UC San Diego

UC San Diego Previously Published Works

Title

Production of the Light p-Process Nuclei in Neutrino-driven Winds

Permalink

<https://escholarship.org/uc/item/4np04959>

Journal

The Astrophysical Journal, 460(1)

ISSN

0004-637X

Authors

Hoffman, RD
Woosley, SE
Fuller, GM
et al.

Publication Date

1996-03-01

DOI

10.1086/176986

Peer reviewed

PRODUCTION OF THE LIGHT p -PROCESS NUCLEI IN NEUTRINO-DRIVEN WINDS

R. D. HOFFMAN AND S. E. WOOSLEY

University of California Observatories/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California,
 Santa Cruz, Santa Cruz, CA 95064

G. M. FULLER

Physics Department, University of California, San Diego, La Jolla, CA 92093

AND

B. S. MEYER

Department of Physics and Astronomy, Clemson University, Clemson, SC 29634

Received 1995 February 13; accepted 1995 September 28

ABSTRACT

Recent studies of nucleosynthesis that occurs in the neutrino-driven wind following the delayed explosion of a Type II or Ib supernova have provided a promising site for the synthesis of the r -process isotopes. One worrisome aspect of these models is a large overproduction of $N = 50$ (closed neutron shell) nuclei in about $0.01 M_{\odot}$ of the ejecta with entropy per baryon $S/(N_A k) \approx 50$ originating before the r -process epoch, at times $t \lesssim 1$ s after core bounce. This overproduction is a consequence of the low electron fraction ($Y_e \approx 0.46$) employed in these calculations. We have found that raising Y_e in the wind at this time to ≈ 0.485 cures the difficulty. The problematic nucleosynthesis disappears and is replaced by the moderate production of ^{70}Ge and some interesting light p -process nuclei, ^{74}Se , ^{78}Kr , ^{84}Sr , and ^{92}Mo , thus potentially turning a major shortcoming of this model into a success. The early neutrino-heated ejecta must have $Y_e \gtrsim 0.484$ to effect a cure of the $N = 50$ overproduction problem and produce the light p -nuclei up to ^{92}Mo . If $Y_e \gtrsim 0.488$, production of light p -nuclei is lost, but the $N = 50$ overproduction is still avoided. In addition, ^{64}Zn is produced in amounts that could be important for galactic chemical evolution. It is interesting that the r -process and some light p -process nuclei may be coproduced. We are also able to place approximate limits on the mass a typical Type II supernova can eject as a function of Y_e . In particular, the ejected mass having $Y_e \lesssim 0.47$ must be $\lesssim 10^{-4} M_{\odot}$.

Subject headings: elementary particles — nuclear reactions, nucleosynthesis, abundances — supernovae: general

1. INTRODUCTION

The origin in nature of the neutron-deficient stable isotopes of the elements heavier than ^{74}Se and lighter than ^{196}Hg , known collectively as the p -process nuclei, has been one of continual fascination for the nuclear astrophysicist for 40 years (see, e.g., the reviews by Lambert 1992 and Meyer 1994). Burbidge et al. (1957) adopted the name and suggested that the p -process nuclei were made by a combination of (p, γ) and (γ, n) reactions taking place on previously existing r - and s -process seed in a proton-rich environment. Woosley & Howard (1978) proposed a different mechanism, the γ -process, whereby the p -nuclei are created by a combination of photodisintegration reactions, (γ, n), (γ, p), and (γ, α), happening for peak temperatures between 2 and 3 billion degrees as the shock propagates through the neon and oxygen layers of a Type II supernova. Repeated studies of increasing realism have shown that this γ -process can give good agreement with the solar ratios of the p -nuclei in modern supernova models (e.g., Prantzos et al. 1990; Rayet, Prantzos, & Arnould 1990; Arnould, Rayet, & Hashimoto 1992; Rayet et al. 1994). Two major deficiencies have emerged, however: (1) The overall yield of the p -nuclei may be too low, by about a factor of 4 with respect to oxygen (Rayet et al. 1994), and (2) the “light” p -nuclei of Sr, Mo, Ru, Pd, and Cd ($84 \lesssim A \lesssim 108$) are always substantially underproduced (especially Mo and Ru) with respect to the other heavier p -nuclei.

We report here what may be one missing piece to this puzzle, a new kind of “ p -process” for the nuclei from mass 74–92. This mechanism operates in addition to the usual

γ -process, which is probably responsible for the heavier neutron-deficient isotopes, as well as some other still-unknown process responsible for the production of ^{94}Mo and $^{96,98}\text{Ru}$. Charged particle reactions occurring during the freezeout of material from nuclear statistical equilibrium (NSE) in the presence of a large excess of free α -particles produce abundances of ^{74}Se , ^{78}Kr , ^{84}Sr , and ^{92}Mo that, if sufficient material in the ejecta were to experience the conditions we shall explore, could account for their full solar abundance. No initial abundances of r - or s -process seed need be invoked, and this component of the p -process is primary rather than secondary. Similar conditions and nucleosynthesis have been discussed by Woosley & Hoffman (1992; see especially their Table 4 for $0.05 \leq \eta \leq 0.08$, or $0.475 \geq Y_e \geq 0.465$). Our results differ here by following a zone taken from a recent supernova model that had a different entropy profile that freezes out over a longer timescale. We also explore the physics responsible for this synthesis and its sensitivity to key parameters and demonstrate that it cannot make ^{94}Mo and $^{96,98}\text{Ru}$.

The conditions we require, insofar as entropy, timescale, and α -particle concentration are concerned, are achieved in the last $\sim 0.001 M_{\odot}$ ejected by a typical Type II supernova (Wilson & Mayle 1993). However, we will require an adjustment of Y_e upward by about 5% compared to what the supernova model gave at an age of ~ 1 s. Other than this adjustment in Y_e , these are the same conditions studied for the r -process by Woosley et al. (1994, hereafter Paper I). A solar r -process was later produced in those calculations but

at a time ($t \sim 10\text{--}15$ s) when the entropy was much higher (300–400 vs. 50) and Y_e much lower ($\lesssim 0.40$ vs. 0.46). A major problem in that and other recent studies (Witti, Janka, & Takahashi 1993; Howard et al. 1993) was a large overproduction of $N = 50$ (closed neutron shell) nuclei. The overproductions were so great, in fact, that no heavy element production (other than these rare nuclei) could occur. Here we show that the solution to this problem currently yields the interesting light *p*-process synthesis and places tight limits on the amount of neutron-rich material the supernova can eject.

2. NUCLEOSYNTHESIS CALCULATIONS

The most problematic zone of Paper I (trajectory 14, Table 1 of that paper) had a mass $2.3 \times 10^4 M_\odot$. We calculated the nucleosynthesis in that zone starting at time 0.5895 s (post-bounce) when the temperature had declined to 9×10^9 K and continued to a time at which all strong nuclear reactions ceased ($T_9 \lesssim 1.0$, $T_9 \equiv T/10^9$ K). Figure 1 shows the temperature and density history for this zone. The dimensionless entropy at the beginning of the calculation [$S/N_A k = 49$] remained nearly constant during the time considered. As in Paper I, the starting composition was assumed to be pure ^4He and neutrons in proportions required by the initial value of the electron mole number (Y_{ei}) at $T = 0.5$ MeV. Initially, two models were calculated. One, using $Y_{ei} = 0.460$, duplicated the original results of Paper I; the other used an arbitrary initial value of $Y_{ei} = 0.485$. For further details of the computational procedure and reaction rate information used, see Paper I and Woosley & Hoffman (1992). The reaction network used here is more proton rich than these previous works and is given in Table 1.

