IMPACT OF SUPERnova DYNAMICS ON THE $\nu$p-PROCESS

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ABSTRACT

We study the impact of the late-time dynamical evolution of ejecta from core-collapse supernovae on $\nu$p-process nucleosynthesis. Our results are based on hydrodynamical simulations of neutrino-driven wind ejecta. Motivated by recent two-dimensional wind simulations, we vary the dynamical evolution during the $\nu$p-process and show that final abundances strongly depend on the temperature evolution. When the expansion is very fast, there is not enough time for antineutrino absorption on protons to produce enough neutrons to overcome the $\beta^+$-decay waiting points and no heavy elements beyond $A = 64$ are produced. The wind termination shock or reverse shock dramatically reduces the expansion speed of the ejecta. This extends the period during which matter remains at relatively high temperatures and is exposed to high neutrino fluxes, thus allowing for further ($p, \gamma$) and $(n, p)$ reactions to occur and to synthesize elements beyond iron. We find that the $\nu$p-process starts to efficiently produce heavy elements only when the temperature drops below $\sim 3$ GK. At higher temperatures, due to the low alpha separation energy of $^{60}\text{Zn}$ ($S_\alpha = 2.7$ MeV) the reaction $^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$ is faster than the reaction $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$. This results in the closed NiCu cycle that we identify and discuss here for the first time. We also investigate the late phase of the $\nu$p-process when the temperatures become too low to maintain proton captures. Depending on the late neutron density, the evolution to stability is dominated by $\beta^+$ decays or by $(n, \gamma)$ reactions. In the latter case, the matter flow can even reach the neutron-rich side of stability and the isotopic composition of a given element is then dominated by neutron-rich isotopes.

Key words: nuclear reactions, nucleosynthesis, abundances – supernovae: general

Online-only material: color figures

1. INTRODUCTION

Neutrino-driven winds from core-collapse supernova explosions contribute to the synthesis of elements beyond iron. After the explosion, the hot proto-neutron star cools emitting neutrinos. These neutrinos interact with the stellar matter and deposit energy in the outer layers of the proto-neutron star leading to a supersonic outflow known as neutrino-driven wind (Duncan et al. 1986). Although neutrino-driven winds were considered the site where heavy elements are produced by the $r$-process (Woosley et al. 1994), recent simulations (Arcones et al. 2007; Hüdepohl et al. 2010; Fischer et al. 2010; Roberts et al. 2010) cannot reproduce the extreme conditions required for producing heavy $r$-process elements (see, e.g., Hoffman et al. 1997; Otsuki et al. 2000; Thompson et al. 2001). The wind entropy is too low (less than $100k_B$/nuc) and, even more significant, the ejecta is proton rich (the electron fraction $Y_e$ remains above 0.5 for seconds; see Hüdepohl et al. 2010; Fischer et al. 2010). Even if the $r$-process does not take place in every neutrino-driven wind, lighter heavy elements (e.g., Sr, Y, Zr) can be synthesized in this environment as suggested by Qian & Wasserburg (2001). In proton-rich conditions Fröhlich et al. (2006) showed that elements beyond $^{64}\text{Ge}$ can be synthesized. Wanajo et al. (2011b) found Sr, Y, Zr in small pockets of neutron-rich material ejected after the explosion of low-mass progenitors. Recently, Arcones & Montes (2011) performed a systematic nucleosynthesis study that strongly supports the production of lighter heavy elements in proton- and neutron-rich neutrino-driven winds.

