Explosive nucleosynthesis in core-collapse supernovae

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Abstract. The specific mechanism and astrophysical site for the production of half of the elements heavier than iron via rapid neutron capture (r-process) remains to be found. In order to reproduce the abundances of the solar system and of the old halo stars, at least two components are required: the heavy r-process nuclei ($A > 130$) and the weak r-process which correspond to the lighter heavy nuclei ($A < 130$). In this work, we present nucleosynthesis studies based on trajectories of hydrodynamical simulations for core-collapse supernovae and their subsequent neutrino-driven winds. We show that the weak r-process elements can be produced in neutrino-driven winds and we relate their abundances to the neutrino emission from the nascent neutron star. Based on the latest hydrodynamical simulations, heavy r-process elements cannot be synthesized in the neutrino-driven winds. However, by artificially increasing the wind entropy, elements up to $A = 195$ can be made. In this way one can mimic the general behavior of an ejecta where the r-process occurs. We use this to study the impact of the nuclear physics input (nuclear masses, neutron capture cross sections, and beta-delayed neutron emission) and of the long-time dynamical evolution on the final abundances.

1. Introduction
Half of the elements heavier than iron are produced by rapid neutron captures in a yet unknown astrophysical scenario. After the initial success of [1] in reproducing observed solar r-process abundances, core-collapse supernovae and the subsequent neutrino-driven winds became one of the most promising candidates for the production of r-process elements because their extreme explosive conditions are very close to the ones needed for the r-process (see e.g., [2–4]). Moreover, galactic chemical evolution models favor core-collapse supernovae, since they occur early and frequently enough to account for the abundances observed in old halo stars and in the solar system [5, 6]. Although the necessary conditions to produce heavy elements ($A > 130$) are identified [7] (high entropies, low electron fractions, and short expansion timescales), these are not found in the most recent long-time supernova simulations [8–12].

When a supernova explodes, matter surrounding the proto-neutron star is heated by neutrinos and expands very fast reaching sometimes even supersonic velocity [3, 13]. This neutrino-driven wind moves through the early supernova ejecta and eventually collides with it. The interaction of the wind with the slow-moving ejecta results in a wind termination shock or reverse shock where kinetic energy is transformed into internal energy. Therefore, the expansion velocity drops and the temperature (and thus the entropy) increases after the reverse shock. The matter near the proto-neutron star consists mainly of neutrons and protons due to the high temperatures in this region. When a mass element expands, its temperature decreases and neutrons and protons recombine to form alpha particles. The density also decreases but the triple-alpha reaction combined with different alpha capture reactions are still operating, resulting in heavy
seed nuclei [14, 15]. The evolution once the alpha particles start forming heavier nuclei depends on the neutron-to-seed ratio.

The results presented here are based on our hydrodynamic simulations [9] where the neutron-to-seed ratio is too low for the r-process to produce elements up to the third peak ($A = 195$). In Sect. 3 the nucleosynthesis obtained from such simulations is discussed. In Sect. 4 we have used the neutrino-driven wind simulations with the entropy artificially increased to study the impact of the long-time evolution and nuclear physics input on the dynamical r-process. More details can be found in [16, 18].

2. Supernova simulations and nucleosynthesis networks

The investigation of the nucleosynthesis in neutrino-driven winds is done in two steps. First, the evolution of the supernova ejecta is followed during several seconds with hydrodynamical simulations. Second, the composition is calculated by means of extended nuclear reaction networks which include nuclei from stability to both drip lines, reaching thus regions where no experimental data are available and theoretical predictions are quite uncertain.

The modeling of the supernova ejecta during several seconds after explosion is currently difficult since the supernova explosion mechanism is not yet well understood [19] and it is computationally expensive to perform long-time, multidimensional, systematic studies for different progenitor stars, as would be desirable in nucleosynthesis studies. Possible ways to overcome this limitation include using parametric steady-state wind models (e.g., [3]) and forcing an explosion by artificially changing neutrino properties [9, 11]. The evolution of the outflow is rather independent of the details of the explosion mechanism, but depends more on the evolution of the neutron star and on the neutrino emission. Therefore, such approximations are a good basis for nucleosynthesis studies. Although steady-state wind models cannot consistently describe hydrodynamical effects (e.g., reverse shock or multidimensional instabilities), both approaches agree in the wind phase [20].