TABLE 1
NUCLEAR REACTION NETWORK

Z	$A_{\min}$	$A_{\max}$	Z	$A_{\min}$	$A_{\max}$
H	1	3	V	45	60
He	3	4	Cr	47	62
Li	6	7	Mn	49	64
Be	7	9	Fe	51	66
B	8	11	Co	53	69
C	11	14	Ni	55	72
N	13	15	Cu	57	75
O	15	18	Zn	59	78
F	17	20	Ga	61	81
Ne	19	24	Ge	63	84
Na	21	26	As	65	87
Mg	23	28	Se	67	90
Al	25	31	Br	69	93
Si	27	34	Kr	71	96
P	29	37	Rb	73	99
S	31	40	Sr	76	102
Cl	33	43	Y	77	105
Ar	35	46	Zr	78	108
K	37	49	Nb	82	111
Ca	39	52	Mo	87	114
Sc	41	55	Tc	89	117
Ti	43	58	Ru	91	120

Figure 2 shows the results. Each production factor is defined as the final mass fraction (after all weak decays) of the given stable nucleus divided by its solar abundance (Anders & Grevesse 1989) and normalized to the amount of ejecta in the zone ($2.3 \times 10^{-4} M_\odot$ divided by the $18.5 M_\odot$ of material ejected from the $20 M_\odot$ supernova model). The most abundant isotope in the solar distribution for a given element is plotted in Figure 2 as an asterisk; isotopes of a given element are connected by solid lines. A diamond

FIG. 1.—Temperature ($T_9 = 10^9$ K, solid line) and density (g cm^{-3} , dotted line) vs. time in trajectory 14 of Woosley et al. (1994)

FIG. 2a

FIG. 2b

FIG. 2.—Production factors (the ratio of the final mass fraction of a given isotope to its mass fraction in the sun after all nuclear activity has ceased and all weak decays completed), normalized to the mass of the zone ($2.3 \times 10^{-4} M_{\odot}$) and total mass ejected ($18.5 M_{\odot}$) from a $20 M_{\odot}$ supernova model (Woosley et al. 1994). Solid lines connect isotopes of a given element. The most abundant isotope in the Sun for a given element is plotted as an asterisk. A diamond around the data point indicates its production as a radioactive progenitor. Shown are the results for two runs that followed the thermodynamic history shown in Fig. 1 for two assumed initial compositions characterized by (a) $Y_{ei} = 0.460$ and (b) $Y_{ei} = 0.485$.

around a data point indicates that it is produced chiefly as a radioactive progenitor. The dotted horizontal lines indicate an approximate "normalization band" bounded above by the isotope with the largest production factor in the zone and bounded below by a factor of 10 less. Nuclei that fall within this band will be the dominant species produced. Typically, in order to account for the solar abundances of most nuclides attributed to Type II supernovae (e.g., ^{16}O), the production factor should be ~ 10 when averaged over all supernova progenitors (e.g., Mathews, Bazan, & Cowan, 1992; Timmes, Woosley, & Weaver 1995; Woosley & Weaver 1995).

The results of Figure 2b show that the change in Y_{ei} greatly reduces the production of $N = 50$ isotopes. The dominant species are now ^{70}Ge and the light *p*-process nuclei ^{74}Se , ^{78}Kr , ^{84}Sr , and ^{92}Mo , all made as themselves. In addition, the production factors are reduced to approximately 10. These abundances would pose no problem for Galactic chemical evolution, and if a mass comparable to that of zone 14 experienced these conditions, it could in fact account for the origin of these species in nature.

Encouraged by this possibility, we surveyed the nucleosynthesis resulting for this single trajectory (Fig. 1) for a variety of initial Y_{ei} values. Figure 3a shows the production factors for ^{70}Ge and six of the light *p*-nuclei for $0.46 \leq Y_{ei} \leq 0.5$. Production that might explain their solar abundances is apparently limited to a relatively narrow range ($0.484 \leq Y_e \leq 0.488$), outside of which the composition is dominated either by the rare $N = 50$ nuclei ($Y_e < 0.482$) or species in the iron group ($Y_e > 0.49$). The time evolution of

some key composition quantities for the calculations shown in Figure 3 is given in Table 2, and final composition quantities for select values of Y_{ei} are given in Table 3. In both tables, $\langle A \rangle$ is the mean atomic weight (excluding α -particles and nucleons). In Table 3, $(Y_e)_{\text{eff}} = (1 - \eta_{\text{eff}}/2)$, where η_{eff} is the effective neutron excess, $\eta_{\text{eff}} = \eta_{\text{final}}/[1 - X_{\text{final}}(\alpha)]$.

Of some interest is the *p*-nucleus ^{92}Mo , which has been underproduced in all previous studies of the *p*-process (e.g., Rayet et al. 1994). Here ^{92}Mo is made with a mass fraction $\sim 10^{-4}$ for all runs with $0.466 \leq Y_{ei} \leq 0.488$ and is produced in greatest abundance for $Y_{ei} = 0.486$ [$X(^{92}\text{Mo}) = 9.3 \times 10^{-4}$]. During the freezeout at $T_9 \sim 3$, ^{92}Mo reaches half its final abundance. Interestingly, under these conditions ^{92}Mo is in a quasi-equilibrium (QSE) cluster that contains ^{90}Zr (Fig. 4). Its abundance is then given by a Saha equation (Bodansky, Clayton, & Fowler 1968; Woosley, Arnett & Clayton 1973),

$$Y(^{92}\text{Mo}) = C(^4Z, T_9, \rho) Y(^{90}\text{Zr}) Y_p^2. \quad (1)$$

Thus, ^{92}Mo synthesis depends sensitively on Y_e , which must be high enough to allow for a nonnegligible free-proton abundance (Table 2), yet not so high that the α -particle flows responsible for assembling material above the iron-group encounter regions of small ($S_\alpha \leq 4$ MeV) α -separation energy, where photodisintegration would impede the upward flow (Fig. 5; see also Woosley & Hoffman 1992, § 2). In addition, Y_e must be low enough to produce some nuclei in the $N = 50$ closed neutron shell, especially ^{90}Zr , whose abundance sets the equilibrium value of ^{92}Mo and provides for its continued synthesis during the

