Nucleosynthesis in neutrino-driven winds: influence of the nuclear physics input

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Abstract. We have performed hydrodynamical simulations of the long-time evolution of proto-neutron stars to study the nucleosynthesis using the resulting wind trajectories. Although the conditions found in the present wind models are not favourable for the production of heavy elements, a small enhancement of the entropy results in the production of r-process elements with A $\approx$ 195. This allows us to explore the sensitivity of their production to the hydrodynamical evolution (wind termination shock) and nuclear physics input used.

1. Introduction

Half of the heavy elements are produced by rapid neutron capture (known as r-process). In the last years different scenarios have been proposed, but many questions remain still open (see [1] for a review). There are two conditions for a successful r-process: 1) the number of neutrons per seed nuclei has to be high ($\approx$ 100). 2) Once the astrophysical site has been identified, nucleosynthesis calculations based on simulations have to reproduce observations. In order to get the ratio between two elements as observed in ultra metal poor stars, in addition to high neutron-to-seed ratio, one needs to find the right evolution of matter along the NZ plane, even after r-process freezes out when matter moves back to stability. The question then emerges: where in the Universe can such conditions be realized?

Our results presented here show that the final abundances depend strongly on dynamical evolution and on the variation of the nuclear physics input. In particular, we have explored the influence of various theoretical mass models with consistent sets of neutron capture rates.

2. Neutrino-driven wind

There are several possible scenarios where r-process takes place [1]. Based on galactic chemical evolution [2] core-collapse supernovae and the subsequent neutrino-driven winds remain the most promising scenario. Therefore, we concentrate our study on neutrino-driven winds [3], which are baryonic outflows from proto-neutron stars formed in core-collapse supernova explosions. This supersonic outflow expands through slow-moving matter, which was ejected at the beginning of the explosion and leads to a wind termination shock or reverse shock. This shock has a great influence on the dynamical evolution of the outflow, and therefore on the nucleosynthesis.

The conditions for r-process in neutrino-driven winds are well understood [4] but requires extreme high entropy, fast expansion or very low electron fraction. In recent simulations [3],

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that we use for our study, the entropies are too low or the electron fraction too high to get a high enough neutron-to-seed ratio. Therefore it is still an open question whether there is some physical aspects missing in the long-time evolution of the ejecta or if the r-process takes place in some other astrophysical site. More investigations of the neutrino-driven wind and other astrophysical environments are necessary to understand where heavy elements are created. However, the available simulations are a useful basis to explore the influence of the nuclear physics input on nucleosynthesis, when the entropy is increased by a small factor. This simulates a dynamical evolution of the matter that will be similar also to other astrophysical environments where the r-process may occur.

3. Nucleosynthesis studies

We take the temperature and density evolution from trajectories of hydrodynamical simulations [3] as input to the nucleosynthesis network combined with a given electron fraction. In addition, the density is reduced by a factor of two in order to increase the entropy. As discussed, this allows us to study the later r-process phase.

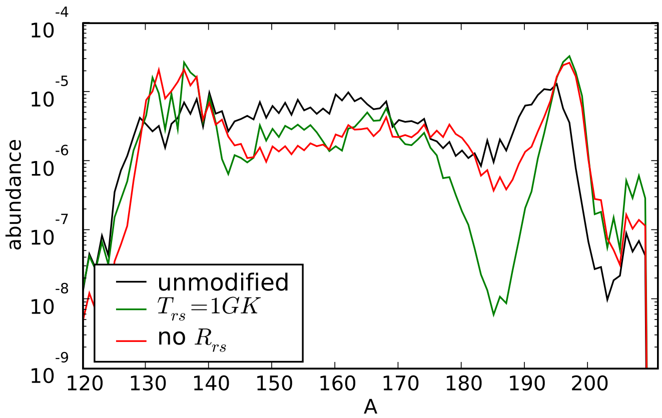

Figure 1. Final abundances for the same trajectory (i.e., same initial neutron-to-seed ratio) but different position of the reverse shock. For the black line, the position of the reverse shock is not changed from the simulation [3]. For the green line, the reverse shock has been moved to a temperature of 1 GK. The red line represents a case without reverse shock, where we have taken the expansion to be adiabatic at the temperature of the former reverse shock. In all cases the entropy has been increased by a factor of two compared to the value from the simulation [3]. The mass model used here is ETFSI-Q [12]. Other mass models will be explored in Fig. 2.

3.1. Dependence on late-time dynamical evolution and the reverse shock

The r-process starts when the ejecta reach temperatures of around 1 GK and is very sensitive to its subsequent evolution, that depends on the interaction of the wind with the supernova ejecta. This interaction produces a wind termination shock which is not a steady-state phenomenon, therefore, it can only be studied within a full hydrodynamical simulation. However, there are some possibilities to parametrize the behaviour of the reverse shock using an artificial outer boundary with constant pressure [6, 7], temperature [8, 9], or density [10, 11]. We have used data directly from our simulations [3] and subsequently changed the position of the reverse shock in a consistent way (for details see Ref. [5]).

