

Neutron Captures in the r-Process – Do We Know Them and Does It Make Any Difference?

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1. INTRODUCTION

Nucleosynthesis of elements beyond the iron peak requires reactions with neutrons due to the high Coulomb barriers which prevent charged particle reactions. Approximately half of the intermediate and heavy elements are created in the r-process with neutron number densities $n_n > 10^{22} \text{ cm}^{-3}$, effective neutron energies around 100 keV, and short process times of up to a few seconds. These conditions point to an explosive site but the actual site has yet to be identified. Self-consistent SNII models show persistent problems in explaining r-nucleosynthesis. In consequence, most r-process investigations focus on simplified, parameterized models which allow to study the required conditions and their sensitivities to nuclear inputs. Due to the high neutron densities the r-process synthesizes very neutron-rich nuclei far off stability which subsequently decay to stability when the process ceases due to lack of neutrons or low temperatures. This raises the question whether we can predict reactions far off stability sufficiently well to make statements about r-process conditions.

2. UNCERTAINTIES IN REACTION RATES FAR FROM STABILITY

There are two main problems in predicting nuclear cross sections far from stability. The first concerns the prediction of the nuclear properties needed as inputs to the reaction models, i.e. of nuclear structure far from stability with all its uncertainties [1]. The second problem is to identify the relevant reaction mechanism and possible interplay between different mechanisms. With decreasing neutron separation energy S_n , direct neutron capture becomes more and more important relative to compound capture and below a certain level density the Hauser-Feshbach statistical model for compound capture cannot be applied anymore [2,3]. However, the situation is not grave since it is not necessary to know the rates directly in the r-process path. It is a misconception to view the formation of r-isotopes as a sequence of neutron captures and β -decays, similar to an s-process but proceeding further out from stability. In fact, at high temperature T and high n_n all neutron captures and photodisintegrations occur faster by several orders of magnitude than any β -decay in a given isotopic chain [3]. Since forward and backward rates are related by detailed balance, the cross sections cancel out and the ratio is mainly

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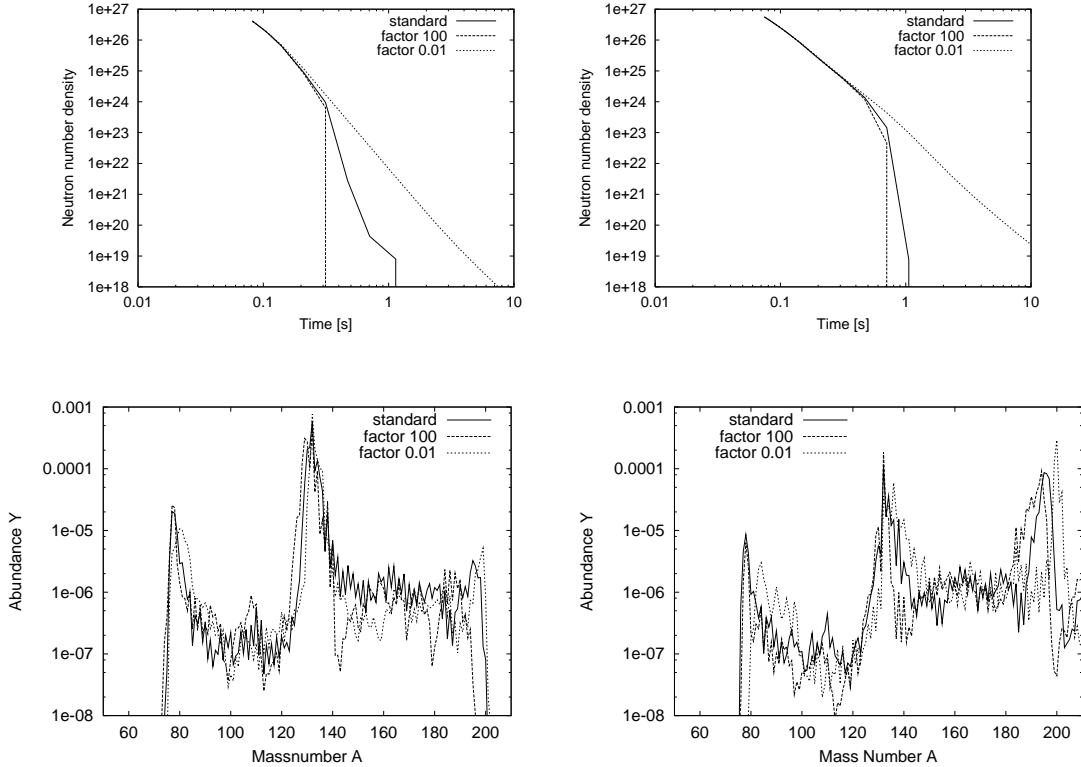