TABLE 2
KEY EVOLUTIONARY QUANTITIES

$t(\text{s})$	T_9	X_n	X_p	X_α	$\langle A \rangle$	4Z_1	$X(^4Z)_1$	4Z_2	$X(^4Z)_2$	4Z_3	$X(^4Z)_3$
$(Y_e)_i = 0.460, (Y_e)_f = 0.4606$											
1.00(−20).....	8.97	8.00(−2)	6.7(−16)	9.20(−1)	...	^3H	2.0(−15)	^3He	7.1(−16)	^9Be	1.2(−17)
1.602(−2).....	7.45	1.17(−1)	3.86(−2)	8.44(−1)	30.6	^2H	6.43(−6)	^3H	1.24(−7)	^{12}C	6.17(−8)
2.521(−2).....	6.58	8.26(−2)	3.85(−3)	9.13(−1)	52.3	^{50}Ti	4.58(−5)	^{54}Cr	3.61(−5)	^{51}V	1.31(−5)
3.104(−2).....	6.03	4.86(−2)	6.37(−4)	6.88(−1)	55.8	^{54}Cr	5.32(−2)	^{58}Fe	3.23(−2)	^{50}Ti	2.82(−2)
3.584(−2).....	5.57	2.05(−2)	1.61(−4)	5.10(−1)	60.6	^{64}Ni	8.58(−2)	^{66}Ni	5.37(−2)	^{58}Fe	5.34(−2)
4.303(−2).....	4.89	1.93(−3)	3.41(−5)	4.02(−1)	66.6	^{64}Ni	1.94(−1)	^{66}Ni	5.25(−2)	^{62}Ni	4.37(−2)
4.635(−2).....	4.58	3.10(−4)	2.52(−5)	3.67(−1)	70.2	^{88}Sr	1.40(−1)	^{64}Ni	1.35(−1)	^{62}Ni	1.09(−1)
5.002(−2).....	4.23	3.43(−5)	1.73(−5)	3.43(−1)	72.8	^{88}Sr	2.78(−1)	^{62}Ni	1.88(−1)	^{64}Ni	5.25(−2)
6.478(−2).....	4.00	4.67(−6)	1.49(−5)	3.30(−1)	74.1	^{88}Sr	3.12(−1)	^{62}Ni	2.16(−1)	^{89}Y	3.07(−2)
9.429(−2).....	3.54	1.27(−7)	3.58(−6)	3.13(−1)	75.7	^{88}Sr	2.54(−1)	^{62}Ni	1.93(−1)	^{90}Zr	9.35(−2)
1.635(−1).....	3.05	1.15(−9)	2.25(−7)	2.94(−1)	77.4	^{90}Zr	2.01(−1)	^{88}Sr	1.70(−1)	^{62}Ni	1.19(−1)
1.848(−1).....	2.96	3.9(−10)	1.21(−7)	2.92(−1)	77.6	^{90}Zr	2.07(−1)	^{88}Sr	1.63(−1)	^{62}Ni	1.06(−1)
6.079(−1).....	2.18	3.9(−14)	2.73(−9)	2.86(−1)	77.8	^{90}Zr	2.13(−1)	^{88}Sr	1.52(−1)	^{66}Zn	1.24(−1)
4.953(0).....	1.16	3.2(−19)	3.2(−10)	2.86(−1)	77.7	^{90}Zr	2.13(−1)	^{88}Sr	1.52(−1)	^{66}Zn	1.23(−1)
$(Y_e)_i = 0.485, (Y_e)_f = 0.4855$											
1.00(−20).....	8.97	3.00(−2)	7.0(−16)	9.70(−1)	...	^3H	2.1(−15)	^3He	7.5(−16)	^9Be	4.8(−18)
1.658(−2).....	7.40	8.03(−2)	5.12(−2)	8.69(−1)	16.6	^2H	5.94(−6)	^3H	8.28(−8)	^{12}C	6.79(−8)
2.907(−2).....	6.21	2.77(−2)	2.83(−3)	9.30(−1)	54.1	^{54}Cr	8.81(−3)	^{50}Ti	5.17(−3)	^{58}Fe	4.82(−3)
3.370(−2).....	5.78	7.67(−3)	1.38(−3)	7.66(−1)	56.0	^{58}Fe	4.83(−2)	^{54}Cr	3.85(−2)	^{55}Mn	1.92(−2)
3.927(−2).....	5.25	8.40(−4)	8.17(−4)	6.82(−1)	57.9	^{58}Fe	6.47(−2)	^{62}Ni	5.30(−2)	^{56}Fe	5.13(−2)
4.382(−2).....	4.82	1.06(−4)	4.83(−4)	6.58(−1)	59.1	^{62}Ni	9.62(−2)	^{56}Fe	7.12(−2)	^{58}Fe	3.46(−2)
4.881(−2).....	4.34	8.61(−6)	2.21(−4)	6.44(−1)	60.1	^{62}Ni	1.22(−1)	^{60}Ni	9.41(−2)	^{56}Fe	5.01(−2)
6.807(−2).....	3.95	6.08(−7)	9.45(−5)	6.27(−1)	60.6	^{60}Ni	1.78(−1)	^{62}Ni	1.04(−1)	^{61}Ni	3.48(−2)
9.826(−2).....	3.48	1.36(−8)	2.25(−5)	6.10(−1)	61.2	^{60}Ni	2.50(−1)	^{62}Ni	6.31(−2)	^{66}Zn	2.08(−2)
1.788(−1).....	2.98	5.2(−11)	3.51(−6)	5.89(−1)	62.0	^{60}Ni	2.54(−1)	^{64}Zn	6.68(−2)	^{66}Zn	3.43(−2)
3.832(−1).....	2.52	4.4(−13)	4.94(−7)	5.69(−1)	62.6	^{60}Ni	1.91(−1)	^{64}Zn	1.48(−1)	^{66}Zn	2.30(−2)
8.965(−1).....	1.72	6.9(−16)	1.49(−8)	5.60(−1)	62.3	^{60}Ni	1.76(−1)	^{64}Zn	1.54(−1)	^{66}Zn	1.69(−2)
4.802(0).....	1.13	2.4(−19)	7.2(−10)	5.54(−1)	61.8	^{60}Ni	1.68(−1)	^{64}Zn	1.53(−1)	^{66}Zn	1.60(−2)

NOTE.— $a(b) = a \times 10^b$.

FIG. 3a

FIG. 3b

FIG. 3.—Normalized production factors for the dominant productions over a range of assumed initial compositions with $0.460 \leq Y_{ei} \leq 0.50$. (a) ^{70}Ge and the six light p -nuclei ^{74}Se , ^{78}Kr , ^{84}Sr , $^{92,94}\text{Mo}$, and ^{96}Ru , which dominate the nucleosynthesis over a narrow range $0.484 \leq Y_{ei} \leq 0.488$. (b) The nuclei that dominate outside this range, the $N = 50$ isotones (^{88}Sr , ^{89}Y , and ^{90}Zr), and nuclei within the iron group (^{62}Ni and ^{64}Zn). Also plotted is the ratio (by final mass fraction) $X(^{92}\text{Nb})/X(^{93}\text{Nb})$ for all runs with initial compositions characterized by $0.460 \leq Y_{ei} \leq 0.491$.

