Nucleosynthesis in early supernova winds III:
No significant contribution from neutron-rich pockets

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ABSTRACT

Recent nucleosynthesis calculations of Type II supernovae using advanced neutrino transport
determine that the early neutrino winds are proton-rich. However, a fraction of the ejecta emitted
at the same time is composed of neutron-rich pockets. In this paper we calculate the nucleosyn-
thesis contribution from the neutron-rich pockets in the hot convective bubbles of a core-collapse
supernova and show that they do not contribute significantly to the total nucleosynthesis.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: supernovae

1. Introduction

During a delayed Type II supernova explo-
sion, the collapsing core emits neutrinos and anti-
neutrinos. These cool the shrinking proto-neutron
star and heat the infalling matter which expands
outwards, reverses the in-going accretion shock,
and hypothetically causes the supernova to ex-
plode. The heating is sufficiently rapid to estab-
lish and maintain a convective region between the
infalling matter and the proto-neutron star. The
matter — originally part of the progenitor’s sil-
icon burning shell — in this convective region com-
prise electrons, positrons, and completely photo-
disintegrated nuclei (protons with a mass fraction,
$Y_e$, neutrons with mass fraction $1 - Y_e$). The neu-
trinos irradiate the convectively overturning bub-
bles, so this matter is not simply “adiabatically
expanding” nor is it subject to a uniform history
of neutrino irradiation. This is important because the neutrino-luminosities drive the matter proton-rich
due to the lighter proton mass (Pruet et al. 2005;
Fröhlich et al. 2006a,b) given approximately equal
neutrino luminosities of the neutrinos and anti-
neutrinos (Liebendorfer et al. 2003). Thus dif-
ferent pockets in the bubbles will have different
compositions and different $Y_e$, some of which are
neutron-rich.

The contribution to the nucleosynthesis of the neutron-rich bubbles was investigated by
Pruet et al. (2005) and the contribution to the nucleosynthesis of the proton-rich winds was inves-
tigated by Pruet et al. (2006). Both calculations
were based on the Lagrangian ($\rho, T$)-histories of
tracer particles in the 2D model of Janka et al.
(2003). However, some bubbles also contained
neutron-rich pockets which whose nucleosynthe-
sis was not explored in those papers. This is the
subject of this paper.

We have extracted tracer particle trajectories
for these neutron-rich pockets and investigate
their nucleosynthesis contribution to the overall ejecta. In the following, \[2\] describes the supernova model and the \(Y_e\)-distribution of matter in more detail. The nucleosynthesis results are given in \[3\] followed by a conclusion in \[4\].

2. Supernova model

Our calculations of the nucleosynthesis contribution of neutron-rich pockets use the same supernova model as \[\text{Pruet et al. (2005, 2006)}\] but here we consider the \((\rho, T, Y_e)\)-trajectories with \(Y_e < 0.5\) thus complementing our earlier calculations.

The model is described in \[\text{Janka et al. (2003)}\] (see \[\text{Rampp & Janka (2002)}\] for specific code details and \[\text{Pruet et al. (2003)}\] for more details). In this model, the progenitor is based on a non-rotating \(15\, M_{\odot}\) model \((\text{S15A)}\) of \[\text{Woosley & Weaver (1995)}\] which is transferred to a 2D polar grid \((400\) non-equidistant radial zones and 32 poloidal zones\) using random velocity perturbations of the order of \(10^{-3}\) to seed the convection and an artificial 20–30% enhancement of the neutrino flux to ensure the supernova explosion.

The simulation commences at \(t_i = -175\) ms prior to the core bounce and uses embedded tracer particles to provide a history of \((\rho, T, Y_e)\) for a range of electron abundances until \(t_f = 470\) ms after the core bounce at which time the 2D simulation was stopped due to CPU-constraints.

At \(t_f\), the temperature is still several billion K so the nucleosynthesis is still in partial statistical equilibrium and not yet frozen out. To continue the nucleosynthesis calculation, the density and the temperature was mapped from the 2D model to a 1D grid and extrapolated by assuming a homologous expansion with a constant electron abundance and a constant entropy. These assumptions are acceptable for calculating the \((T, \rho)\)-response to the subsequent expansion since the nuclear decays are too slow to change \(Y_e\) over the expansion timescale. Also the rate of expansion is so large that the “\(r^{-2}\)”-dependent neutrino-luminosity quickly becomes irrelevant \[\text{Pruet et al. (2005)}\].

Fig. 1 shows 4 representative trajectories of \(\rho\) and \(T_9(=10^9\) K\) out of the 40 neutron-rich trajectories that were tracked during the simulation and subsequently extrapolated to lower temperatures. The transition to the extrapolation from the 2D simulation happens around \(T_9 = 4–5\). The entropy is approximately \(15k_B/\text{nucleon}\).