Figure 1. Time evolution of neutron number densities (top, starting at t_α) and resulting abundances (bottom) for $S = 240$ (left) and $S = 310$ (right). The neutron rates were multiplied by factors 1 (full line), 100 (dashed), and 0.01 (dotted), respectively.

depending on S_n , T , and ρ . Neutron captures will only start to matter during freeze-out when the lifetimes become longer due to lower T and lower n_n . It has been shown that the freeze-out proceeds very quickly for realistic conditions [4]. On one hand this limits the importance of neutron captures, on the other hand it validates the investigations which were performed using approximations such as instantaneous freeze-out [5].

3. ADIABATICALLY EXPANDING HOT BUBBLES

Studying neutron captures in the freeze-out necessitates dynamic r-process simulations. In this work calculations in the model of an adiabatically expanding hot bubble were performed similar to [4], combining a charged-particle and an r-process network, but with updated, temperature-dependent rates [6], thus improving a previous, more simple comparison [3]. In this model of a primary r-process, a blob of matter at high temperature ($T_9 = 9$) expands and cools. Due to the initially high T , all reactions, including charged-particle reactions, are in equilibrium and the resulting abundances are determined by NSE. The charged-particle reactions, in particular the α captures, cease at time $t_\alpha \approx 0.08$

s at around $T_9 \approx 2.5$. Below that temperature a simpler network can be employed, only including (n,γ) , (γ,n) , and β -decays (subsuming β -delayed neutron emission). The seed abundances for this r-process network are given by the freeze-out abundances of the charged-particle network. If the triple- α rate is too slow to convert all α 's to heavy mass nuclei at the given charged-particle freeze-out conditions, an α -rich freeze-out is found. The process conditions are specified by the entropy S , the electron abundance Y_e , and the expansion timescale τ . The number of free neutrons available for capture after the charged freeze-out also depends on these conditions. Due to the high T , we still find an (n,γ) - (γ,n) equilibrium at t_α . The β -halflives of the most abundant nuclei in each isotopic chain (these are only one or two due to the shape of the equilibrium equation) determine how fast material can be converted to the next element. Each chain remains in equilibrium until time t_e , when the neutron reactions become too slow to maintain it. Later, at time t_{f_0} , finally the neutron reactions fully freeze out. Thus, neutron capture rates are only relevant for $t_e \leq t \leq t_{f_0}$.

Since the uncertainties in the neutron capture rates might be large, a few exemplary cases are shown here: with standard rates and with neutron captures multiplied by a factor of 100 and a factor of 0.01, respectively (this implies that the photodisintegrations are changed by the same factor). The same expansion was chosen as used by [4] in their case of $\tau = 50$ ms. Assuming $Y_e = 0.45$, for $S \leq 140$ no or only few free neutrons are left after t_α [4]. With such entropies peaks in the mass range $A \leq 110$ are directly produced from NSE abundances (slightly modified by final α captures), favoring nuclei (Z,A) with $Z/A=Y_e$ and high binding energies, but neutrons do not play a role yet. They are only involved in reaching the third r-process peak at higher entropies. For two entropies $S = 240, 310$ Fig. 1 presents the n_n as a function of time and the final abundances. It was previously shown [4] that the freeze-out at higher entropy is slower and that final neutron captures can alter the resulting abundances of heavy nuclei but not of light ones. The trough before the high-mass peak was filled by late neutron captures.