TABLE 3
 FINAL COMPOSITION QUANTITIES

$(Y_e)_i$	$(Y_e)_f$	$(Y_e)_{\text{eff}}$	X_{α}	$\langle A \rangle$	$^A Z_1$	$X(^A Z)_1$	$^A Z_2$	$X(^A Z)_2$	$^A Z_3$	$X(^A Z)_3$
0.460.....	0.461	0.445	0.286	77.7	^{90}Zr	2.13(-1)	^{88}Sr	1.52(-1)	^{66}Zn	1.23(-1)
0.462.....	0.463	0.446	0.302	76.6	^{90}Zr	2.27(-1)	^{66}Zn	1.36(-1)	^{88}Sr	1.04(-1)
0.464.....	0.465	0.448	0.319	75.4	^{90}Zr	2.34(-1)	^{66}Zn	1.46(-1)	^{62}Ni	7.12(-2)
0.466.....	0.467	0.450	0.337	74.2	^{90}Zr	2.32(-1)	^{66}Zn	1.52(-1)	^{62}Ni	6.56(-2)
0.468.....	0.469	0.451	0.357	73.0	^{90}Zr	2.20(-1)	^{66}Zn	1.55(-1)	^{62}Ni	5.93(-2)
0.470.....	0.471	0.453	0.378	71.7	^{90}Zr	1.99(-1)	^{66}Zn	1.54(-1)	^{60}Ni	6.15(-2)
0.472.....	0.473	0.454	0.399	70.4	^{90}Zr	1.72(-1)	^{66}Zn	1.45(-1)	^{60}Ni	7.73(-2)
0.474.....	0.475	0.456	0.422	69.0	^{90}Zr	1.42(-1)	^{66}Zn	1.34(-1)	^{60}Ni	9.37(-2)
0.476.....	0.477	0.458	0.446	67.7	^{66}Zn	1.22(-1)	^{90}Zr	1.11(-1)	^{60}Ni	1.10(-1)
0.478.....	0.479	0.460	0.469	66.4	^{60}Ni	1.24(-1)	^{66}Zn	1.04(-1)	^{64}Zn	8.85(-2)
0.480.....	0.481	0.461	0.494	65.0	^{60}Ni	1.38(-1)	^{64}Zn	1.05(-1)	^{66}Zn	8.53(-2)
0.482.....	0.483	0.464	0.519	63.7	^{60}Ni	1.52(-1)	^{64}Zn	1.23(-1)	^{66}Zn	6.12(-2)
0.484.....	0.484	0.466	0.543	62.4	^{60}Ni	1.65(-1)	^{64}Zn	1.43(-1)	^{66}Zn	3.14(-2)
0.485.....	0.485	0.467	0.554	61.8	^{60}Ni	1.68(-1)	^{64}Zn	1.53(-1)	^{66}Zn	1.60(-2)
0.486.....	0.486	0.469	0.567	61.2	^{60}Ni	1.69(-1)	^{64}Zn	1.60(-1)	^{61}Cu	1.48(-2)
0.488.....	0.488	0.472	0.589	60.0	^{64}Zn	1.40(-1)	^{60}Ni	1.32(-1)	^{58}Ni	5.70(-2)
0.490.....	0.490	0.476	0.609	59.1	^{58}Ni	1.20(-1)	^{64}Zn	9.79(-2)	^{60}Ni	7.93(-2)
0.492.....	0.492	0.480	0.630	58.2	^{58}Ni	1.85(-1)	^{64}Zn	5.33(-2)	^{62}Zn	3.43(-2)
0.494.....	0.494	0.484	0.649	57.1	^{58}Ni	2.46(-1)	^{62}Zn	3.83(-2)	^{56}Ni	8.23(-3)
0.496.....	0.496	0.489	0.667	56.2	^{58}Ni	1.67(-1)	^{56}Ni	7.52(-2)	^{62}Zn	2.75(-2)
0.498.....	0.498	0.495	0.683	55.4	^{56}Ni	1.62(-1)	^{58}Ni	6.50(-2)	^{57}Ni	2.37(-2)
0.500.....	0.500	0.500	0.695	54.9	^{56}Ni	2.30(-1)	^{60}Zn	3.17(-2)	^{52}Fe	1.30(-2)

 NOTE.— $a(b) = a \times 10^b$.

freezeout from NSE. While in quasi-equilibrium with ^{90}Zr , ^{92}Mo is not made in equilibrium with any of the lighter p -nuclei contained in our network.

We note the disappointingly small production of ^{94}Mo (Fig. 3a); its abundance is always less than other p -nuclei coproduced in this zone. Unfortunately, ^{96}Ru and ^{98}Ru are also not made in appreciable abundance for any range of initial Y_e studied. Ruthenium is at the end of the network used in the present study, but calculations of this trajectory with an extended r -process network (Meyer et al. 1992) for $Y_{ei} = 0.481, 0.483, 0.485$, and 0.487 showed negligible production of any nuclei with $A \geq 96$.

This deficiency can be understood if we assume that these heavier p -nuclei are produced in equilibrium with ^{90}Zr , say, as might be expected owing to their small α -particle separa-

tion energies (Fig. 5). Their relative abundances can be estimated by detailed balance (eq. [1]). For comparison, Table 4 shows results from both the network and equilibrium calculations for $^{92,94}\text{Mo}$ and $^{96,98}\text{Ru}$, while only equilibrium abundances are given for the heavier p -nuclei. The good agreement for the $A \leq 98$ nuclei indicate that the equilibrium assumption is valid for the conditions shown in Table 4. All the $A \geq 96$ p -nuclei drop out of equilibrium with ^{90}Zr below $T_9 \sim 3$, before they reach one-half their final abundance at $T_9 \sim 2.5$, and by then the equilibrium assumption may not be valid. However, we do not believe that substantial flow proceeds beyond $A \geq 94$ at these late times during the freezeout (certainly not to Xe), owing to a combination of increasing charge barrier and lower particle separation energies. Recent studies suggest the solar abun-

FIG. 4.—Quasi-equilibrium clusters in the calculation that used initial $Y_{ei} = 0.485$ sampled at $T_9 = 2.98$, $\rho = 1.26 \times 10^5 \text{ g cm}^{-3}$. Two large clusters exist at this time: they extend from the iron group to germanium ($58 \leq A_{\text{const}} \leq 70$) and from yttrium to ruthenium (the end of our reaction network). Nuclei connected by lines are defined to be in equilibrium with neutrons (horizontal lines), protons (vertical lines), and α -particles (diagonal lines) when the net nuclear flow (the product of abundance, density, and reaction rate minus a similar product for the inverse reaction) is less than one-half the forward flow. Filled squares indicates locations of the stable isotopes.

FIG. 5.—Contours of constant α -particle separation energy. The contours are given by the first isotope of each element to have a separation energy less than the specified value. Open triangles indicate locations of the stable isotopes. Three lines of constant $Y_e = 0.5, 0.48$, and 0.46 are shown.

dance of ^{102}Pd and ^{106}Cd can be produced during the operation of the γ -process (Rayet et al. 1994), but $^{96,98}\text{Ru}$ remain a mystery.

The nuclei ^{70}Ge and ^{74}Se are made in a separate QSE cluster that extends (at $T_9 \sim 3.5$) from the iron group all the way to Kr. However, this cluster does not include ^{78}Kr and ^{84}Sr , which are located in the gap between the two clusters just described. (At $T_9 \sim 3.0$, ^{74}Se , ^{78}Kr , and ^{84}Sr achieve half their final abundance, but by then they are separate from the QSE cluster that still contains ^{70}Ge and the iron group.) Thereafter, all three light p -nuclei owe their continued synthesis to reaction flows linking the two QSE clusters (Fig. 6); they are not made in equilibrium with the iron group or ^{90}Zr .