![Fig. 1.— This figure shows \(\rho\) vs \(T_9(=10^9\) K\) for some representative \(Y_e\) trajectories. The transition to the extrapolation from the 2D simulation happens around \(T_9 = 4–5\).](image)

3. Neutron-rich nucleosynthesis

In this supernova model, the amount of matter with \(Y_e < 0.47\) is \(\lesssim 10^{-4}\, M_{\odot}\). This prevents an unacceptable overproduction of \(N = 50\) nuclei \[\text{Hoffman et al. (1996)}\].

In the following we consider the nucleosynthesis in the \(0.47 < Y_e < 0.50\) range \((M = 5 	imes 10^{-3}\, M_{\odot})\) using the trajectories described above. Nucleosynthesis calculations commence at \(T_9 = 9.0\) and proceed until freeze-out below \(T_9 \sim 1.\) At \(T_9 = 9.0\), the matter comprises protons with a mass fraction, \(Y_e\), and neutrons with mass fraction \(1 - Y_e\).

Therefore the initial conditions is completely defined by the initial values of \(\rho, T,\) and \(Y_e\). Between \(T_9 \sim 9\) and \(T_9 \sim 6,\) \(^4\text{He}\) quickly recombines which depletes the neutrons and protons equally thus keeping \(Y_e\) constant. At \(T_9 \sim 4–6\), the helium recombines into the iron group elements along the \(N = 28\) isotope and then forms \(Z = 28\) isotopes as the temperature drops to \(T_9 \sim 2–3\). The electron-abundance or neutron to proton ratio determines the subsequent reaction flow.

For \(Y_e\) closer to 0.5, primarily \(^{56,57,58}\text{Ni}\) are formed. The flow from these nuclei leads to \(^{64}\text{Ge}\).
Unlike the $\nu p$-process [Fröhlich et al. 2006b], there is not a sufficient amount of protons left at this time for neutrinos to provide a sufficient number of neutrons to capture on $^{64}$Ge and thus move beyond this waiting point. As a result, heavier isotopes are not co-produced with the $^{62}$Ni and $^{64}$Zn. In particular, there is no production of the light $p$-nuclei for $Y_e \sim 0.5$.

For $Y_e$ closer to 0.47, primarily $^{58,59,60}$Ni are formed. This means that the $^{64}$Ge waiting point is easily circumvented which leads to overproduction of $^{74}$Se, $^{78}$Kr, and $^{92}$Mo which is co-produced with $^{64}$Zn. With increasing $Y_e$, the $^{92}$Mo production falls off [Hoffman et al. 1996].

3.1. Production factors

The total nucleosynthesis contribution is given by the sum of the mass weighted production factors $P(i)$, defined as

$$P(i) = \sum_j \frac{M_j X^i_j}{M_e X^i_{\odot}},$$

where $M_j$ is the mass in the $j$th bin (trajectory), $M_e = 13.5 M_{\odot}$ is the total mass ejected in the supernova explosion, $X^i_j$ is the mass fraction of the $i$th isotope in the $j$th bin and $X^i_{\odot}$ is the solar abundance of the $i$th isotope taken from Lodders (2003).

The production factors for neutron-rich pocket trajectories are shown in Fig. 2. The most produced isotopes in the neutron-rich parts of the bubble relative to solar abundances are $^{62}$Ni and $^{64}$Zn which originate in pockets with $Y_e$ closer to 0.5. These are co-produced along with $^{74}$Se and $^{78}$Kr which originate in the pockets with $Y_e$ closer to 0.47.

The figure also shows the contributions from the proton-rich bubble and the proton-rich winds trajectories (emitted later). We note that the contribution of the neutron-rich pocket outflow is insignificant compared to the total outflow. The neutron-rich pockets add $^{74}$Se, $^{78}$Kr, and $^{92}$Mo to the bubble-outflow, but this contribution is much smaller than the contribution from the proton-rich winds when neutrino interactions are included. The neutron-rich pockets also add $^{62}$Ni and $^{64}$Zn to the total outflow but only in comparable amounts to the wind and proton-pockets outflows. Here $^{64}$Zn production is increased by $\sim 30\%$ while $^{62}$Ni production is increased by a factor 1.5.

4. Conclusion

Our results show that the overproduction factors of the neutron-rich pockets folded with the mass-ejecta does not contribute significantly to the nucleosynthesis of the light $p$-nuclei of compared to the nucleosynthesis of the proton-rich pockets and winds.

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Fig. 2.— Production factors of the neutron-rich trajectories of the convective bubble ejecta. The most abundant isotope for a given element is shown with an asterisk. Diamonds indicate that the isotope was made primarily as a radioactive progenitor.