_e$ is the primary
reason why Zn production is much smaller when previous
progenitor models by Nomoto & Hashimoto (1998) are
used (Thielemann et al. 1996). (Note that, for hypernova-
like explosion energies, Zn is abundantly produced even if
$Y_e$ is smaller while Zn production is suppressed otherwise.)
Differences from WW95 likely stem from the differences in
$M_{\text{cut}(i)}$. Limongi, Straniero, & Chieffi (2000) have also
shown their yields for some $Z = 0$ models. However, their
nuclear reaction network is not large enough to calculate
$^{64}$Zn synthesis (M. Limongi 2001, private communication).

2. In Figure 14 $[\text{Zn}/\text{Fe}]$ is shown as a function of $M$ and
$E$, where the plotted ratios correspond to the maximum
values for given $E$. We have found that models with $E_{51} = 1$
do not produce sufficiently large $[\text{Zn}/\text{Fe}]$. To be compatible
with the observations of $[\text{Zn}/\text{Fe}] \sim 0.5$, the explosion
energy must be much larger, i.e., $E_{51} \gtrsim 2$ for $M \sim 13 M_\odot$
and $E_{51} \gtrsim 20$ for $M \gtrsim 20 M_\odot$. 

Fig. 13.—$[\text{Zn}/\text{Fe}]$ ratios of the present and previous works as a func-
tion of stellar mass. Here WW95 denotes Woosley & Weaver (1995) and
NH88 denotes Nomoto & Hashimoto (1998) models. The observed large
$[\text{Zn}/\text{Fe}]$ ratios in very low metal stars ($[\text{Fe/H}] < -2.6$) found in Primas et
al. (2000) and Blake et al. (2001) are represented by a thick arrow. The
$[\text{Zn}/\text{Fe}]$ ratios of the present work shown here correspond to the
maximum values. If the mass cut is larger, the $[\text{Zn}/\text{Fe}]$ ratios become
smaller.

Fig. 14.—Maximum $[\text{Zn}/\text{Fe}]$ ratios as a function of $M$ and $E_{51}$. The
arrow ("Obs.") indicates the range of observed high $[\text{Zn}/\text{Fe}]$ values at
$[\text{Fe/H}] < -2.6$ (Fig. 1).
FIG. 15.—Abundance pattern in the ejecta (after radioactive decay) for the 13 and 15 $M_\odot$ models normalized by the solar abundances of $^{16}$O. Mixing and fallback are assumed for 15 $M_\odot$ but not for 13 $M_\odot$. The mass cut is chosen to eject 0.0756$^{64}$Ni. [See the electronic edition of the Journal for a color version of this figure.]

Observationally, the requirement of the large E might suggest that large M stars are responsible for large [Zn/Fe] because E and M can be constrained from the observed brightness and light-curve shape of SNe as follows. (The uncertainties in theoretical models for gravitational collapse are still too large to determine E; e.g., Mezzacappa et al. 2001; Rampp & Janika 2000.) The recent supernovae SN 1987A, SN 1993J, and SN 1994I indicate that the progenitors of these normal SNe are 13–20 $M_\odot$ stars and $E_{\gamma}$ ∼ 1–1.5 (Nomoto et al. 1993, 1994; Shigeyama et al. 1994; Blinnikov et al. 2000). On the other hand, the masses of the progenitors of hypernovae with $E_{\gamma}$ > 10 (SN 1998bw, SN 1997ef, and SN 1997cy) are estimated to be $M$ ≥ 25 $M_\odot$ (Nomoto et al. 2000; Iwamoto et al. 1998, 2000; Woosley, Eastman, & Schmidt 1999; Turatto et al. 2000). This could be related to the stellar mass dependence of the explosion.

FIG. 16.—Abundance pattern in the ejecta normalized by the solar $^{16}$O abundances for the mixing fallback 20 $M_\odot$ model with $E_{\gamma}$ = 1 and 5. The mass cuts are chosen to give large [Zn/Fe] and [O/Fe] = 0. [See the electronic edition of the Journal for a color version of this figure.]

FIG. 17.—Abundance pattern in the ejecta normalized by the solar $^{16}$O abundances for the mixing fallback (25 $M_\odot$, $E_{\gamma}$ = 10) and (30 $M_\odot$, $E_{\gamma}$ = 20) models. The mass cuts are chosen to give large [Zn/Fe] and [O/Fe] = 0. [See the electronic edition of the Journal for a color version of this figure.]
mechanisms and the formation of compact remnant, i.e., less massive stars form neutron stars, while more massive stars tend to form black holes.

To explain the observed relation between [Zn/Fe] and [Fe/H], we further need to know how $M$ and $E$ of SNe and [Fe/H] of metal-poor halo stars are related. In the early galactic epoch when the galaxy is not yet chemically well mixed, [Fe/H] may well be determined by the first generation of SNe. The formation of metal-poor stars has been suggested to be driven by an SN shock, so that [Fe/H] is determined by the ejected Fe mass and the amount of circumstellar hydrogen swept up by the shock wave (Ryan et al. 1996).