TABLE 4

ABUNDANCES ASSUMED IN QUASI-EQUILIBRIUM WITH ^{90}Zr

AZ	$\delta_{n,p,\alpha}$	Q_{α}^b	$[X(AZ)]_{\text{QSE}}^c$	$[X(AZ)]_{\text{ntwk}}^c$	$X(AZ)_0^c$
^{90}Zr	0, 0, 0	...	8.48(−3)	8.48(−3)	1.34(−8)
^{92}Mo	0, 2, 0	12.617	3.48(−4)	2.86(−4)	8.80(−10)
^{94}Mo	0, 0, 1	2.066	1.28(−6)	1.52(−6)	5.61(−10)
^{96}Ru	0, 2, 1	14.304	1.20(−8)	1.20(−8)	2.50(−10)
^{98}Ru	0, 0, 2	4.301	3.72(−10)	5.51(−10)	8.68(−11)
^{102}Pd	0, 0, 3	6.426	7.03(−14)	...	3.66(−11)
^{106}Cd	0, 0, 4	8.057	1.94(−18)	...	5.39(−11)
^{108}Cd	2, 0, 4	26.316	5.88(−20)	...	3.91(−11)

^a $Y_e = 0.485$, $T_9 = 2.98$, $\rho = 1.26 \times 10^5 \text{ g cm}^{-3}$; $Y_n = 5.17 \times 10^{-11}$, $Y_p = 3.15 \times 10^{-6}$, $Y_\alpha = 0.1473$.

^b $Q_{\alpha} = \text{BE}(AZ) - \text{BE}(^{90}\text{Zr}) - \delta_\alpha \text{BE}(\alpha)$.

^c $a(b) = a \times 10^b$.

The light p -nuclei are produced by particle capture on the most abundant isotopes in nuclear statistical equilibrium for a specific Y_e . For $Y_e = 0.485$, these are ^{60}Ni and $^{64,66}\text{Zn}$ (see Tables 2 and 3). ^{64}Zn is the dominant isotope of zinc in nature (Anders & Grevesse 1989). Elsewhere we have ascribed its synthesis to explosive helium burning and to the α -rich freezeout (Woosley 1986), where it is made as ^{64}Ge . However, a recent survey of massive star nucleosynthesis and stellar evolution (Timmes et al. 1995) showed substantial underproduction of ^{64}Zn made in this fashion. The conditions described here are a promising alternative.

As the layers we are describing are ejected, they are likely to mix. The r -process which is produced later has higher entropy and, we speculate, will tend to float above this layer, with the lower entropy material containing the proposed light p -component falling through the rising plumes along narrow streams (Colgate, Herant, & Benz 1993; Herant & Woosley 1994). Thus, an interesting possibility is that some material containing r -process and (light) p -process nuclei will become mixed. With this in mind, we note with interest the production of the long-lived radioactivity ^{92}Nb , as well as the light p -nuclei ^{78}Kr and ^{84}Sr , all of which show anomalous abundances in meteorites (Lambert 1992).

^{92}Nb ($\tau_{1/2} = 3.5 \times 10^7 \text{ yr}$) is made (by mass fraction) at the $(3-8) \times 10^{-5}$ level over a range $0.466 \leq Y_e \leq 0.484$, with its peak abundance occurring at $Y_e = 0.477$. Harper, Wiesman, & Nyquist (1991) have reported ^{92}Zr anomalies in two meteorites (Allende and the Touluca) correlated with the Nb to Zr abundance ratios, from which they infer a

FIG. 6.—Net flows (the product of abundance, density, and reaction rate minus a similar product for the inverse reaction) for $30 \leq Z \leq 42$ in the run that started with $Y_e = 0.485$ sampled at a time at which most of the light p -nuclei have reached half their final abundance ($t_{pb} = 0.769$ s, $T_9 = 2.98$, $\rho = 1.26 \times 10^5$ g cm $^{-3}$). The strength of the flow is indicated by line type: solid arrows represent flows that are at least 0.01 of the largest flow [$^{66}\text{Zn}(\alpha, \gamma)^{70}\text{Ge} = 1.3 \times 10^{-3}$ s $^{-1}$]. Dotted arrows represent flows that are less than a factor of 0.01 but greater than a factor of 0.001 of the largest flow.

$^{92}\text{Nb}/^{93}\text{Nb}$ ratio at the time the Sun formed of $(2 \pm 1) \times 10^{-5}$. Over the range of Y_{ei} that produces the light p -nuclei shown in Figure 3a, the ratio of $X(^{92}\text{Nb})/X(^{93}\text{Nb})$ ranges from 10 to 40 at the source (Fig. 3b) depending upon the value of Y_e in the ejecta and the fraction of ^{93}Nb that comes from the α -process. These ratios are much higher than those reported in previous surveys of the α -process (Woosley & Hoffman 1992). However, this is only the ratio of $^{92}\text{Nb}/^{93}\text{Nb}$ in this zone. Both species are made elsewhere in the star, and ^{93}Nb could have an s -process contribution, so the ratio here might be an upper bound. Also, the calculation here used only the slow ground state decay rate for ^{92}Nb . In the hot thermal environment associated with its production, nuclear excited states may have facilitated its decay. Beyond $Y_{ei} \gtrsim 0.491$, the abundances of both isotopes become smaller than 10^{-11} , and the ratio is not plotted.

Papanastassiou & Wasserburg (1978) report isotopic anomalies for ^{84}Sr with respect to other Sr isotopes in EK 1-4-1 and C1. The anomaly is a deficiency of ^{84}Sr . Figure 3a shows that at least part of ^{84}Sr in the Sun can be produced in a site separate from the s -process and, presumably, the heavier p -process isotopes. Therefore, it might not be unusual for a sample to be deficient in this particular component. Similar statements apply to ^{78}Kr in interstellar microdiamonds, where ^{78}Kr is *underabundant* with respect to the other krypton isotopes. This krypton is found in association with xenon, whose p -process nuclei are *overabundant* (Lambert 1992; Frick 1977; Lewis, Gros, & Anders 1977). Xenon p -process nuclei (along with other heavier p -process nuclei) would have a different production site in our model.

Fuller & Meyer (1994) suggested another venue for the production of the light p -nuclei which, as in this paper, exploits the neutrino-driven ejecta in the post-core bounce supernova outflow at times less than 1s. In Fuller & Meyer

(1995), the production of the light p -nuclei is facilitated by an intense neutrino flux incident on relatively low-entropy material with a significant α -particle mass fraction. The production of ^{92}Mo is also aided by neutrino captures on heavy nuclei followed by neutron captures. However, this mechanism will not work for the vigorous early outflow found in the supernova model of Paper I. The Fuller & Meyer scenario would require that material at early times remains relatively close to the neutrino sphere (~ 100 km) for times of order 0.5 s. We feel that such conditions may be very difficult to realize in successful supernova models. No detailed supernova models, including two-dimensional calculations with convection, suggest such conditions.

An important issue is the absolute yield of light p -process nuclei ejected in the neutrino-heated wind of Paper I. Since for now we are allowing ourselves the freedom of small arbitrary adjustments in Y_e , this question may be considered in terms of how much material can experience a range of Y_e in order not to violate galactic chemical evolution constraints. The parameters that directly affect the nucleosynthesis for each of the first 24 zones in Paper I are shown in Table 5, which gives the mass of each zone, the initial and final values for the dimensionless entropy (sampled at the beginning and end of the calculations, i.e., when $T_9 = 9$ and 1, respectively), the expansion timescale, defined here as the time for the material to cool to $T_9 = 3$, where the final α -particle mass fraction has typically reached within $\sim 2\%$ its final value, and the value of Y_e at $T = 0.5$ MeV, all values adopted from Paper I.

