“Heavy” elements produced in neutrino-driven winds

Almudena Arcones
Department of Physics, University of Basel, Klingelbergstraße 82, 4056, Basel, Switzerland
E-mail: a.arcones@unibas.ch

Abstract. We present nucleosynthesis studies based on trajectories of hydrodynamical simulations for core-collapse supernovae and their subsequent neutrino-driven winds. Based on recent hydrodynamical simulations, heavy r-process elements (Z > 56) cannot be synthesized in the neutrino-driven winds because the entropy is too low and ejected matter is proton-rich. We have shown that the lighter heavy elements (e.g., Sr, Y, Zr) are produced in neutron- and proton-rich winds and could explain the abundance observed in some very old halo stars.

1. Introduction

The astrophysical site where half of the heavy elements are produced by the r-process (rapid neutron capture compared to beta decay) remains unknown. The necessary neutron-rich conditions, i.e., 100 free neutrons per seed nuclei, point to violent events like core-collapse supernova and neutron star mergers (see [1] for a review). Core-collapse supernovae and the subsequent neutrino-driven winds have attracted vast attention as candidates for the production of r-process elements because they occur early and frequently enough to account for the abundances observed in old halo stars and in the solar system [2]. The necessary conditions to produce heavy elements (A > 130) are identified [3] (high entropies, low electron fractions, and short expansion timescales), however these are not found in the most recent long-time supernova simulations [4–7].

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 [8] for recent review). The elemental abundances observed in the atmosphere of these very old stars come from a few nucleosynthesis 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 [8]. This suggests that at least two types of events contribute to the r-process abundances (see e.g., [9]). The process leading to elements with A < 130 has been called in the literature the weak r-process [10], charged-particle reaction (CPR) process [11–13], and Light Elemental Primary Process (LEPP) [14, 15]. 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. [14] which used a galactic chemical evolution model to search for possible astrophysical environments producing the elements such as Sr, Y, and Zr. Montes et al. in Ref. [15] 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.
2. Neutrino-driven wind and nucleosynthesis

When a supernova explodes, matter surrounding the proto-neutron star is heated by neutrinos and expands very fast reaching sometimes even supersonic velocity [16]. 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 [4]. Therefore, the expansion velocity drops and the temperature (and thus the entropy) increases after the reverse shock. Recently, we have extended our spherically symmetric study [4] to two dimensional simulations [7]. In these multidimensional explosions we have showed that the neutrino-driven wind remains spherically symmetric due to the isotropic neutrino emission from a neutron star that stays spherical in the absence of rotation. Although the wind develops identically in all directions, our results demonstrate that the anisotropic distribution of early supernova ejecta has a great impact on the position of the wind termination shock and the long-time evolution (see Fig. 1). This suggests that hydrodynamic instabilities after core bounce and the resulting asymmetries have important effects on the conditions relevant to the synthesis of heavy nuclei.

![Image of neutrino-driven wind and entropy](image)

**Figure 1.** The neutrino-driven wind is the region of constant entropy in this two-dimensional simulation [7]. Notice the anisotropic distribution of the slow, early supernova ejecta.

In most recent hydrodynamic simulations with detailed neutrino transport, the neutrino-driven wind has relative low entropy and is proton-rich [5, 6]. The electron fraction is extremely sensitive to details of the neutrino interactions and transport around the neutrinosphere where neutrinos decouple from matter (see Fig. 2). The evolution of this region depends on the nuclear equation of state and on neutrino interactions, which are both key inputs for supernova simulations, but still very uncertain. Therefore, the electron fraction is only known approximately and its variation can lead to three different nucleosynthesis regimes in the neutrino-driven wind [17] assuming the same expansion: 1) for low electron fraction \((Y_e < 0.4)\), the \(r\)-process can produce heavy nuclei up to uranium (also entropy \(S > 100 \text{kB/nuc}\) is required); 2) in slightly neutron-rich winds \((Y_e \approx 0.49\) and \(S \approx 50 - 100 \text{kB/nuc}\)) the weak \(r\)-process produces elements up to \(A = 90\) corresponding to neutron magic number \(N = 50\); 3) proton-rich winds are the site for the \(\nu p\)-process [18] that can explain the origin of light \(p\)-nuclei.

At present it is unclear if neutrino-driven winds are extreme enough for a successful \(r\)-process, but it is certain that core-collapse supernovae are fascinating hosts where various nucleosynthesis processes produce neutron-rich and neutron-deficient nuclei. As suggested in Ref. [13], neutrino-driven winds can also be the site where lighter heavy elements (e.g., Sr, Y, Zr) are produced by the weak \(r\)-process or by the \(\nu p\)-process. These can account for the suggested
LEPP contribution [14], responsible for the abundances of these elements at low metallicities in very old stars where the s-process is not active yet.

3. The origin of LEPP nuclei in supernovae

We have shown that the lighter heavy elements [17] can be synthesized in neutrino-driven winds as suggested in Ref. [13]. We have performed the first comparison between the LEPP abundances observed in some UMP stars and nucleosynthesis calculations based on long-time hydrodynamic simulations of core-collapse supernovae. Our results show that neutrino-driven winds can explain the observed LEPP pattern in proton- and neutron-rich conditions.

The exact calculation of the electron fraction remains a very challenging open problem [6]. As shown in Fig. 2, the antineutrino energy has decreased 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 top panel in Fig. 3 shows that the LEPP pattern (dots obtained from observation as in Ref. [21]) is reproduced in proton-rich winds. Moreover, we found that this abundance pattern is quite robust under variations of the evolution of $Y_e$. 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 [18, 22, 23]. The left bottom panel in Fig. 3 shows the production factor for various isotopes (see [17] for detailed discussion). There is not strong overproduction (indicated by the dotted line) and the elemental abundances nicely reproduce the observed LEPP pattern in UMP stars. Almost only neutron-deficient isotopes are produced suggesting that proton-rich winds contribute to synthesize light p-nuclei [24].

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 $Y_e$ (right column in Fig. 3). This scenario may contribute to the LEPP elements found in the solar system abundances (marked with circles in the production factor figures) 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.,[25]). This overproduction problem and the fact that most recent supernova simulations [5, 6] favor proton-rich winds could suggest that neutron-rich winds are rare events.
4. 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 [6]. However, the LEPP elements (e.g., Sr, Y, Zr) can be produced in proton- and neutron-rich neutrino-driven winds following the abundance distribution of some UMP star.

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.

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