In proton-rich winds, charged particle reactions ($\alpha$ and proton captures) build nuclei up to $^{56}\text{Ni}$ and even up to $^{64}\text{Ge}$ once the temperature drops below 3 GK. Due to their long beta-decay lifetimes and low thresholds for proton capture, the nuclei $^{56}\text{Ni}$ and $^{64}\text{Ge}$ act as bottlenecks that inhibit the production of heavier elements. In the $\nu$p-process, their decay is sped up by $(n, p)$ reactions, with the neutrons produced by antineutrino absorption on the abundant free protons. This allows for the production of elements beyond iron and may explain the origin of $p$-nuclei (Fröhlich et al. 2006; Pruet et al. 2006; Wanajo 2006; Wanajo et al. 2011a). The synthesis of elements by the $\nu$p-process depends thus on neutrino spectra and luminosities but also on the dynamical evolution as matter expands through the slow, early supernova ejecta. This produces a wind termination shock or reverse shock where kinetic energy is transformed into internal energy (Arcones et al. 2007). The reverse shock has a big impact on the nucleosynthesis because temperature and density increase and the expansion is strongly decelerated. This hydrodynamical feature has been extensively studied for $r$-process nucleosynthesis (Qian & Woosley 1996; Sumiyoshi et al. 2000; Wanajo 2007; Panov & Janka 2009; Arcones & Martínez-Pinedo 2011). Recently, Wanajo et al. (2011a) have also explored the relevance of the reverse shock on the $\nu$p-process. Motivated by their work and by new two-dimensional hydrodynamical simulations of the neutrino-driven wind (Arcones & Janka 2011), we investigate here the wind termination shock to gain further insights into the dynamical evolution relevant for the $\nu$p-process.

Here we use a trajectory from hydrodynamical simulations (Section 2) combined with a complete nucleosynthesis network

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In two-dimensional simulations, we will use different values of tails. To account for the differences found in the late evolution (Section 4.3). Our conclusions are summarized in Section 5.

2. LONG-TIME DYNAMICAL EVOLUTION

Our study is based on one trajectory obtained from hydrodynamical simulations by Arcones et al. (2007). These simulations follow the supernova explosion and the subsequent neutrino-driven wind.

Figure 1 presents the evolution of density and temperature for the chosen trajectory. In the following, we always use the same initial evolution and modify it at temperatures below 3 GK. We assume the wind terminates at a temperature $T_{\text{wt}}$ and the evolution thereafter is varied using the prescription introduced by Arcones & Martínez-Pinedo (2011) and motivated by one- and two-dimensional hydrodynamical simulations (Arcones et al. 2007; Arcones & Janka 2011). The thermodynamical conditions at the termination of the wind depend on both the intrinsic properties of the wind, like its velocity and mass outflow rate, and on the pressure of the slow moving ejecta. The wind properties are determined by the neutrino energies and luminosities and by the neutron star mass and radius (see, e.g., Qian & Woosley 1996). These conditions depend mainly on the nuclear equation of state and are similar for different progenitors (Arcones et al. 2007; Fischer et al. 2010). The properties of the slow supernova ejecta are related to the progenitor and become very anisotropic during the evolution (Arcones & Janka 2011).

In our calculations, we use a simple model that reproduces the main features seen in hydrodynamical simulations. Once the wind reaches the early supernova ejecta we use the Rankine–Hugoniot conditions to determine the behavior of temperature, density, and velocity. When the wind moves supersonically these quantities jump at the reverse shock. The evolution after such discontinuity is determined assuming constant density and temperature during a time $\Delta t$. As the mass outflow is constant ($M = 4\pi r^2 \rho v$) the velocity drops as $v \propto r^{-2}$. At later times, the velocity stays constant and the density decreases as $\rho \propto r^{-2}$ (see Arcones & Martínez-Pinedo 2011 for more details). To account for the differences found in the late evolution in two-dimensional simulations, we will use different values of $\Delta t$ and explore the impact on the nucleosynthesis.