Explosions with the following two combinations of $M$ and $E$ may be responsible for the formation of stars with very small [Fe/H]:

1. Energetic explosions of massive stars ($M \gtrsim 25 M_\odot$). For these massive progenitors, the SN shock wave tends to propagate farther out because of the large explosion energy and large Strömgren sphere of the progenitors (Nakamura et al. 1999). The effect of $E$ may be important since the hydrogen mass swept up by the SN shock is roughly proportional to $E$ (e.g., Ryan et al. 1996; Shigeyama & Tsujimoto 1998).

2. Normal SN explosions of less massive stars ($M \sim 13 M_\odot$). These SNe are assumed to eject a rather small mass of Fe (Shigeyama & Tsujimoto 1998), and most SNe are assumed to explode with normal $E$ irrespective of $M$.

The above relations lead to the following two possible scenarios to explain [Zn/Fe] \sim 0.5 observed in metal-poor stars:

1. Hypernova-like explosions of massive stars ($M \gtrsim 25 M_\odot$) with $E_{51} > 10$. Contribution of highly asymmetric explosions in these stars may also be important. The question is what fraction of such massive stars explode as hypernovae; the IMF-integrated yields must be consistent with [Zn/Fe] \sim 0 at [Fe/H] \gtrsim -2.5.

2. Explosion of less massive stars ($M \lesssim 13 M_\odot$) with $E_{51} \gtrsim 2$ or a large asymmetry. This scenario, after integration over the IMF, might reproduce the observed abundance pattern for [Fe/H] \gtrsim -2 (Tsujimoto & Shigeyama 1998). However, the Fe yield has to be very small in order to satisfy the observed [O/Fe] value (\sim 0.5) for the metal-poor stars. For example, the $^{56}$Ni mass yield of our $13 M_\odot$ model has to be less than 0.006 $M_\odot$, which appears to be inconsistent with the observed luminosities (and thus the $^{56}$Ni mass) of core collapse supernovae SN 1993J and SN 1994I, whose progenitor masses are estimated to be 13–15 $M_\odot$ (see, e.g., Fig. 10 of Iwamoto et al. 2000).

It seems that the [O/Fe] ratio of metal-poor stars and the $E-M$ relations from SN observations favor the massive
TABLE 5

| Element | Yield |
|---------|-------|
| Li      | 6.666E+00 |
| Be      | 3.338E-09 |
| C       | 1.625E-09 |
| O       | 4.601E-06 |
| Na      | 2.516E-05 |
| Al      | 1.311E-04 |
| Si      | 2.296E-02 |
| S       | 3.885E-06 |
| K       | 4.259E-10 |
| Ca      | 5.565E-05 |
| Ti      | 3.842E-06 |
| V       | 9.538E-06 |
| Mn      | 3.211E-05 |
| Co      | 1.759E-04 |
| Ni      | 1.499E-11 |
| Zn      | 6.092E-08 |
| Ge      | 1.281E-08 |

Note: $\left[M_{\text{act}}, M_{\text{Si}}, M_{\text{act}/M_{\text{Si}}} \right] = (1.54, 1.67, 1.54), [\text{O/Fe}] = -0.54, \text{and } [\text{Zn/Fe}] = 0.16.$

5. DISCUSSION

5.1. Mn

We note that our Mn yields are roughly a factor of 10 smaller than in Nomoto et al. (1997) and Nakamura et al. (1999), and Cr is slightly overproduced. The main source of the differences is that $Y_e$ in the incomplete Si-burning region of our models is larger than that of previous models. If $Y_e$ in the incomplete Si-burning layers is slightly reduced from 0.49996 to 0.49977, for example, the Mn yield is enhanced by a factor of ~10 and the Cr yield is slightly reduced. Smaller $Y_e$ leads to a smaller Zn mass fraction. For $Y_e = 0.49977$, however, the produced amount of Zn is almost the same as in our current models as far as $Z > 10^5$ ergs. Such $Y_e$ would be obtained for models with very low but nonzero metallicity. In other words, the Mn abundance may be a good indicator of real Population III ejecta.

5.2. Co

Our Co/Fe ratios as in all previous works (Nomoto et al. 1997; WW95; Nakamura et al. 1999) are at least a factor of 3–5 smaller than the observed ones. However, we consider that the deficiency of Co is not as serious as Zn for the following reasons. First, we have not included neutrino processes yet, but they might enhance the Co yield (WW95).

TABLE 6

| Element | Yield |
|---------|-------|
| p       | 7.581E+00 |
| Li      | 4.748E-09 |
| Be      | 2.242E-21 |
| C       | 8.899E-09 |
| O       | 1.767E-04 |
| Na      | 7.035E-05 |
| Al      | 1.419E-04 |
| Si      | 3.330E-02 |
| S       | 5.086E-06 |
| Cl      | 1.093E-10 |
| K       | 4.292E-05 |
| Ca      | 2.266E-06 |
| Ti      | 4.311E-06 |
| Mn      | 1.505E-05 |
| Co      | 6.883E-05 |
| Ni      | 3.083E-13 |
| Zn      | 2.314E-08 |
| Ge      | 1.152E-08 |

Note: $\left[M_{\text{act}}, M_{\text{Si}}, M_{\text{act}/M_{\text{Si}}} \right] = (1.76, 2.06, 2.02), [\text{O/Fe}] = -0.08, \text{and } [\text{Zn/Fe}] = 0.09.$
of metal-poor stars shows no clear trend (see, e.g.,
also interesting. Unlike the elements we have focused on,
Ni/Fe]. Similar results have also been found by Norris,
halo stars. They, on the other hand, did not Ðnd oversolar

Second, Co is the decay product of odd-Z element 59Cu,
and its yield depends on uncertain reaction rates involving
protons and neutrons. On the other hand, Zn is mainly the
decay product of even-Z element 64Ge, and its abundance
is most likely determined by the less uncertain Q-values and partition
functions of α-nuclei.