For our nucleosynthesis studies we use trajectories, i.e. density and temperature evolutions, from Ref. [9]. The composition is calculated initially by assuming nuclear statistical equilibrium at $T = 10$ GK, almost only nucleons and few alpha particles are present. The evolution of the composition is then followed using a full reaction network [21], which includes nuclei from H to Hf with both neutron- and proton-rich isotopes. Reactions with neutral and charged particles were taken from the calculations of the statistical code NON-SMOKER [22] and experimental rates were included (NACRE, [23]) when available. The theoretical weak interaction rates are the same as in Ref. [21]. When the conditions of the supernova outflow are favourable for the r-process, i.e. high neutron-to-seed ratio, we use a r-process network after charged-particle reactions freeze out. This network, which includes photodissociation, neutron capture, beta decay, and fission, is fully implicit. Therefore, it can be used to study the late evolution when matter decays to stability and the neutron density becomes very low.

3. The origin of LEPP nuclei in supernovae

Most of the recent progress in understanding the origin of elements commonly associated with the r-process is due to observations of ultra metal-poor (UMP) stars (see [25] for recent review). The elemental abundances observed in the atmosphere of these very old stars come from a few events. These stars generally present a robust pattern for “heavy” elements $56 < Z < 83$, in agreement with the expected contribution of the r-process to the solar system, but show some scatter for “light” elements $Z < 47$ [25]. This suggests that at least two types of events contribute to the r-process abundances [26–31]. Qian and Wasserburg [17] argued that supernovae from low-mass progenitors with $8M_{\odot} < M < 12M_{\odot}$ lead to all “heavy” and some “light” elements, and that explosions of more massive progenitors, $12M_{\odot} < M < 25M_{\odot}$, contribute to the remaining light $A < 130$ elements.
The process leading to elements with $A < 130$ has been called in the literature the weak r-process [32], charged-particle reaction (CPR) process [14,17,33], and Light Elemental Primary Process (LEPP) [28,31]. We refer to this as LEPP because such name does not make any reference to the specific nuclear reactions or astrophysical environment. The term LEPP was first introduced in Ref. [28] which used a galactic chemical evolution model to search for possible astrophysical environments producing the elements such as Sr, Y, and Zr. Taking into account the standard s-process and r-process contributions, they found that non-negligible abundances of several isotopes ($^{86}$Sr, $^{93}$Nb, $^{96}$Mo, $^{100}$Ru, $^{104}$Pd, $^{110}$Cd) were still unexplained. They argued that a new “light element primary process” may have produced them and they discussed where and how this LEPP could occur in order to explain their solar system abundances. Montes et al. in Ref. [31] suggested that the LEPP observed in UMP stars show a hint of robustness of the process and could have contributed to the solar system abundances.

Figure 1. Integrated abundances compared to the LEPP pattern [34] rescaled to $Z=39$. The abundances of different progenitors with a similar evolution of the proto-neutron star are shown in the left panel, while the right panel gives the abundances of the same progenitor with different proto-neutron star evolution.

Figure 1 shows the integrated nucleosynthesis for different stellar progenitors with masses of 10, 15, and 25 $M_\odot$, as well as for a model with low wind entropy and slow expansion (due to the less compact neutron star) which is labeled as 15M(s). Our results confirm that no heavy r-process elements can be synthesized in such explosions, however the LEPP can be realized based on the simulations and for a range of realistic conditions. By comparing models 15M and 15M(s), we explore the known dependence of the nucleosynthesis on the entropy and expansion timescale [35]. The third wind parameter is the electron fraction which is given by the neutrino properties determined by neutrino interactions and transport. Therefore, the exact calculation of the electron fraction remains a very challenging open problem [12]. Figure 2 shows the electron neutrino and antineutrino energies for different supernova models. The antineutrino energy has decrease as the neutrino reactions and transport have been improved leading to proton-rich winds in the most recent simulations as shown by the $Y_e$ contours. This motivated our exploration of the impact of the electron fraction on the production of the LEPP elements. Figure 3 illustrates that the LEPP elements can be obtained for different proton- and neutron-rich conditions.

Left panel in Fig. 4 shows that the LEPP pattern (dots obtained from observation as in Ref. [34]) is reproduced in proton-rich winds. Moreover, we found that this abundance pattern is quite robust under small variations of the evolution of $Y_e$ and of the wind parameters (e.g. changes of 20% in the entropy). However, elements heavier than iron-group nuclei can be produced only when the neutrino fluxes are high enough to allow a successful $\nu$p-process [8,21,37]. The right panel of Fig. 4 shows the production factor for various isotopes (see [16].
Figure 2. Contours represent the electron fraction based on the approximation of [35] (black contours: $L_{\bar{\nu}_e}/L_{\nu_e} = 1$, grey contours: $L_{\bar{\nu}_e}/L_{\nu_e} = 1.1$). The points indicate approximately the electron neutrino and antineutrino energies for different supernova models: the green square from [36], the black circle from model M15-l1-r6 of [9], the red triangle is from a $10 M_\odot$ progenitor of [11], and the blue diamond from [12], all at 10 s after bounce.