3. NUCLEOSYNTHESIS NETWORK

The evolution of the composition is calculated using a full reaction network (Frölich et al. 2006). All calculations start when the temperature drops below 10 GK and are followed until the temperature reaches 0.01 GK. We assume the initial composition to be determined from nuclear statistical equilibrium for a fixed electron fraction $Y_e = 0.52$. The reaction network includes 1869 nuclei from free nucleons to dysprosium ($Z = 66$). Neutral and charged particle reactions are taken from the REACLIB compilation, containing theoretical statistical-model rates by Rauscher & Thielemann (2000; NON-SMOKER) and experimental rates by Angulo et al. (1999). The theoretical weak interactions are taken from Langanke & Martínez-Pinedo (2001) and Fuller et al. (1982). Where available, experimental beta-decay rates are used from NuDat2 supplemented by theoretical beta-decay rates (Möller et al. 2003). Neutrino absorption on nucleons and nuclei is also taken into account. We assume a constant neutrino luminosity for neutrinos and antineutrinos ($L_{\nu_e} = L_{\bar{\nu}_e} = 5 \times 10^{51}$ erg), and Fermi–Dirac spectra with a temperature consistent with the hydrodynamical simulations.

In order to understand the nucleosynthesis evolution, it is useful to look at the time variations of the mean lifetimes for $\beta^+$-decays, $(n, \gamma)$, $(p, \gamma)$, $(n, p)$, $(\gamma, n)$, and $(\gamma, p)$ reactions. These mean lifetimes (or average timescales) are defined as

$$\tau_{\beta^+} \equiv \frac{1}{Y_h} \sum_{Z>2,A} \lambda_{\beta^+}(Z, A)Y(Z, A),$$

$$\tau_{\nu\gamma} \equiv \frac{\rho Y_e}{Y_h} N_A \sum_{Z>2,A} (\sigma \nu)(n, \gamma)(Z, A)Y(Z, A),$$

$$\tau_{\nu\nu} \equiv \frac{\rho Y_e}{Y_h} N_A \sum_{Z>2,A} (\sigma \nu)(p, \gamma)(Z, A)Y(Z, A),$$

$$\tau_{\nu n} \equiv \frac{1}{Y_h} \sum_{Z>2,A} \lambda_{\nu n}(Z, A)Y(Z, A),$$

and

$$\tau_{\nu p} \equiv \frac{1}{Y_h} \sum_{Z>2,A} \lambda_{\nu p}(Z, A)Y(Z, A),$$

where $\lambda_{\beta^+}(Z, A)$ denotes the decay rate of nucleus $(Z, A)$, $(\sigma \nu)(x, Z, A)$ denotes the reaction rate for process $x$ on nucleus $(Z, A)$, and $\lambda_{\nu n}(Z, A)$ and $\lambda_{\nu p}(Z, A)$ denote the photodisassociation reaction rates with emission of neutron and proton, respectively. In these equations, $N_A$ is the Avogadro number. The average is taken over the heavy nuclei ($Z > 2$):

$$Y_h = \sum_{Z>2,A} Y(Z, A).$$

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6. “National Nuclear Data Center, information extracted from the NuDat 2 database,” http://www.nndc.bnl.gov/nudat2/
Figure 2. Different temperature evolutions are shown in the upper panel. The solid black line corresponds to the original trajectory. The abundances for these evolutions are presented (with same colors and line styles) in the middle and bottom panels vs. mass and proton numbers, respectively.

Another useful quantity to understand the nucleosynthesis evolution is the reaction flow between two nuclei \(i\) and \(j\) defined as

\[
F_{ij} \equiv \dot{Y}(i \to j) - \dot{Y}(j \to i).
\]  

The quantity \(\dot{Y}(i \to j)\) denotes the change in abundance of nucleus \(i\) due to all reactions connecting nucleus \(i\) with nucleus \(j\). The largest reaction flows at each time step indicate the key reactions and thus the nucleosynthesis path.

Figure 3. Averaged time scales of the most relevant reactions indicated in the labels. The three panels correspond to the wind termination at 1, 2, and 3 GK from the top to the bottom.

(A color version of this figure is available in the online journal.)