5.3. Ni

The observed trend of another iron peak element, Ni, is
also interesting. Unlike the elements we have focused on,
[Ni/Fe] of metal-poor stars shows no clear trend (see, e.g.,
Ryan et al. 1996; Nakamura et al. 1999). Theoretically,
this is understood as the fact that Ni is produced abundantly by
both complete and incomplete Si burning. Recently, Ellis-
on, Ryan, & Prochaska (2001) observed DLA abundance
and found [Co/Fe] > 0, which is similar to the metal-poor
halo stars. They, on the other hand, did not find oversolar
[Ni/Fe]. Similar results have also been found by Norris,
Ryan, & Beers (2001), who observed abundances of five
halo stars with [Fe/H] ≤ −3.5. They discussed that the
results are inconsistent with the predictions of Nakamura et al. (1999),
where the enhancement of [Co/Fe] appears to be
accompanied by the enhancement of [Ni/Fe].

We note that the increase in [Ni/Fe] along with the increase in [Co/Fe] is not significant in the models shown
in this paper. Let us compare the low-[Co/Fe] model in
Table 6 (20 M_☉, E_51 = 1, M^{66Ni} = 0.07, [Zn/Fe] = 0.02)
and the high-[Co/Fe] model in Table 13 (30 M_☉, E_51 = 50,
M^{66Ni} = 0.087, [Zn/Fe] = 0.43). In the former model, the
ejected masses of Co and Ni (the two most abundant
isotopes are 60Ni and 58Ni) are (59Co, 60Ni,
58Ni) = (2.0 \times 10^{-3}, 2.0 \times 10^{-3}, 1.2 \times 10^{-4}) M_☉. In
the latter model, (59Co, 60Ni, 58Ni) = (3.4 \times 10^{-4}, 2.8 \times 10^{-3},
8.5 \times 10^{-4}) M_☉, so that Co is larger by a factor of 17, while
Ni is larger by only a factor of 1.8 than in the former model.

The apparent difference from the results in Nakamura et al. (1999) can be understood as follows. In Nakamura et al. (1999), the explosion energy was fixed to be E_51 = 1. They

### Table 7

Yields in the Ejecta in M_☉ after Radioactive Decay (except 26Al) for the 20 M_☉ E_51 = 1 Model Shown in Table 4

| Element | Yield     | Element | Yield     | Element | Yield     | Element | Yield     | Element | Yield     |
|---------|-----------|---------|-----------|---------|-----------|---------|-----------|---------|-----------|
| p       | 9.396E+00 | d        | 2.768E+00 | ^3He    | 2.556E+00 | ^4He    | 6.258E+00 | ^5Li     | 7.648E+10 |
| ^7Li     | 1.154E+08 | ^9Be     | 4.661E+19 | ^10B    | 1.252E+09 | ^11B    | 5.613E+09 | ^12C     | 2.569E+01 |
| ^11C     | 4.559E-08 | ^14N     | 2.688E-04 | ^15N    | 1.769E-06 | ^16O    | 1.550E+00 | ^17O     | 2.385E-07 |
| ^15O     | 4.878E-06 | ^19F     | 3.298E-07 | ^20Ne   | 1.240E+01 | ^21Ne   | 1.712E+05 | ^22Ne    | 1.175E+05 |
| ^23Na    | 3.468E-04 | ^24Mg    | 7.069E-02 | ^29Si   | 2.423E+04 | ^30Si   | 3.682E-05 | ^30Si    | 9.127E-07 |
| ^25Al    | 4.785E-04 | ^28Si    | 9.815E-02 | ^29Si   | 2.423E+04 | ^30Si   | 3.682E-05 | ^30Si    | 9.127E-07 |
| ^34S     | 4.111E-02 | ^36S     | 8.979E-05 | ^38Ar   | 4.062E+00 | ^40Ar   | 7.280E-13 | ^40Ar    | 9.696E-07 |
| ^37Cl    | 7.208E-06 | ^41K     | 7.139E-07 | ^46Ca   | 6.124E+03 | ^48Ca   | 9.705E-09 | ^48Ca    | 2.692E-08 |
| ^46Ti    | 2.906E-06 | ^49Ti    | 1.205E-04 | ^50Ti   | 2.106E-06 | ^50Ti   | 3.776E-13 | ^50Ti    | 3.424E-13 |
| ^51V     | 2.800E-06 | ^50Cr    | 5.588E-07 | ^52Cr   | 1.190E+03 | ^53Fe   | 1.120E+03 | ^53Fe    | 2.661E-12 |
| ^53Mn    | 3.223E-05 | ^54Fe    | 4.456E-05 | ^56Fe   | 7.000E-02 | ^56Fe   | 1.210E+03 | ^56Fe    | 5.539E+12 |
| ^58Co    | 2.009E-05 | ^58Ni    | 1.154E-04 | ^60Ni   | 1.995E-03 | ^61Ni   | 5.286E-05 | ^61Ni    | 1.684E-05 |
| ^64Ni    | 1.013E-02 | ^63Cu    | 1.591E-06 | ^65Cu   | 6.779E-07 | ^64Zn   | 1.249E-04 | ^64Zn    | 2.438E-06 |
| ^67Zn    | 9.175E-09 | ^69Zn    | 9.031E-08 | ^70Zn   | 7.743E-13 | ^69Ga   | 9.441E-09 | ^69Ga    | 3.297E-12 |
| ^76Ge    | 1.064E-08 | ^72Ge    | 6.328E-12 | ^73Ge   | 3.331E+12 | ^74Ge   | 2.699E-12 | ^74Ge    | 3.331E+12 |