Table 6 shows the results of a survey in Y_{ei} that gives the largest normalized production factors for each zone calculated with an assumed initial value of Y_e between 0.5 and 0.47 (both the value of the overproduction and the nucleus responsible are shown). In order to not violate galactic chemical evolution constraints (i.e., the supernova makes

TABLE 5
KEY EVOLUTION PARAMETERS (PAPER 1: ZONES 1–24)

Zone number	Mass ($M_{\odot}$)	$S/(N_A k)_i$ ($T_9 = 9$)	$S/(N_A k)_f$ ($T_9 = 1$)	τ_{exp} (s)	Y_{ei}
1	1.21(–2)	15	20	0.392	0.456
2	7.48(–3)	19	19	0.350	0.445
3	1.99(–3)	22	21	0.350	0.443
4	2.61(–3)	21	21	0.331	0.443
5	1.23(–3)	24	24	0.329	0.445
6	1.61(–3)	25	26	0.326	0.448
7	7.56(–4)	26	29	0.325	0.454
8	9.91(–4)	27	31	0.321	0.458
9	4.66(–4)	30	34	0.328	0.465
10	6.10(–4)	32	36	0.331	0.470
11	2.87(–4)	36	40	0.304	0.475
12	3.76(–4)	42	43	0.299	0.475
13	1.77(–4)	49	49	0.233	0.463
14	2.32(–4)	49	49	0.179	0.459
15	1.09(–4)	56	59	0.122	0.461
16	1.43(–4)	59	64	0.100	0.461
17	6.70(–5)	70	60	0.096	0.465
18	8.78(–5)	72	80	0.089	0.462
19	4.13(–5)	78	92	0.079	0.465
20	5.41(–5)	83	100	0.070	0.466
21	2.54(–5)	96	117	0.069	0.459
22	3.33(–5)	102	128	0.080	0.460
23	1.56(–5)	117	149	0.059	0.472
24	2.05(–5)	114	164	0.059	0.475

NOTE.— $a(b) = a \times 10^b$.

^{16}O), the ejecta from each zone must have a specific value of Y_{ei} that, when mass-averaged over all zones, does not overproduce anything by more than a factor of ~ 10 (the normalized production factors add linearly; see eq. [8] of Paper I). For zone 1, which has the largest mass of any zone considered, the initial value of Y_{ei} cannot be less than 0.494 in order not to overproduce ^{62}Zn (which decays to ^{62}Ni). Since ^{62}Zn is the dominant species produced for $0.49 \leq Y_e \leq 0.5$ for the first several zones, the mass-averaged results of the calculations that used $Y_e = 0.498$ for zone 1 and $Y_e = 0.496$ for zones 2–5 could account for the solar abundance of ^{62}Ni . Admittedly, this particular choice of parameters is somewhat arbitrary, but the actual Y_e distribution at early times, when so much matter is ejected, must have a proton-rich character. That is, $Y_e = 0.443$ – 0.456 (Table 5) for trajectories 1–3 in Paper I must actually be ≥ 0.494 . This points out the need for better understanding of supernova physics during the first few seconds of the explosion.

Similar considerations imply that the $20 M_{\odot}$ model calculated by Wilson in Paper I should have ejected (for the assumed entropies and expansion timescales shown in Table 5) $\sim 0.02 M_{\odot}$ for $Y_e \gtrsim 0.495$ (e.g., zones 1 and 2), $\sim 0.01 M_{\odot}$ for $Y_e \lesssim 0.495$ (zones 3–10), $\sim 10^{-3} M_{\odot}$ for $Y_e \lesssim 0.48$ (zones 11–24), and $\sim \text{few} \times 10^{-5} M_{\odot}$ to perhaps $10^{-4} M_{\odot}$ for $Y_e \lesssim 0.47$ (beyond zone 24). The amount of mass allowable in each range of Y_e is the sum of the masses in a column below the line very crudely indicated by the underlined production factors in Table 6.

In addition, the absolute mass of light p -process nuclei ejected depends critically on the values of Y_e adopted for each zone subject to the same constraints mentioned above. Combining the productions contained in zone 14 and one or two adjacent zones would be enough to produce the solar abundance of the light p -nuclei (up to and including ^{92}Mo) with respect to ^{16}O and many other nucleosynthetic

products (i.e., those that had $X_{ej}/X_{\odot} \sim 10$). Following these restrictions, none of the light p -process nuclei would be overproduced, and suitable values could be chosen that would account for their solar abundances.

3. WHY MIGHT Y_e BE LARGER AT EARLIER TIMES?

The electron fraction Y_e is determined by the competing processes of ν_e and $\bar{\nu}_e$ capture on neutrons and protons, respectively:

$$\nu_e + n \rightleftharpoons p + e^-, \quad (2a)$$

$$\bar{\nu}_e + p \rightleftharpoons n + e^+. \quad (2b)$$

when such an equilibrium holds, Qian et al. (1993) have shown that the electron fraction $Y_e = 1/(n/p + 1)$ is given by

$$Y_e \approx \frac{1}{1 + \lambda_{\bar{\nu}_e}/\lambda_{\nu_e}} \approx \frac{1}{1 + \bar{E}_{\bar{\nu}_e}/\bar{E}_{\nu_e}}, \quad (3)$$

where the last approximate equality is only true when the luminosities of ν_e and $\bar{\nu}_e$ become nearly equal at later times. Here $\bar{E}_{\bar{\nu}_e}$ and $\bar{E}_{\nu_e}$ are the average energies of $\bar{\nu}_e$ and ν_e , respectively.

So long as there is no neutrino flavor mixing, the average energies of the neutrino species at (and above) the neutrino sphere will satisfy $\bar{E}_{\nu(\mu)} = \bar{E}_{\bar{\nu}(\mu)} > \bar{E}_{\bar{\nu}_e} > \bar{E}_{\nu_e}$. The inequality $\bar{E}_{\bar{\nu}_e} > \bar{E}_{\nu_e}$ simply reflects the fact that the proto-neutron star left after the supernova explosion is (eventually) made mostly of neutrons. The rate of reaction (2b), $\lambda_{\bar{\nu}_e}$, will win out over the rate of reaction (2a), λ_{ν_e} , and the material flowing out above the neutrino sphere will be neutron rich, whenever the above inequalities hold, and provided that the neutrino energies are so large and discrepant that the threshold effects in reactions (2a)–(2b) can be ignored. In fact, these constraints are met during the r -process epoch at times after core bounce of ~ 10 s.

However, at the earlier times we are interested in here, the average energies of the ν_e and $\bar{\nu}_e$ are not so different that the threshold effects in equations (2a)–(2b) can be neglected. The rates of the reactions in equations (2a)–(2b) are discussed in detail in Fuller & Meyer (1995). The process of electron neutrino capture on the neutron (eq. [2a]) is a “no-threshold” reaction, since the neutron is heavier than the proton by ≈ 1.293 MeV, but there is a threshold for the reverse reaction (eq. [2b]), corresponding to electron anti-neutrino capture on protons. The significance of this threshold grows as both the average neutrino energies and the difference $\bar{E}_{\bar{\nu}_e} - \bar{E}_{\nu_e}$ decrease.

In fact, were the energy spectra for ν_e and $\bar{\nu}_e$ identical, the threshold effects guarantee the inequality $\lambda_{\bar{\nu}_e} < \lambda_{\nu_e}$, and equation (3) would predict that the supernova outflow would be proton rich! Of course, the energy spectra for these neutrino species can never be identical, but at the early times relevant for p -process nucleosynthesis they are much more similar than they are at the later times characteristic of the r -process epoch. Though the detailed neutrino-transport calculations employed in Paper I predict $Y_e \approx 0.46$ at $t_{\text{pb}} < 1$ s, even a small change in neutrino spectra of order $\sim 10\%$ could result in $Y_e \approx 0.49$. In turn, this value of Y_e would cure the $N = 50$ overproduction problem and perhaps result in production of the light p -nuclei as discussed above.