4. RESULTS

4.1. Constant Temperature

We study here the impact of the wind termination, varying the temperature at which it occurs. We assume that the velocity is subsonic and hence there is no jump in temperature, density, and velocity. The different temperature evolutions and their nucleosynthesis are shown in Figure 2. The original trajectory (solid black line) is also included for completeness and comparison purposes. In the modified trajectories the wind termination
Figure 4. Arrows indicate the flow of different reactions normalized to the strongest one. The colors and sizes of the arrows are proportional to the flow. Abundances are also shown with colors and stable nuclei are indicated with a dot. The upper panel corresponds to the early evolution when the temperature is around 3.3 GK and in the bottom panel it has dropped down to \( \sim 2.2 \) GK. (A color version of this figure is available in the online journal.)

is at \( T_{\text{wt}} = 1, 1.5, 2, 2.5, \) and 3 GK. The resulting abundances change significantly with temperature \( T_{\text{wt}} \). There is an optimal \( T_{\text{wt}} \) around 2 GK for producing heavier elements (Wanajo et al. 2011a). Moreover, the nucleosynthesis evolution is very different for temperatures higher and lower than this optimal temperature. This can be seen in Figure 3 where the relevant averaged timescales (see Section 3) are shown for the trajectories with \( T_{\text{wt}} = 1, 2, \) and 3 GK. Initially, there is \( (p, \gamma) \) - \( (\gamma, p) \) equilibrium in all cases. The timescales for the \( (p, \gamma) \) and \( (\gamma, p) \) reactions are much shorter when the wind termination occurs at higher temperatures (see bottom panel of Figure 3).

For the wind termination at low temperatures, \( T_{\text{wt}} = 1, 1.5 \) GK, only elements up to germanium are produced in substantial amounts. In these evolutions matter expands very fast. Therefore, it only stays for a short time in the temperature rage of 1.5–3 GK where charged-particle reactions can effectively synthesize heavier nuclei. In addition, matter rapidly reaches large radii where the antineutrino flux is rather low. Similar conditions are found in explosions of low-mass progenitors where the expansion of the supernova ejecta is very fast (Hoffman et al. 2008; Wanajo et al. 2009, 2011a; Roberts et al. 2010). Note that the wind termination at a slightly higher temperature, 1.5 GK instead of 1 GK, allows somewhat higher mass number to be reached.

For the wind termination at high temperatures, one would expect that photodissociation stops the synthesis of heavier
elements. In this case, the abundance would continuously shift toward lower mass number as temperature increases. However, in our calculations we see an abrupt change in the abundances when the wind termination temperature exceeds a certain value. This points to a key reaction acting as a bottleneck at high temperatures. We have identified such a reaction using the reaction flows introduced in Section 3. Figure 4 shows these flows at two different temperatures for the evolution with $T_{wt} = 2$ GK. The upper panel corresponds to $T \approx 3.3$ GK, and the bottom one to $T \approx 2.2$ GK; both represent conditions before the constant temperature phase. Note that the reactions that determine the nucleosynthesis flow are different at high and low temperatures. At high temperatures, the reaction $^{59}$Cu($p$, $\alpha$)$^{56}$Ni dominates over $^{59}$Cu($p$, $\gamma$)$^{60}$Zn while at low temperatures the contrary is true (see Figure 5). When the $^{59}$Cu($p$, $\alpha$) reaction
dominates, the nucleosynthesis flow is confined into a closed NiCu cycle. A similar behavior has been found in the rp-process for the SnSbTe cycle (Schatz et al. 2001).