Note.—[M_{c1}(f), M_{c1}, M_{c1}(f)] = (2.20, 3.00, 2.80), [O/Fe] = 0.43, and [Zn/Fe] = 0.02.

### Table 8

Yields in the Ejecta in M_☉ after Radioactive Decay (except 26Al) for the 25 M_☉ E_51 = 1 Model Shown in Table 4

| Element | Yield     | Element | Yield     | Element | Yield     | Element | Yield     |
|---------|-----------|---------|-----------|---------|-----------|---------|-----------|
| p       | 1.081E+01 | d        | 6.294E-17 | ^3He    | 3.929E-05 | ^4He    | 7.929E+00 | ^5Li     | 7.899E-22 |
| ^7Li     | 3.344E-10 | ^9Be     | 1.223E-19 | ^10B    | 6.319E+10 | ^11B    | 2.554E-09 | ^12C     | 6.138E-01 |
| ^11C     | 4.218E-08 | ^14N     | 3.583E-04 | ^15N    | 8.050E-08 | ^16O    | 1.217E+00 | ^17O     | 1.707E-07 |
| ^15O     | 1.964E-06 | ^19F     | 4.055E+10 | ^20Ne   | 2.034E-01 | ^21Ne   | 1.219E-05 | ^22Ne    | 1.302E-05 |

Note.—[M_{c1}(f), M_{c1}, M_{c1}(f)] = (2.20, 3.00, 2.80), [O/Fe] = 0.50, and [Zn/Fe] = −0.13.
The dominant Ni isotope is obtained for more massive SNe II by assuming \( \text{[Fe/O]} = 0.30 \), \( [\text{Ni/Fe}] = 0.56 \) for smaller \( Y_e \), the Co abundance is larger, but the abundance of Ni (especially \( ^{58}\text{Ni} \)) is enhanced by a factor of \( 10^4 \) by [Ni/Fe] was unavoidable, unless neutrinos significantly enhance \( Y_e \) in the deep complete Si-burning region.

In our model, increasing the abundance of Co, Zn, and \( ^{58}\text{Ni} \) increase more than that of \( ^{60}\text{Ni} \). Therefore, Co and Zn abundances can be enhanced without appreciable increase in the Ni abundance. In this sense, the abundance trends of very metal-poor stars are better explained with hypernova models than with the simple “deep” mass cut models (Nakamura et al. 1999).

### 5.4. Pair Instability Supernovae?

One may wonder whether the abundance anomaly of iron peak elements discussed in this paper may be related to the peculiar IMF of Population III stars. It is quite likely that the IMF of Population III stars is different from that of Population I and II stars and that more massive stars are abundant for Population III (e.g., Nakamura & Umemura 1999; Omukai & Nishi 1999; Bromm, Coppi, & Larson 1999). They have discussed that the IMF of Population III and very low metal stars may have a peak at even lower masses, around approximately one hundred to a few hundred solar masses. If \( M \leq 130 \text{M}_\odot \), then these stars are likely to form black holes either without explosion or with energetic explosions. The nucleosynthesis of the latter case