Figure 3. Dependence of the abundances of representative elements (Sr, Y, Zr, Cd, Ba and Eu) on the electron fraction. These abundances result from a mass element ejected at 5s after the explosion in model 15M.

for detailed discussion). Although there is no overproduction (i.e. production factors are below dotted line in Fig. 4) and the elemental abundances nicely reproduce the observed LEPP pattern in UMP stars, almost only neutron-deficient isotopes (p-nuclei) are produced. Therefore, proton-rich conditions can explain the LEPP elements observed in UMP stars but not the missing isotopic abundances in the solar system [28]. An exciting possibility of proton-rich winds is the synthesis of the light p-nuclei, since mainly neutron-deficient isotopes are present in the wind ejecta [21, 38, 39].

When the electron fraction is assumed to evolve towards neutron-rich conditions, the LEPP pattern can be also reproduced but it is very sensible under variations of $Y_e$ or of the wind parameters. This scenario may contribute to the LEPP elements found in the solar system abundances because neutron-rich isotopes are produced. However, we find an overproduction around $A \sim 90$ that was already pointed out in previous nucleosynthesis studies based on supernova simulations (see e.g., [40]). This overproduction problem and the fact that most recent supernova simulations [11, 12] favor proton-rich winds could suggest that neutron-rich winds are rare events.

Observation of isotopic abundances in UMP stars are very promising to constraint the neutron richness of the neutrino-driven wind and thus the evolution of the electron fraction and the neutrino properties in supernovae.

4. Impact of the nuclear physics input on the dynamical r-process

We investigate the sensitivity of r-process abundances to the combined effects of the long-time dynamical evolution and nuclear physics input and provide a link between the behaviour of
nuclear masses far from stability and features in the final abundances. The trajectory for this study is also from the neutrino-driven wind simulations of Ref. [9] where no heavy r-process elements can be synthesized [16]. Therefore, we need to artificially increase the neutron-to-seed ratio in order to produce the third r-process peak. This allows us to study the nucleosynthesis of heavy elements in a typical high-entropy neutrino-driven wind in a more consistent way than with fully parametric expansions [33, 41] or with steady-state wind models (see e.g., [3, 4]), which cannot consistently explore the interaction of the wind with the slow supernova ejecta that results in a reverse shock.

The evolution of temperature and density during the alpha-process determines the neutron-to-seed ratio and thus the possibility of forming heavy elements. However, the dynamical evolution after the freeze-out of charged-particle reactions is affecting the final abundances. In the left panel of Fig. 5 we present the three trajectories used for our calculations. The trajectory labeled as “unmodified” correspond to the hydrodynamical simulations with the entropy increased and the reverse shock as in the simulations. We change the position of the reverse shock to investigate the effect of the variation of the dynamical evolution during the r-process, keeping the same initial neutron-to-seed. In the trajectory labeled as $T_{\text{rs}} = 1 \text{ GK}$ the reverse shock is at high temperature, while in the one labeled as “no rs” there is no reverse shock. The abundances resulting from these three evolution are shown in the right panel of Fig. 5, compared to the solar abundances shown by dots. Notice that the long time evolution has a big impact on the position of the peaks and on the troughs.

When the reverse shock is at high temperatures the evolution proceeds under a $(n, \gamma)$–$(\gamma, n)$ equilibrium which lasts until neutrons are exhausted. This equilibrium evolution is similar to the classical r-process [42] and it is also known as hot r-process [43]. If the evolution proceeds at low temperatures ($T < 0.5 \text{GK}$), there is a competition between neutron capture and beta decay. This non-equilibrium evolution correspond to the cold r-process introduced in Ref. [43]. Figure 6 shows the evolution of timescales for the three relevant processes: neutron capture, photodissociation, and beta decay. The main difference between hot (left panel) and cold (right panel) r-process is that in the latter photodissociation is negligible. Therefore, the r-process path can move farther away from stability reaching nuclei with shorter half-lives and leading to a faster evolution and an earlier freeze out. Moreover, neutron separation energies have
4.1. Sensitivity to the mass model