In the calculation with \( T_{\text{wt}} = 3 \text{ GK} \), when temperatures are still above \( \approx 3.2 \text{ GK} \) (see Figure 5) the heaviest nucleus produced is \(^{56}\text{Ni}\) due to the NiCu cycle. Once the temperature drops, the cycle opens and the path reaches \(^{64}\text{Ge}\). However, during the high constant temperature phase, the triple alpha reaction maintains a continuous production of seed nuclei from light nuclei with \( A \lesssim 7 \) (Wanajo et al. 2011a). This leads to a reduction of the proton abundance and thus of the neutrons produced by antineutrino absorption. Note that the ratio of neutrons produced per seed nucleus is a useful guide to the strength of the \( \nu p \)-process (Pruet et al. 2006). Both effects (the NiCu cycle and the reduced neutron-to-seed ratio) result in a complete shutdown of \( \nu p \)-process nucleosynthesis.

When the wind termination temperature is very high (\( \approx 3 \text{ GK} \)) or very low (\( \approx 1 \text{ GK} \)), elements beyond germanium are hardly synthesized. However, the final abundances are different for these two extreme cases. When the wind termination takes place at high temperatures (\( \gtrsim 3 \text{ GK} \)), matter accumulates in iron group nuclei due to the NiCu cycle and to the continuous production of seed nuclei. While for the wind termination at low temperatures matter moves fast to large distances where the antineutrino flux is not large enough to produce a \( \nu p \)-process. In addition, the low temperatures inhibit the production of seed nuclei. Therefore, the final proton abundance is significantly higher in the evolution with the wind termination at temperatures \( \lesssim 2 \text{ GK} \).

4.2. Reverse Shock

When matter moves supersonically there is a jump at the wind termination in temperature and density, also called reverse shock. Here, we analyze the impact of such a jump on the \( \nu p \)-process nucleosynthesis using the trajectories shown in Figure 6. The trajectory without jump corresponds to the evolution with \( T_{\text{wt}} = 2 \text{ GK} \) presented in the previous section. The trajectory with jump is chosen such that the temperature increases after the wind termination reaches \( \approx 2 \text{ GK} \) (same temperature as in the trajectory without jump). The constant temperature phase is the same for both evolutions (\( \Delta t = 0.5 \text{ s} \)). However, the final abundances are very different as shown in Figure 6.

In the evolution with jump, the expansion continues very fast between the moment the temperature reaches \( 2 \text{ GK} \) (marked with an A in the temperature curve, Figure 6) and the position of the wind termination shock (marked with B). During this phase, there is not enough time for antineutrino absorption on protons to produce the necessary amount of neutrons to reach heavier nuclei. Already in this phase, between A and B, matter starts to beta decay toward stability because temperatures become too low for proton-capture reactions. The temperature rise at the wind termination, from point B to C, increases the effectiveness of proton-capture reactions. This results in the matter flow moving again away from stability and toward heavier nuclei. Note that the temperature and matter distribution after the wind termination are very similar for both trajectories (points A and C).

The relevant timescales for the trajectory with jump are presented in Figure 7. This can be compared to the middle panel in Figure 3 that corresponds to the trajectory without jump. After the wind termination, proton captures are faster for the evolution without jump. More significant are the differences in \((n, \gamma)\) and \((n, p)\) timescales: both are much shorter in the evolution without jump (middle panel in Figure 3). These differences in the relevant timescales have a big impact on the abundances.

The reactions involving neutrons, i.e., \((n, \gamma)\) and \((n, p)\), depend on the neutron density which is shown in Figure 8 for the two evolutions. In the trajectory with jump (solid line), the neutron density remains lower than in the trajectory without jump at all times, even at the wind termination (feature \( t \approx 0.02 \text{ s} \)). In the \( \nu p \)-process there is an equilibrium between neutron capture and neutron production by antineutrino absorption. The relevant timescales for the trajectory with jump are \( \lesssim 0.5 \text{ s} \) (solid black), \( 0.5 \text{ s} \) (dashed green), and \( 1.0 \text{ s} \) (dotted red). Abundances for these evolutions are shown vs. mass number \( A \) (middle panel) and vs. atomic number \( Z \) (bottom panel).

(A color version of this figure is available in the online journal.)