| Element | Yield | Element | Yield | Element | Yield | Element | Yield |
|---------|-------|---------|-------|---------|-------|---------|-------|
| \( ^{6}\text{He} \) | 3.931E-05 | \( ^{6}\text{He} \) | 7.893E-00 | \( ^{6}\text{Li} \) | 2.211E-18 |
| \( ^{11}\text{B} \) | 6.579E-10 | \( ^{13}\text{C} \) | 3.131E-06 | \( ^{12}\text{C} \) | 3.987E-01 |
| \( ^{15}\text{N} \) | 3.131E-06 | \( ^{15}\text{O} \) | 1.534E+00 | \( ^{16}\text{O} \) | 1.598E-07 |
| \( ^{20}\text{Ne} \) | 1.075E-01 | \( ^{21}\text{Ne} \) | 4.190E-06 | \( ^{22}\text{Ne} \) | 6.606E-06 |
| \( ^{23}\text{Mg} \) | 1.276E-04 | \( ^{23}\text{Mg} \) | 2.536E-05 | \( ^{24}\text{Al} \) | 1.960E-06 |
| \( ^{28}\text{Si} \) | 5.011E-05 | \( ^{28}\text{Si} \) | 3.767E-05 | \( ^{30}\text{P} \) | 9.133E-05 |
| \( ^{32}\text{S} \) | 5.153E-05 | \( ^{32}\text{S} \) | 2.536E-05 | \( ^{33}\text{Cl} \) | 2.136E-05 |
| \( ^{34}\text{Ar} \) | 2.580E-05 | \( ^{34}\text{Ar} \) | 6.692E-06 | \( ^{37}\text{Cl} \) | 2.136E-05 |
| \( ^{40}\text{Ar} \) | 1.052E-11 | \( ^{40}\text{Ar} \) | 1.052E-11 | \( ^{39}\text{K} \) | 1.057E-05 |
| \( ^{60}\text{Ni} \) | 2.190E-03 | \( ^{60}\text{Ni} \) | 5.708E-04 | \( ^{64}\text{Cu} \) | 1.042E-07 |
| \( ^{64}\text{Zn} \) | 6.493E-07 | \( ^{64}\text{Zn} \) | 3.467E-06 | \( ^{68}\text{Ga} \) | 9.127E-11 |
| \( ^{74}\text{Ge} \) | 5.454E-11 | \( ^{74}\text{Ge} \) | 5.454E-11 | \( ^{10}\text{Be} \) | 3.498E-22 |
| \( ^{14}\text{N} \) | 2.099E-03 | \( ^{14}\text{N} \) | 2.099E-03 | \( ^{14}\text{N} \) | 0.665E-06 |
| \( ^{20}\text{Ne} \) | 5.912E-02 | \( ^{20}\text{Ne} \) | 2.099E-03 | \( ^{20}\text{Ne} \) | 2.099E-03 |
| \( ^{24}\text{Mg} \) | 3.482E-05 | \( ^{24}\text{Mg} \) | 3.482E-05 | \( ^{26}\text{Si} \) | 3.767E-05 |
| \( ^{34}\text{S} \) | 5.753E-05 | \( ^{34}\text{S} \) | 3.767E-05 | \( ^{36}\text{Ar} \) | 2.580E-05 |
may not be so different from the models considered here. This might favor the scenario that invokes the hypervola-
like explosions for large [Zn/Fe].

If stars are even more massive than ~ 150 \( M_\odot \), these stars become PISNe and their nucleosynthesis is different from
core collapse SNe as summarized in the Appendix (Barkat, Rakavy, & Sack 1967; Ober, El Eid, & Fricke 1983;
Woosley & Weaver 1982). In particular, PISNe produce
[Zn/Fe] < -1.5 because in PISNe iron peak elements are
mostly produced by incomplete Si burning so that the mass
fraction of complete Si-burning elements is much smaller
than that of SNe II (Figs. 18 and 19). We thus conclude that
PISNe are unlikely to produce a large enough Zn/Fe ratio
to explain the observations.

5.5. Concluding Remarks

In this paper we have shown that such a large Zn
abundance as [Zn/Fe] ~ 0.5 observed in metal-poor stars can be
realized in certain SN models. This implies that the assumption
of [Zn/Fe] ~ 0 usually adopted in the DLA abundance
analyses may not be well justified. Rather, [Zn/Fe] may
provide important information on the IMF and/or the age
of the DLA systems.

We have considered only a few elements to constrain the
nucleosynthesis of Population III stars because their trends
are most clear. Data for other elements show less clear
trends or currently have relatively large error bars.
However, additional information will be very useful. For
example, [S/Fe] and [C/O] may be important to dis-
tinguish the scenarios of \( M \lesssim 13 \ M_\odot \) and \( M \gtrsim 20 \ M_\odot \).
In addition, mass cut independent ratios [Ca, S, Si/Mg] will
be important to constrain the explosion energies of SNe.

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### Table 11

| Element | Yield | Element | Yield |
|---------|-------|---------|-------|
| p       | 2.148E+02 | d       | 1.664E-15 |
| Li      | 2.966E-10 | Be      | 2.780E-21 |
| C       | 2.372E-08 | N       | 9.203E-05 |
| O       | 9.132E-02 | F       | 1.098E-06 |
| Na      | 4.135E-04 | Mg      | 1.303E-01 |
| Al      | 1.134E-02 | Si      | 3.708E-01 |
| K       | 5.457E-05 | Ar      | 3.456E-02 |
| Ca      | 6.938E-09 | Ti      | 8.493E-06 |
| Cr      | 1.745E-04 | Fe      | 3.572E-11 |
| Mn      | 1.373E-05 | Ni      | 2.510E-06 |
| Co      | 2.285E-05 | Cu      | 3.572E-11 |
| Ni      | 7.030E-11 | Zn      | 1.949E-07 |
| Ge      | 2.167E-08 | Se      | 1.853E-10 |

Note.—[M_{\text{w}(0)}, M_{\text{w}(1)}, M_{\text{w}(f)}] = (2.83, 6.01, 5.81), [O/Fe] = 0.50, and [Zn/Fe] = -0.18.