We find that, when the wind termination shock occurs at high temperature ($\sim$ 1 GK), the r-process takes place in (n,γ)-(γ,n) equilibrium, as in the classical r-process. In this case the neutron separation energies determine the abundances along an isotopic chain. On the other hand, when the reverse shock is at low temperatures ($<$ 0.5 GK) photo-dissociation becomes negligible and there is a competition between neutron capture and beta decay. Consequently the relevant nuclear physics input will depend on the dynamical evolution of the outflow. This translates into different r-process paths and differences in the final abundances, as shown in Fig. 1.

3.2. Dependence on mass models

Here we describe only the case where the evolution takes place at high temperatures and therefore in (n,γ)-(γ,n) equilibrium. Other cases and more details can be found in Ref. [5]. In Fig. 2 we present the final abundances obtained for the same trajectory but different mass models. We find that the region before the third peak is remarkable different but also the abundances between peaks vary considerably.

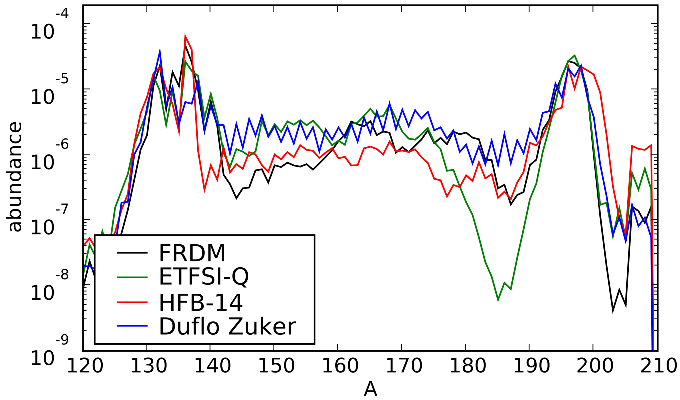

Figure 2. Final abundances obtained from different mass models. All cases are calculated with the same trajectory which reaches (n,γ)-(γ,n) equilibrium, because the reverse shock is at 1 GK.

In order to assess the impact of nuclear masses, we compare the abundances obtained from FRDM to ETFSI-Q at freeze-out ($Y_n/Y_{\rm seed} = 1$) and when all decays have occurred. In Fig. 3 we observe remarkable odd-even effects following the behavior of the neutron separation energies. However, the final abundances in Fig. 4 are smoother similar to solar abundances.

In the long-time evolution there is a competition between beta decay and neutron capture and we have found that neutron captures still play an important role when matter moves back to stability, even when neutron densities and neutron-to-seed ratios are low ($N_n \approx 10^{17}$cm^{-3} and $Y_n/Y_{\rm seed} \approx 10^{-5}$). Neutron captures can fill holes, move peaks to higher mass number and reduce odd-even effects in the abundances. Moreover, the masses also enter in the neutron capture cross sections, and this can explain the differences in Fig. 4 between the two mass models.

4. Conclusions

The late-time evolution of the ejecta, also after freeze-out of the r-process, is very important to determine details in the final abundances. Therefore, we performed nucleosynthesis studies in neutrino-driven winds by means of long-time hydrodynamical simulations of core-collapse supernova explosions. The conditions found in the simulations (low wind entropies and/or high electron fraction) do not allow the formation of heavy elements. However, an artificial increase of the entropy by a factor around two is enough to reach A=195 and allow us to explore the sensitivity of the wind termination shock and the nuclear physics input.

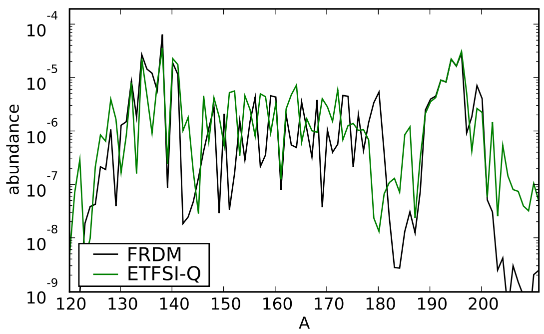

Figure 3. Abundances for $Y_n/Y_{seed} = 1$.

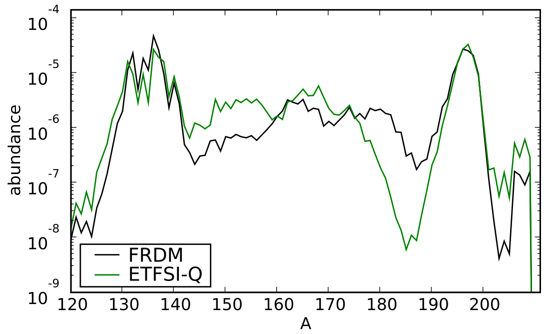

Figure 4. Final abundances after all decays.

Depending on whether the evolution takes place at high or low temperatures the relevant nuclear physics input will change. When (n,γ)-(γ,n)equilibrium is valid the masses and beta decays determine the abundances. In the low temperature case, beta decays and neutron capture are crucial. In both cases, the final abundance distribution is determined by a competition between neutron capture and beta decays, when matter moves back to stability.

4.1. Acknowledgments

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