The sensitivity of the mass model have been investigated by consistently changing neutron separation energies and neutron capture rates for the mass models: FRDM [44], ETFSI-Q [45], HFB-17 [46], and Duflo-Zuker [47]. The presence and position of peaks and trough in the abundances depends on features of the two neutron separation energy ($S_{2n}$) shown in Fig. 7. When $S_{2n}$ abruptly drops for increasing $N$, matter accumulates leading to the formation of peaks. While in regions where $S_{2n}$ is flat or presents a saddle point behaviour, several neutron captures occur almost instantaneously leaving a trough in the abundances. This feature of the two neutron separation energy is present in all mass models before $N = 126$ as nuclei change from deformed to spherical. In the equilibrium evolution, where photodissociation is very important, this leads to the formation of a big trough in the abundances at the moment neutrons are almost
exhausted, i.e. when $Y_n/Y_{\text{seed}} = 1$. Afterwards, as matter decays to stability, neutron capture can fill up this trough or make it bigger as it occurs in the abundances based on ETFSI-Q. Our results shown in Fig. 8 present also some behaviours that are characteristic of every mass model. In ETFSI-Q the quench before $N = 82$ leads to a slow down of the evolution and to a delayed freeze-out. Moreover, the fluctuation of $S_{2n}$ before $N = 126$ in this mass model makes the trough around $A \approx 185$ bigger due to neutron captures when matter moves back to stability. Results based on FRDM are clearly affected by the anomalous behaviour of $S_{2n}$ before $N = 90$, which produces the accumulation of matter and thus the formation of peaks around $A \approx 135$ even in the non-equilibrium evolution (Fig. 8).

4.2. Way back to stability

The abundances at freeze-out present a lot of fluctuations while the final ones, after decay to stability, are smooth like the solar system abundances. In the classical r-process calculation (waiting point approximation) this is explained by beta-delayed neutron emission (see e.g., [42]). However, in dynamical r-process calculations also neutron captures contribute to redistribution of matter. The neutron captures become very important after freeze-out, when only few neutrons are available and nuclei compete to capture them. We find that the rare earth peak is due to neutron captures when matter moves back to stability, as suggested in Ref. [48]. This implies that the freeze-out cannot be very fast because neutrons are still needed to form this feature which is present in the solar r-process abundances.
Figure 8. Abundances for the mass models indicated in the caption and for the equilibrium (left) and non-equilibrium (right) evolutions, compared to solar (dots).

Finally, we found that the main contribution of the beta-delayed neutron emission is the supply of neutrons. In our equilibrium evolution there are almost no difference in the abundance calculated with and without beta-delayed neutron emission. Since temperature are high, photodissociation prevents the path to reach the regions far from stability where the probability of emitting neutrons after beta decay is higher. In contrast, in the non-equilibrium evolution the neutron density is significantly smaller when no beta-delayed neutron emission is assumed. The evolution of the neutron-to-seed ratio is shown in the left panel of Fig. 9 for the calculations with and without beta-delayed neutron emission. The significant smaller neutron-to-seed ratio, when non beta-delayed neutron emission is considered (green line), leads to less shift of the third peak after freeze-out but also inhibits the formation of the rare earth peak (right panel in Fig. 9).

Figure 9. Neutron-to-seed ratio and abundances for the non-equilibrium evolution. The black lines are for the reference case which is calculated with the standard nuclear input where neutrons are emitted with given probability ($P_n$) after beta decay. The green lines are for the case where $P_n = 0$, therefore A is conserved during beta-decay.

5. Conclusions
Recent long-time supernova simulations do not produce r-process elements because the wind entropy is too low and the electron fraction high, even staying proton rich during several seconds [12]. However, the LEPP elements can be produced as we have shown by comparing for the
fist time the LEPP pattern in UMP stars and integrated nucleosynthesis calculations based on hydrodynamical wind simulations [16]. In proton-rich winds the LEPP pattern is very robust and reproduces observed abundances from UMP stars. Neutron-rich winds are necessary to explain the LEPP isotopes found in the solar system abundances, but they do not lead to a robust pattern and overproduced nuclei around $A=90$. This suggests that only a small fraction of the supernovae or of the mass ejected by them can be neutron rich. Future observations of isotopic abundances in ultra-metal poor stars could constrain the evolution of the electron fraction in the neutrino-driven winds and thus the neutrino properties (energy and luminosity).

The impact of the long-time dynamical evolution and of nuclear masses on the $r$-process abundances can be still studied based on current simulations by artificially increasing the entropy. This mimics the hydrodynamical conditions of a neutrino-driven wind where the $r$-process does occur. We have found that the relevance of the different nuclear physics inputs depends on the long-time dynamical evolution [18]. If an $(n,\gamma)-(\gamma,n)$ equilibrium is reached, nuclear masses have a big influence on the final abundances. While for a cold $r$-process there is a competition between neutron capture and beta decay and these two processes become relevant. This rises the importance of future experiments to measure nuclear masses that will provide a direct input for network calculations and constraints for the theoretical mass models.

In both types of evolutions as matter decays to stability, our results show that neutron captures are key to understand the final abundances. Moreover, we found that beta-delayed neutron emission is important not only for the redistribution of matter, but also for the supply of neutrons. The late neutron captures are necessary to explain features in the solar system abundances, such as the rare earth peak. More experimental effort is necessary to test the validity of the current theoretical cross sections and more sensitivity studies of the impact of the neutron capture rates on the final abundances will give rise to new insights.

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