Within the uncertainties of the supernova models, it then seems plausible that Y_e is large enough at this epoch to effect a good solution to the $N = 50$ overproduction problem and

TABLE 6
LARGEST NORMALIZED PRODUCTION FACTORS
A. OVERPRODUCTION VALUES

Zone	0.500	0.498	0.496	0.494	0.492	0.490	0.488	0.486	0.484	0.482	0.480	0.478	0.476	0.474	0.472	0.470
1	1.25	3.14	6.38	9.55	12.7	15.6	18.5	21.3	24.5	56.1	86.3	114.	140.	162.	177.	568.
2	0.86	1.98	4.04	6.07	8.05	9.99	11.9	13.1	23.2	42.9	61.5	78.4	93.8	107.	230.	691.
3	0.24	0.52	<u>1.05</u>	<u>1.58</u>	<u>2.10</u>	<u>2.60</u>	<u>3.09</u>	<u>3.18</u>	7.41	12.4	17.1	21.4	25.2	28.2	101.	215.
4	0.32	0.67	1.37	2.05	2.72	3.37	3.99	4.02	10.2	16.7	22.7	28.2	33.2	39.5	152.	289.
5	0.16	0.32	0.64	0.96	1.27	1.58	1.86	2.20	<u>5.30</u>	8.31	11.1	13.6	15.8	25.7	90.4	145.
6	0.22	0.42	0.85	1.27	1.68	2.07	2.44	3.46	7.52	<u>11.4</u>	15.1	18.3	21.2	47.5	141.	205.
7	0.11	0.20	0.41	0.61	0.81	0.99	1.15	2.17	4.08	5.88	7.60	9.11	11.3	45.4	90.7	111.
8	0.15	0.28	0.55	0.81	1.08	1.33	1.47	3.40	5.95	8.30	<u>10.5</u>	12.5	27.2	92.7	145.	163.
9	0.08	0.13	0.26	0.39	0.52	0.64	0.81	2.02	3.20	4.28	5.32	8.49	36.5	68.8	84.1	85.1
10	0.10	0.17	0.34	0.51	0.67	0.82	1.35	2.92	4.42	5.84	7.12	21.1	69.6	103.	116.	124.
11	0.04	0.08	0.15	0.23	0.30	0.36	0.73	1.42	2.08	2.70	3.24	<u>12.6</u>	32.0	43.1	45.9	51.7
12	0.07	0.11	0.21	0.31	0.40	0.53	1.45	2.34	3.19	3.94	14.6	40.9	56.9	61.6	73.8	107.
13	0.03	0.05	0.09	0.12	0.16	0.20	0.58	0.96	1.31	1.64	1.89	8.65	14.6	16.9	16.7	17.5
14	0.07	0.06	0.12	0.17	0.67	1.24	2.47	15.8	31.6	38.5	50.5	76.0	103.	133.	160.	186.
15	0.09	0.03	0.05	0.27	1.04	8.60	12.6	15.0	26.0	38.7	52.1	65.4	<u>77.8</u>	87.2	91.9	93.1
16	0.03	0.04	0.07	0.09	0.30	0.58	0.86	1.10	3.59	6.86	8.43	8.58	8.81	<u>15.9</u>	24.5	32.4
17	0.01	0.01	0.03	0.04	0.14	0.24	0.40	0.51	1.68	3.21	3.95	4.02	4.13	7.46	16.2	19.3
18	0.02	0.02	0.03	0.04	0.14	0.24	0.33	0.44	0.90	2.21	4.84	8.97	14.0	20.7	25.1	26.8
19	0.02	0.09	0.05	0.50	2.46	5.67	8.44	10.4	11.5	11.9	11.8	11.1	10.1	12.4	<u>15.3</u>	18.5
20	0.01	0.01	0.04	0.09	0.52	1.09	3.54	7.13	10.6	13.5	15.5	16.8	17.3	17.2	16.7	15.7
21	0.01	0.00	0.01	0.04	0.51	2.03	4.22	6.70	9.04	11.2	12.8	13.9	14.3	14.3	13.6	12.7
22	0.01	0.01	0.09	1.43	4.82	8.44	11.6	13.9	15.2	15.3	14.7	13.2	10.6	12.4	15.1	15.4
23	0.00	0.17	1.04	1.21	1.90	3.62	3.37	5.34	6.99	6.25	5.39	9.36	10.7	10.6	18.6	24.9
24	0.00	0.22	1.36	1.58	2.49	4.75	4.42	7.01	9.19	8.21	7.08	12.3	14.1	14.0	24.4	<u>32.7</u>

B. NUCLEI RESPONSIBLE FOR PRODUCTION FACTORS

Zone	0.500	0.498	0.496	0.494	0.492	0.490	0.488	0.486	0.484	0.482	0.480	0.478	0.476	0.474	0.472	0.470
1	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se
2	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se
3	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se
4	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se
5	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se
6	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se
7	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se
8	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se
9	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se
10	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁹⁰ Zr
11	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁹⁰ Zr
12	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁹⁰ Zr	⁹⁰ Zr
13	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁹⁰ Zr	⁹⁰ Zr
14	⁴⁹ Mn	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁹² Mo	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr
15	⁴⁹ Mn	⁴⁴ Ti	⁶² Zn	⁶⁴ Zn	⁹² Mo	⁹² Mo	⁷⁴ Se	⁷⁴ Se	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr
16	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr
17	⁶⁴ Ge	⁶² Zn	⁶² Zn	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁷⁴ Se	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr
18	⁶⁴ Ge	⁴⁴ Ti	⁶² Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁶⁴ Zn	⁷⁴ Se	⁷⁴ Se	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr
19	⁴⁵ V	⁴⁴ Ti	⁶⁴ Zn	⁷⁴ Se	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁸⁸ Sr	⁸⁸ Sr	⁸⁸ Sr
20	⁴⁵ V	⁴⁴ Ti	⁶⁴ Zn	⁷⁴ Se	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr
21	⁶⁰ Zn	⁶¹ Zn	⁶¹ Cu	⁹² Mo	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr
22	⁶⁰ Zn	⁶² Zn	⁹² Mo	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁹⁰ Zr	⁸⁸ Sr	⁸⁸ Sr	⁸⁷ Rb
23	⁴⁹ Mn	⁹⁰ Zr	⁹⁰ Zr	⁸⁹ Y	⁸⁷ Rb	⁸⁷ Rb	⁸⁶ Kr	⁹² Sr	⁹² Sr	⁹² Sr	⁹⁴ Sr	⁹⁴ Sr	⁹⁴ Sr	⁹⁴ Sr	⁹⁷ Y	⁹⁷ Y
24	⁴⁹ Mn	⁹⁰ Zr	⁹⁰ Zr	⁸⁹ Y	⁸⁷ Rb	⁸⁷ Rb	⁸⁶ Kr	⁹² Sr	⁹² Sr	⁹² Sr	⁹⁴ Sr	⁹⁴ Sr	⁹⁴ Sr	⁹⁴ Sr	⁹⁷ Y	⁹⁷ Y

produce the light p -process nuclei. This problem deserves further investigation, but we do believe that when the entire p -process (and r -process) history is understood, this will likely form a part of it. If it turns out that future detailed neutrino transport calculations show that there is no way that we can have the requisite value of Y_e at this epoch, then we may have to seek the solution to this problem in new neutrino physics (see Fuller et al. 1992; Fuller 1993; Qian et al. 1993).