### Table 12

| Element | Yield | Element | Yield |
|---------|-------|---------|-------|
| p       | 2.148E+02 | d       | 1.664E-15 |
| Li      | 2.966E-10 | Be      | 2.780E-21 |
| C       | 2.372E-08 | N       | 9.203E-05 |
| O       | 9.132E-02 | F       | 1.098E-06 |
| Na      | 4.135E-04 | Mg      | 1.303E-01 |
| Al      | 1.134E-02 | Si      | 3.708E-01 |
| K       | 5.457E-05 | Ar      | 3.456E-02 |
| Ca      | 6.938E-09 | Ti      | 8.493E-06 |
| Cr      | 1.745E-04 | Fe      | 3.572E-11 |
| Mn      | 1.373E-05 | Ni      | 2.510E-06 |
| Co      | 2.285E-05 | Cu      | 3.572E-11 |
| Ni      | 7.030E-11 | Zn      | 1.949E-07 |
| Ge      | 2.167E-08 | Se      | 1.853E-10 |

Note.—[M_{\text{w}(0)}, M_{\text{w}(1)}, M_{\text{w}(f)}] = (2.83, 6.01, 5.81), [O/Fe] = 0.50, and [Zn/Fe] = -0.34.
TABLE 13
YIELDS IN THE EJECTA IN $M_\odot$ AFTER RADIOACTIVE DECAY (EXCEPT $^{26}$Al) FOR THE 30 $M_\odot$ $E_{\text{A1}} = 50$ MODEL SHOWN IN TABLE 4

| Element | Yield | Element | Yield | Element | Yield | Element | Yield | Element | Yield |
|---------|-------|---------|-------|---------|-------|---------|-------|---------|-------|
| $p$     | 1.157E+01 | $d$     | 9.904E-16 | $^4$He | 2.000E-05 | $^4$He | 8.755E+00 | $^6$Li | 8.284E-18 |
| $^7$Li   | 2.985E-10 | $^9$Be | 0.000E+00 | $^{10}$B | 4.046E-16 | $^{11}$B | 2.323E-12 | $^{13}$C | 1.136E-01 |
| $^{13}$C | 1.958E-08 | $^{14}$N | 4.340E-05 | $^{15}$N | 4.765E-05 | $^{16}$O | 2.119E+00 | $^{18}$O | 1.400E-07 |
| $^{18}$O | 1.152E-04 | $^{19}$F | 1.921E-06 | $^{20}$Ne | 5.777E-02 | $^{21}$Ne | 6.114E-06 | $^{22}$Ne | 6.427E-05 |
| $^{22}$Na | 2.285E-04 | $^{24}$Mg | 8.563E-02 | $^{25}$Mg | 2.349E-04 | $^{28}$Mg | 1.961E-04 | $^{29}$Al | 2.037E-05 |
| $^{27}$Al | 6.201E-04 | $^{28}$Si | 2.406E-01 | $^{29}$Si | 5.870E-04 | $^{30}$Si | 2.531E-04 | $^{31}$P | 3.291E-04 |
| $^{33}$S | 1.575E-01 | $^{34}$S | 4.397E-04 | $^{34}$S | 2.807E-04 | $^{36}$S | 3.732E-09 | $^{39}$Cl | 4.499E-04 |
| $^{35}$Cl | 8.097E-05 | $^{36}$Ar | 4.998E-02 | $^{38}$Ar | 1.899E-04 | $^{40}$Ar | 6.076E-11 | $^{40}$K | 2.726E-04 |
| $^{40}$K | 6.351E-09 | $^{41}$K | 1.433E-05 | $^{40}$Ca | 1.292E-02 | $^{42}$Ca | 5.425E-06 | $^{43}$Ca | 7.554E-07 |
| $^{44}$Ca | 1.674E-04 | $^{46}$Ca | 1.666E-11 | $^{48}$Ca | 4.226E-12 | $^{50}$Ti | 4.926E-07 | $^{51}$Ti | 4.129E-06 |
| $^{46}$Ti | 1.076E-05 | $^{49}$Ti | 2.311E-04 | $^{50}$Ti | 4.454E-06 | $^{50}$Ti | 5.385E-11 | $^{51}$V | 6.394E-11 |
| $^{51}$V | 2.065E-05 | $^{52}$Cr | 9.525E-06 | $^{52}$Cr | 1.083E-03 | $^{52}$Cr | 3.418E-05 | $^{52}$Cr | 6.767E-10 |
| $^{53}$Mn | 3.088E-05 | $^{54}$Fe | 2.110E-04 | $^{56}$Fe | 8.679E-02 | $^{57}$Fe | 1.705E-03 | $^{58}$Fe | 1.006E-09 |
| $^{55}$Co | 3.837E-04 | $^{58}$Ni | 8.460E-04 | $^{60}$Ni | 2.854E-03 | $^{61}$Ni | 5.241E-05 | $^{61}$Ni | 3.304E-05 |
| $^{64}$Ni | 8.406E-11 | $^{63}$Cu | 1.003E-05 | $^{65}$Cu | 9.195E-07 | $^{66}$Zn | 3.909E-04 | $^{66}$Zn | 6.189E-06 |
| $^{66}$Zn | 2.463E-07 | $^{67}$Zn | 1.167E-07 | $^{70}$Zn | 3.716E-11 | $^{69}$Ga | 1.707E-08 | $^{71}$Ga | 4.113E-10 |
| $^{76}$Ge | 1.906E-08 | $^{72}$Ge | 3.417E-10 | $^{73}$Ge | 2.320E-10 | $^{74}$Ge | 2.510E-10 | $^{76}$Ge | 2.510E-10 |