Figure 9. Different temperature evolutions after the wind termination shock which is at \( 2.0 \text{ GK} \) are shown in the top panel. Values for \( \Delta t \) are 0.0 s (solid black), 0.5 s (dashed green), and 1.0 s (dotted red). Abundances for these evolutions are shown vs. mass number \( A \) (middle panel) and vs. atomic number \( Z \) (bottom panel).
Figure 10. Left column is for the case of $\Delta t = 1.0$ s, the right column is for $\Delta t = 0.0$ s. The top row shows average timescales for different reaction types as a function of time. Abundance distributions at selected times are shown as a function of mass number (middle row) and as a function of atomic number (bottom row) for both cases of $\Delta t$. For the case $\Delta t = 1.0$ s, the abundances are shown at $T = 3.0$ (A), 2.0 (B,C), 1.6 (D), 1.0 GK (E), and also the final abundances (F). The abundances at the beginning (B) and at the end (C) of the constant temperature phase differ quite significantly. For the case $\Delta t = 0.0$ s, the abundances are shown at $T = 3.0$ (A), 2.0 (B), 1.9 ($C'$), 1.5 (D), 1.0 GK (E) and also the final abundances (F). Note that while the abundances at C for $\Delta t = 1.0$ s and at $C'$ for $\Delta t = 0.0$ s are similar, the temperature is slightly lower for $C'$ because there is no constant temperature phase in this case.

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absorption on protons. This implies that

$$dY_n/dt = \lambda_{\bar{\nu}_e} Y_p - \sum_{Z,A} N_n Y(Z, A) \langle \sigma v \rangle_{(Z,A)} = 0. \quad (9)$$

Here $\lambda_{\bar{\nu}_e}$ is the electron antineutrino absorption rate and $\langle \sigma v \rangle_{(Z,A)}$ is the sum of reaction rates for $(n, \gamma)$ and $(n, p)$ reactions for nucleus $(Z, A)$. Therefore, the neutron density in equilibrium is given by

$$N_n = \frac{\lambda_{\bar{\nu}_e} Y_p}{\sum_{Z,A} Y(Z, A) \langle \sigma v \rangle_{(Z,A)}}. \quad (10)$$

The nucleosynthesis path is very similar for both trajectories considered here (evolution with and without jump). Therefore, only small variations are expected in the denominator. Consequently, the difference in the neutron densities (see Figure 8) is due to the neutron production by antineutrinos. The deceleration of the expansion at the wind termination occurs at
smaller radii for the trajectory without jump (see bottom panel of Figure 8). The production of neutrons is hence less efficient in the case with jump because matter reaches larger radii where the neutrino flux is reduced due to its $r^{-2}$ dependency. The difference in the abundance pattern for nuclei above mass number $A \approx 80$ (see Figure 6) is due to this difference in the efficiency of neutron production.

### 4.3. Late-time Evolution

We explore the impact of the dynamical evolution after the wind termination. In this section, we assume that the wind termination occurs at $T_{\text{wt}} = 2.0$ GK and we vary the parameter $\Delta t$. The quantity $\Delta t$ characterizes the timescale for the transition from an expansion with constant temperature and density (during which $v \propto r^{-2}$) to a constant velocity expansion with $\rho \propto r^{-2}$. We choose the values $\Delta t = 0.0$, $0.5$, and $1.0$ s, motivated by the anisotropic evolution of the ejecta in two-dimensional hydrodynamical simulations (Arcones & Janka 2011). There is a smooth transition between the two extreme cases of $\Delta t = 1.0$ s and $\Delta t = 0.0$ s, which can be seen in the intermediate case of $\Delta t = 0.5$ s. The latter ($\Delta t = 0.5$ s) was used in previous sections.

The different temperature evolutions (top panel) and the resulting nucleosynthesis (middle and bottom panels) are shown in Figure 9. While all three cases produce similar abundance distributions, the details depend critically on the value of $\Delta t$.