The freeze-out behavior obtained here depends on the chosen neutron rates. The time at which the n_n for the three cases diverge in Fig. 1 indicates t_e . After this point it depends on the entropy how far up in mass nuclei have been produced and on the final neutron captures how their abundances are altered. As can be seen in the figure, t_{f_0} occurs earlier for larger rates, with $0.2 \leq t_{f_0} \leq 30$ s. This reflects the increased capture at $t \geq t_e$. Contrary to the other cases, r-processing with the slowest rates ceases due to low temperatures, not due to lack of neutrons. Nuclei with $A \geq 140$ are mainly produced at $t \geq t_{f_0}$ and are therefore more sensitive to the value of the neutron captures. Especially in the high entropy case it is evident that faster neutron captures smooth the abundance distribution and fill the trough before the $A \approx 200$ peak. Due to the longer duration of the neutron captures, the third peak is shifted to higher A for the slow case.

Despite the fact that there might be considerable uncertainties in the theoretical rates far off stability changing *all* rates in a range of 4 orders of magnitude seems unrealistic. Even if new effects (like pygmy resonances [7,8] or overestimated cross sections [1,8]) might change the rates by factors of 10 – 100 for extremely neutron-rich nuclei, late-time captures will not include such nuclei but will occur closer to stability. Therefore we also used a more realistic variation of the rates as an exponential inversely depending on S_n , thereby simulating the possible enhancement by pygmy resonances. Also accounting for

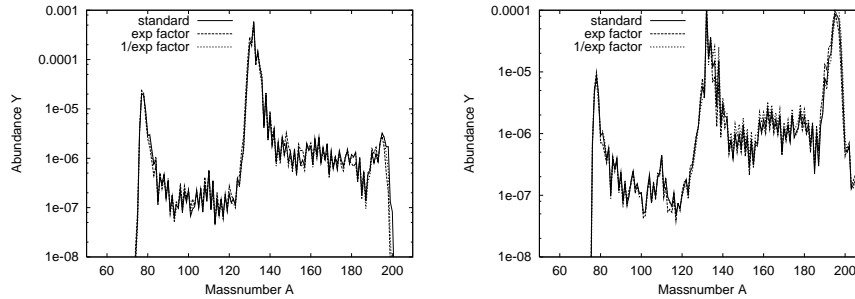


Figure 2. Abundances resulting from an S_n -dependent rate variation for $S=240$ (left), 310 (right). Shown are standard rates (full lines), rates enhanced (dashed), and rates suppressed (dotted) at low S_n .

the fact that the statistical model cannot be applied for low S_n , the resulting overestimate was simulated by using the same function but dividing the rates instead of multiplying them with the correction factor. This factor reaches a value of about 100 towards $S_n \approx 0$ but falls off quickly and is essentially unity already at $S_n \approx 3$ MeV [7]. Fig. 2 shows that there is little impact on the resulting abundances since only few neutron reactions will occur at low S_n .

Concluding, only large modifications of neutron rates lead to appreciable changes in the final abundances due to the short relevant time-scale $\Delta t = t_{fo} - t_e$. The simple comparison shown above for the hot bubble model has to be interpreted cautiously. For reproducing the solar r-process pattern it is necessary to superpose a number of components with different entropies. Thus, effects of rates altered on a large scale, as shown above, can be compensated by a scaling in entropy and a different weight distribution. Details will be discussed in a forthcoming, extended paper. Despite the above caveats the main conclusions are consistent with other studies [4,9]. Components with high entropy freeze out slower and late-time neutron captures can modify the final abundance distribution mainly in the region $A > 140$. Therefore, emphasis has to be put on improving the prediction of nuclear cross sections and astrophysical reaction rates in that mass region far from stability.

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