Note.—$[M_{\text{nuc}(i)}, M_{\text{Si}}, M_{\text{Si}(f)}] = (2.83, 6.01, 5.81)$, [O/Fe] = 0.50, and [Zn/Fe] = 0.43.

APPENDIX

PAIR INSTABILITY SUPERNOVA YIELDS

In this appendix we present the yields of our Population III PISN models with the initial masses $M = 150, 170, 200,$ and $270 M_\odot$. These stars enter into the electron-positron pair instability region during the central oxygen-burning stages and contract quasi-dynamically. Then the central temperature increases to $3 \times 10^9 K$, which is so high that central oxygen burning takes place explosively, being much faster than neutrino energy losses. The generated nuclear energy is large enough for internal energy to exceed the gravitational binding energy. Then the stars disrupt completely without leaving compact remnants and become PISNe. In our $M = 300 M_\odot$ model, the total energy of the star does not become positive after central oxygen and Si burnings and hence the star collapse into a black hole.

The main purpose of this appendix is to show that a large [Zn/Fe] ratio is not realized in these SNe. More detailed explanation will be given elsewhere. In Table 14 we summarize the initial, He core, and C-O core masses and the ejected $^{56}$Ni masses. We note that the amount of ejected $^{56}$Ni masses is quite sensitive to the central temperature at bounce, which depends on the ratio between the kinetic energy and the internal energy generated by nuclear burning. Since the hydrodynamical behavior is rather sensitive to those factors, the results shown here are still preliminary; nevertheless, this uncertainty does not affect the conclusion on [Zn/Fe] described below. In these models the convective mixing parameter is chosen to be $f_k = 0.1$. The yields are shown in Tables 15–18, and the abundance patterns are shown in Figures 18 and 19.

The most striking feature is the small [Zn, Co/Fe] ratios. This is because in PISNe the mass ratio between the complete and incomplete Si-burning regions is much smaller than in core collapse SNe. A large amount of Zn and Co could be produced if the central temperature at bounce is higher. However, in this case the incomplete Si-burning region is also extended. Therefore, the small [Zn, Co/Fe] ratios are inevitable for PISN models, and this conclusion is independent of any possible uncertainties. Therefore, we can conclude that the abundance pattern seen in the very metal-poor halo stars did not result from the pattern of PISNe.

TABLE 14
THE INITIAL, He CORE, AND C-O CORE MASSES OF THE PROGENITORS OF PISN MODELS

| Core Mass | 1 | 2 | 3 | 4 |
|-----------|---|---|---|---|
| $M$       | 150 | 170 | 200 | 270 |
| $M(\text{He})$ | 70.0 | 82.3 | 117 | 129 |
| $M(\text{CO})$ | 62.2 | 72.7 | 109 | 121 |
| $M(^{56}\text{Ni})$ | 0.0 | 3.6 | 7.2 | 9.8 |

Note.—The ejected $^{56}$Ni masses are also shown. Units are all in $M_\odot$.
### TABLE 15
YIELDS IN THE EJECTA IN $M_\odot$ AFTER RADIOACTIVE DECAY (EXCEPT $^{26}$Al) FOR THE 150 $M_\odot$ PISN MODEL

| Element | Yield |
|---------|-------|
| $^7$Li | 3.363E-10 |
| $^{11}$C | 3.693E-07 |
| $^{18}$O | 2.863E-07 |
| $^{23}$Na | 1.062E-02 |
| $^{25}$Mg | 3.181E-02 |
| $^{30}$Si | 6.04E-03 |
| $^{35}$Cl | 6.71E-04 |
| $^{60}$Ni | 2.06E-11 |
| $^{67}$Zn | 9.38E-11 |
| $^{76}$Ge | 1.72E-10 |

### TABLE 16
YIELDS IN THE EJECTA IN $M_\odot$ AFTER RADIOACTIVE DECAY (EXCEPT $^{26}$Al) FOR THE 170 $M_\odot$ PISN

| Element | Yield |
|---------|-------|
| $^7$Li | 5.766E-09 |
| $^{11}$C | 3.84E-07 |
| $^{18}$O | 9.98E-03 |
| $^{23}$Na | 5.76E-03 |
| $^{25}$Mg | 2.03E-02 |
| $^{30}$Si | 8.66E-03 |
| $^{35}$Cl | 1.60E-03 |
| $^{60}$Ni | 2.06E-11 |
| $^{67}$Zn | 9.38E-11 |
| $^{76}$Ge | 3.58E-11 |