For a relatively long phase of constant temperature ($\Delta t = 1.0$ s; left column of Figure 10), the $(p, \gamma) - (\gamma, p)$ equilibrium lasts for quite a long time and allows for many $(n, p)$ and $(p, \gamma)$ reactions to occur. This drives the matter to higher mass number (up to $A \approx 110$), where matter accumulates in Sn ($Z = 50$ closed shell). Due to the extended period of $(p, \gamma) - (\gamma, p)$ equilibrium, significant abundances of nuclei with $64 \lesssim A \lesssim 110$ are synthesized (see line C in Figure 10, left column). Also, during this phase there is a continuous production of seed nuclei at the expense of alpha particles (see Figure 11). Once the temperature drops below $\approx 1.5$ GK (line D), the production of seed stops. In addition, proton-capture reactions become hindered by the Coulomb barrier and $\beta^+$-decays become faster than $(n, p)$ reactions (see the upper left panel in Figure 9). The nucleosynthesis ceases to efficiently proceed to higher masses. During this phase, matter starts to decay toward stability. A small number of late-time neutron-capture reactions smooths the abundance distribution in the mass range $80 \lesssim A \lesssim 110$ (line E). Once the temperature drops below $1.0$ GK (lines E and F), the abundances as a function of mass number do not change anymore, as at this time $\beta^+$-decays dominate. The closed shell at $Z = 50$ acts as a barrier for the nucleosynthesis. This can be seen in the enhanced abundances at $A = 110$ (originating from $^{110}$Sn) in the final abundance distribution.

For the case $\Delta t = 0.0$ s (right column in Figure 10), the situation is very different. The initial phase of $(p, \gamma) - (\gamma, p)$ equilibrium is much shorter than in the case of $\Delta t = 1.0$ s. In this case, nuclei up to mass number $A \approx 110$ are synthesized (line C) when the temperature has already dropped below $2$ GK. Due to the faster temperature decline, the production of seed nuclei is less efficient than in the case of $\Delta t = 1.0$ s (see Figure 11). This leads to lower abundances of nuclei such as $^{12}$C, $^{16}$O, $^{20}$Ne, $^{28}$Si, and $^{40}$Ca for $\Delta t = 0$ s (see Figure 9). The lower abundance of seed nuclei leads to a higher neutron density (see Equation (10)) as in both cases the neutron production rate ($\lambda_\gamma Y_p$) is similar. Therefore, in the evolution with $\Delta t = 0$ s, there are more neutrons available per seed nucleus (Figure 11). The neutron-capture reactions, i.e., $(n, \gamma)$ and $(n, p)$, become faster than $(p, \gamma)$ reactions at temperatures of $T < 1.5$ GK. These neutron captures move matter to the neutron-rich side of stability. This, together with the earlier less efficient production of seeds, results in a depletion of the abundances in the region of $64 \lesssim A \lesssim 110$ (compare black solid and red dashed lines in Figure 9). Toward the end of the evolution, $(n, \gamma)$ reactions are the fastest ones, even faster than $\beta^+$-decays. During this phase, the atomic number $Z$ remains unchanged while the mass number increases (lines D, E, and F in Figure 10). The signature of matter moving to stability via $(n, \gamma)$ reactions can be seen in
We have investigated in detail the impact of dynamical evolution on the $\nu p$-process nucleosynthesis using individual characteristic trajectories. In order to predict the complete $\nu p$-process yields from a supernova simulation, one will need to integrate over all proton-rich ejecta.

In summary, the supernova dynamics as well as individual reactions such as the proton-capture reactions on $^{59}\text{Cu}$ determine how high in proton number the $\nu p$-process can proceed. The dynamical evolution just after the wind termination can greatly affect the nucleosynthesis evolution toward stability as it determines the late neutron density. Our results provide a link between nucleosynthesis in proton-rich winds and the dynamical evolution of the ejected matter and motivate further theoretical and experimental effort on understanding key reactions.

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