4. CONCLUSIONS

We have reexamined the nucleosynthesis ejected during the first 2 s of the 20 $M_\odot$ star studied by Woosley et al. (1994) by exploring a range of starting compositions characterized by $0.46 \leq Y_{ei} \leq 0.5$. While exploring the nucleosynthesis in 24 zones (Table 6), we have concentrated our attention on zone 14 which previously gave grossly unacceptable results. For modest (5%–8%) upward adjustments

in Y_{ei} , the composition is dominated by ^{70}Ge and the light p -process nuclei ^{74}Se , ^{78}Kr , ^{84}Sr , and ^{92}Mo made in proportions that, if ejected, could account for their solar abundances without gross overproduction of anything else.

Of these, ^{70}Ge is made in quasi-equilibrium with nuclei in the iron group, while ^{92}Mo is made in quasi-equilibrium with ^{90}Zr . Three other light p -nuclei, ^{74}Se , ^{78}Kr and ^{84}Sr , are synthesized by reaction flows that bridge the region between these two QSE clusters. The production is primary, and unlike the neutrino-produced p -process of Domogatsky & Nadyozhin (1977, 1978), does not require preexisting r - or s -process seed nuclei to be reprocessed by the operation of either the γ - or ν -processes. Because of their small particle separation energies and increasing charge barriers, we do not envision the heavier p -nuclei, $^{96,98}\text{Ru}$, ^{102}Pd , or $^{106,108}\text{Cd}$, as being made this way. Their abundances probably result from the operation of the more traditional γ -process, although the origins of ^{94}Mo and $^{96,98}\text{Ru}$ remain a mystery. We also find the production of important amounts of ^{64}Zn , the dominant zinc isotope in nature. In addition, the long-lived radioactivity ^{92}Nb is made in quantities (compared to stable ^{93}Nb) which are larger than previously reported. Implications for meteoritic anomalies were discussed.

Our study has also led to interesting limits on the amount of material that can be ejected (for the characteristic entropies and timescales in Paper I) as a function of Y_e . For example, at entropy $S/(N_a k) \gtrsim 50$ the supernova can eject no more than $\sim 10^{-4} M_\odot$ having $Y_e \leq 0.47$ (§ 2, Tables 5 and 6).

The production of the light p -nuclei happens during the first few seconds of the explosion, separate from the r -process, which is made at a later time (10–15 s). At early times, the “hot bubble” will be subject to instabilities which suggest extensive mixing, possibly allowing for the ejection of material enhanced in freshly synthesized proton-rich and neutron-rich nuclei. The evolving character of the neutrino-driven wind during both epochs naturally sets Y_e and the entropy to values that produce such distinct proton-rich and neutron-rich nucleosynthesis.

We appreciate many valuable conversations with Yong-Zhong Qian regarding the physical processes that affect the evolution of entropy and Y_e in the neutrino-driven wind. This work has been supported by the National Science Foundation (NSF-AST-91-15367 and NSF-PHY-92-08881 and NSF-PHY-91-21623) and by NASA grant NAGW-3480.

REFERENCES

- Anders, E., & Grevesse, N. 1989, *Geochim. Cosmochim. Acta*, 53, 197
 Arnould, M., Rayet, M., & Hashimoto, M. 1992, in *Unstable Nuclei in Astrophysics*, ed. S. Kubono & T. Kajino (Singapore: World Scientific), 23
 Bodanski, D., Clayton, D. D., & Fowler, W. A. 1968, *ApJS*, 16, 299
 Burbidge, E. M., Burbidge, G. R., Fowler, W. A., & Hoyle, F. 1957, *Rev. Mod. Phys.*, 135, 694
 Colgate, S. A., Herant, M., & Benz, M. 1993, *Phys. Rep.*, 227, 157
 Domogatskii, G. V., & Nadyozhin, D. K. 1977, *MNRAS*, 178, 33P
 ———. 1978, *Soviet Astron.*, 22(3), 297
 Frick, U. 1977, *Proc. Lun. Sci. Conf.* 8, 273
 Fuller, G. M. 1993, *Phys. Rep.*, 227, 149
 Fuller, G. M., Mayle, R. W., Meyer, B. S., & Wilson, J. R. 1992, *ApJ*, 389, 517
 Fuller, G. M., & Meyer, B. S. 1995, *ApJ*, 453, 792
 Harper, C. L., Wiesman, H., & Nyquist, L. E. 1991, private communication
 Herant, M., & Woosley, S. E. 1994, *ApJ*, 425, 814
 Howard, W. M., Goriely, S., Rayet, M., & Arnould, M. 1993, *ApJ*, 417, 713
 Lambert, D. L. 1992, *A&A, Rev.*, 3, 201
 Lewis, R. S., Gros, J., & Anders, E. 1977, *J. Geophys. Res.*, 82, 779
 Mathews, G. J., Bazan, G., & Cowan, J. J. 1992, *ApJ*, 391, 719
 Meyer, B. S. 1994, *ARA&A*, 32, 153
 Meyer, B. S., Howard, W. M., Mathews, G. J., Woosley, S. E., & Hoffman, R. D. 1992, *ApJ*, 399, 656
 Harper, C. L., Wiesman, H., & Nyquist, L. E. 1991, private communication
 Qian, Y.-Z., Fuller, G. M., Mathews, G. J., Mayle, R. W., Wilson, J. R., & Woosley, S. E. 1993, *Phys. Rev. Lett.*, 71, 1965
 Papanastassiou, D. A., & Wasserburg, G. J. 1978, *Geophys. Res. Lett.*, 5, 595
 Prantzos, N., Hashimoto, M., Rayet, M., & Arnould, M. 1990, *A&A*, 238, 455
 Rayet, M., Arnould, M., Hashimoto, M., Prantzos, N., & Nomoto, K. 1994, *A&A*, 298, 517
 Rayet, M., Prantzos, N., & Arnould, M. 1990, *A&A*, 227, 271
 Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, *ApJS*, 98, 617
 Wilson, J. R., & Mayle, R. W. 1993, *Phys. Rep.*, 227, 97
 Witt, J., Janka, H.-Th., & Takahashi, K. 1993, *A&A*, 286, 841
 Woosley, S. E. 1986, in *16th Advanced Course of the Swiss Society of Astrophysics and Astronomy, Nucleosynthesis and Chemical Evolution*, ed. B. Hauck, A. Maeder, & G. Meynet (Geneva: Geneva Obs. Press), 1
 Woosley, S. E., Arnett, W. D., & Clayton, D. D. 1973, *ApJS*, 26, 231
 Woosley, S. E., & Hoffman, R. D. 1992, *ApJ*, 395, 202
 Woosley, S. E., & Howard, W. M. 1978, *ApJS*, 36, 285
 Woosley, S. E., & Weaver, T. A. 1995, *ApJS*, 101, 181
 Woosley, S. E., Wilson, J. R., Mathews, G. J., Hoffman, R. D., & Meyer, B. S. 1994, *ApJ*, 433, 229 (Paper I)