### TABLE 17
YIELDS IN THE EJECTA IN $M_\odot$ AFTER RADIOACTIVE DECAY (EXCEPT $^{26}$Al) FOR THE 200 $M_\odot$ PISN

| Element | Yield |
|---------|-------|
| $^7$Li | 5.789E-10 |
| $^{11}$C | 3.49E-07 |
| $^{18}$O | 1.05E-04 |
| $^{23}$Na | 6.99E-03 |
| $^{25}$Mg | 1.55E-02 |
| $^{30}$Si | 8.50E-04 |
| $^{35}$Cl | 1.72E-04 |
| $^{60}$Ni | 5.96E-15 |
| $^{67}$Zn | 1.74E-13 |
| $^{76}$Ge | 3.57E-11 |

| Element | Yield |
|---------|-------|
| $^7$Li | 5.789E-10 |
| $^{11}$C | 3.49E-07 |
| $^{18}$O | 1.05E-04 |
| $^{23}$Na | 6.99E-03 |
| $^{25}$Mg | 1.55E-02 |
| $^{30}$Si | 8.66E-03 |
| $^{35}$Cl | 8.10E-04 |
| $^{40}$K | 1.61E-04 |
| $^{44}$Ca | 4.71E-04 |
| $^{48}$Sc | 1.85E-04 |
| $^{51}$V | 1.79E-04 |
| $^{56}$Mn | 2.33E-04 |
| $^{58}$Ni | 4.07E-04 |
| $^{63}$Cu | 1.55E-03 |
| $^{67}$Zn | 4.51E-08 |
| $^{76}$Ge | 5.37E-08 |

| Element | Yield |
|---------|-------|
| $^7$Li | 5.789E-10 |
| $^{11}$C | 3.49E-07 |
| $^{18}$O | 1.05E-04 |
| $^{23}$Na | 6.99E-03 |
| $^{25}$Mg | 1.55E-02 |
| $^{30}$Si | 8.66E-03 |
| $^{35}$Cl | 8.10E-04 |
| $^{40}$K | 1.61E-04 |
| $^{44}$Ca | 4.71E-04 |
| $^{48}$Sc | 1.85E-04 |
| $^{51}$V | 1.79E-04 |
| $^{56}$Mn | 2.33E-04 |
| $^{58}$Ni | 4.07E-04 |
| $^{63}$Cu | 1.55E-03 |
| $^{67}$Zn | 4.51E-08 |
| $^{76}$Ge | 5.37E-08 |
| Element | Yield | Yield | Element | Yield | Yield | Element | Yield | Yield |
|---------|-------|-------|---------|-------|-------|---------|-------|-------|
| $^4\text{He}$ | 3.955E+05 | $^4\text{He}$ | 7.901E+01 | $^1\text{B}$ | 3.622E+16 | $^1\text{C}$ | 1.886E+00 | $^2\text{Ne}$ | 7.623E+04 |
| $^3\text{Li}$ | 9.328E+18 | $^8\text{Be}$ | 4.313E+01 | $^9\text{O}$ | 5.103E+02 | $^1\text{O}$ | 4.431E+01 | $^2\text{Ne}$ | 7.623E+04 |
| $^4\text{Be}$ | 5.220E-09 | $^1\text{O}$ | 3.431E+01 | $^1\text{O}$ | 3.431E+01 | $^1\text{C}$ | 1.886E+00 | $^2\text{Ne}$ | 7.623E+04 |
| $^5\text{B}$ | 1.263E-02 | $^2\text{Ne}$ | 4.697E+00 | $^{28}\text{Mg}$ | 3.092E+03 | $^{29}\text{Al}$ | 2.504E-03 | $^2\text{Ne}$ | 7.623E+04 |
| $^{12}\text{C}$ | 1.263E-02 | $^{29}\text{Si}$ | 1.844E-02 | $^{30}\text{Si}$ | 3.101E-02 | $^{30}\text{Si}$ | 3.101E-02 | $^2\text{Ne}$ | 7.623E+04 |
| $^6\text{Li}$ | 1.844E-02 | $^{30}\text{Si}$ | 8.567E-02 | $^{31}\text{P}$ | 1.374E-02 | $^{31}\text{S}$ | 3.219E-02 | $^2\text{Ne}$ | 7.623E+04 |
| $^{13}\text{O}$ | 2.038E-06 | $^{32}\text{S}$ | 5.236E-02 | $^{33}\text{Cl}$ | 2.695E+00 | $^{34}\text{Ar}$ | 3.902E-02 | $^2\text{Ne}$ | 7.623E+04 |
| $^{14}\text{N}$ | 1.844E+01 | $^{34}\text{S}$ | 2.719E+02 | $^{36}\text{Ar}$ | 3.902E-02 | $^{36}\text{Ar}$ | 3.902E-02 | $^2\text{Ne}$ | 7.623E+04 |
| $^{16}\text{O}$ | 2.038E-06 | $^{35}\text{Cl}$ | 2.719E+02 | $^{38}\text{Ar}$ | 3.902E-02 | $^{38}\text{Ar}$ | 3.902E-02 | $^2\text{Ne}$ | 7.623E+04 |

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