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Nucleosynthesis in neutrino heated matter: The νp-process and the r-process

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This manuscript reviews recent progress in our understanding of the nucleosynthesis of medium and heavy elements in supernovae. Recent hydrodynamical models of core-collapse supernovae show that a large amount of proton rich matter is ejected under strong neutrino fluxes. This matter constitutes the site of the νp-process where antineutrino absorption reactions catalyze the nucleosynthesis of nuclei with $A > 64$. Supernovae are also associated with the r-process responsible for the synthesis of the heaviest elements in nature. Fission during the r-process can play a major role in determining the final abundance patter and in explaining the almost universal features seen in metal-poor r-process-rich stars.

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1. Introduction

In recent years, observations of metal-poor stars have contributed to increase our understanding of the nucleosynthesis of medium and heavy nuclei and its evolution during the history of the galaxy. Metal-poor stars with large enhancements of r-process elements (the abundance of Eu is typically considered to represent the presence of heavy r-process nuclei) with respect to iron show a variation of two to three orders of magnitude in the absolute amount of r-process elements present for stars of similar metallicities [1]. However the relative abundance of elements heavier that $Z > 56$ (but not including the radioactive actinides) shows a striking consistency with the observed solar abundances of these elements [1]. This consistency does not extend to elements lighter than $Z = 56$ where some variations are observed. In most of the cases elements lighter than $Z < 56$ are underabundant when compared with a scaled solar r-process abundance distribution that matches the observed heavy element abundances [1]. However, recent observations of the metal-poor star HD 221170 [2] show that in some cases the agreement between the scaled solar r-process abundance pattern and the observed abundances of elements can be extended to elements heavier than $Z > 37$. All these observations indicate that the astrophysical sites for the synthesis of light and heavy neutron capture elements are different [3, 4] suggesting two distinct r-processes. Possible sites are supernovae and neutron-star mergers. The exact site and operation for both types of r-process is not known, however, there are clear indications that while the process responsible for the production of heavy elements is universal [5] the production of lighter elements (in particular Sr, Y and Zr) has a much more complex Galactic history [6].

Even if the astrophysical site of the r-process(es) is (are) unknown, it is clear that the process is of primary nature. This means that the site has to produce both the neutrons and seeds necessary for the occurrence of a phase with fast neutron captures that characterizes the r-process [7]. Moreover, in order to explain the observed abundances of U and Th the neutron-to-seed ratio needs to be larger than ~ 100. Under these conditions fission of r-process nuclei beyond U and Th can play a major role in explaining the universality of the heavy r-process pattern in metal-poor stars. This issue will be discussed in section 3.

In section 2 we present a new nucleosynthesis process that we denote the νp-process which occurs in proton-rich matter ejected under explosive conditions and in the presence of strong neutrino fluxes. This process seems necessary to explain the observed abundances of light p-process nuclei, including ^{92,94}Mo and ^{96,98}Ru.

2. Nucleosynthesis in proton-rich supernova ejecta

Recent hydrodynamical studies of core-collapse supernovae have shown that the bulk of neutrino-heated ejecta during the early phases (first second) of the supernova explosion is proton-rich [8, 9, 10]. Nucleosynthesis studies in this environment have shown that these ejecta could be responsible for the solar abundances of elements like ^{45}Sc, ^{49}Ti and ^{64}Zn [11, 12]. Once reactions involving alpha particles freeze out, the composition in these ejecta is mainly given by $N = Z$ alpha nuclei and free protons. Proton captures on this nuclei cannot proceed beyond ^{64}Ge due to the low proton separation energy of ^{65}As and the fact that the beta-decay half-life of ^{64}Ge (64 s) is much longer than the typical expansion time scales (a few seconds). However, the proton densities and temperatures in these ejecta resemble those originally proposed for the p-process by B^{2}FH [13]. So it is interesting to ask under which conditions the nucleosynthesis flow can proceed beyond ^{64}Ge and contribute to the production of light p-process nuclei like ^{92,94}Mo and ^{96,98}Ru that are systematically underproduced in other scenarios [14].

Two recent studies [15, 16] have shown that the inclusion of neutrino interactions during the nucleosynthesis permits a new chain of nuclear reactions denoted νp-process in ref. [15]. In this process nuclei form at a typical distance of $\sim$ 1000 km from proto-neutron star where antineutrino absorption reactions proceed on a time scale of seconds that is much shorter than the typical beta decay half-lives of the most abundant nuclei present (eg. ^{56}Ni and ^{64}Ge). As protons are more abundant than heavy nuclei, antineutrino capture occurs predominantly on protons via $\bar{\nu}_e + p \rightarrow n + e^+$, causing a residual density of free neutrons of 10^{14}–10^{15} cm^{-3} for several seconds, when the temperatures are in the range 1–3 GK. These neutrons can easily be captured by neutron-deficient $N \sim Z$ nuclei (for example ^{64}Ge), which have large neutron capture cross sections. The amount of nuclei with $A > 64$ produced is then directly proportional to the number of antineutrinos captured. While proton capture, (p,γ), on ^{64}Ge takes too long, the (n,p) reaction dominates (with a lifetime of 0.25 s at a temperature of 2 GK), permitting the matter flow to continue to heavier nuclei than ^{64}Ge via subsequent proton captures and beta decays till the next nucleus with an integer number of alpha particles, ^{68}Se. Here again (n,p) reactions followed by proton captures and beta decays permit the flow to reach heavier alpha nuclei. This process can continue till proton capture reactions freeze out at temperatures around 1 GK. The νp-process is different to r-process nucleosynthesis in environtments with $Y_e < 0.5$, i.e. neutron-rich ejecta, where neutrino captures on neutrons provide protons that interact mainly with the existing neutrons, producing alpha-particles and light nuclei. Proton capture by heavy nuclei is suppressed because of the large Coulomb barriers [17, 18]. Consequently, in r-process environments an enhanced formation of the heaviest nuclei does not take place when neutrino are present. In proton-rich ejecta, in contrast to expectation [11], antineutrino absorption produces neutrons that do not suffer from Coulomb barriers and are captured preferentially by heavy neutron-deficient nuclei.

As discussed above the νp-process acts in the temperature range of 1–3 GK. The amount of heavy nuclei synthesized depends on the ratio of neutrons produced via antineutrino capture to the abundance of heavy nuclei (this is similar to the neutron-to-seed ratio in the r-process, see also discussion in [16]). This ratio is sensitive to the antineutrino flux and to the proton to seed ratio. The first depends mainly on the expansion time scale of matter and its hydrodynamical evolution. The second is very sensitive to the proton richness of the material and its entropy. Figure 1 shows the nucleosynthesis resulting from several trajectories corresponding to the early proton-rich wind from the protoneutron star resulting of the explosion of a 15 $M_\odot$ star [8]. (These trajectories have also been studied in reference [16].) No production of nuclei above $A = 64$ is obtained if antineutrino absorption reactions are neglected. Once they are included production of elements above $A = 64$ takes place via the chain of reactions discussed in the previous paragraph. This allows to extend the nucleosynthesis beyond Zn producing elements like Ge whose abundance is roughly proportional to the iron abundance at low metallicities [1]. The production of light p-process nuclei like ^{84}Sr, ^{94}Mo and ^{96,98}Ru is also clearly seen in figure 1. However, ^{92}Mo is still underproduced. This could be due to the limited knowledge of masses around ^{92}Pd [16]. The current mass systematics [19] predict a rather low proton separation energy for ^{91}Rh that inhibits the production of ^{92}Pd. Future

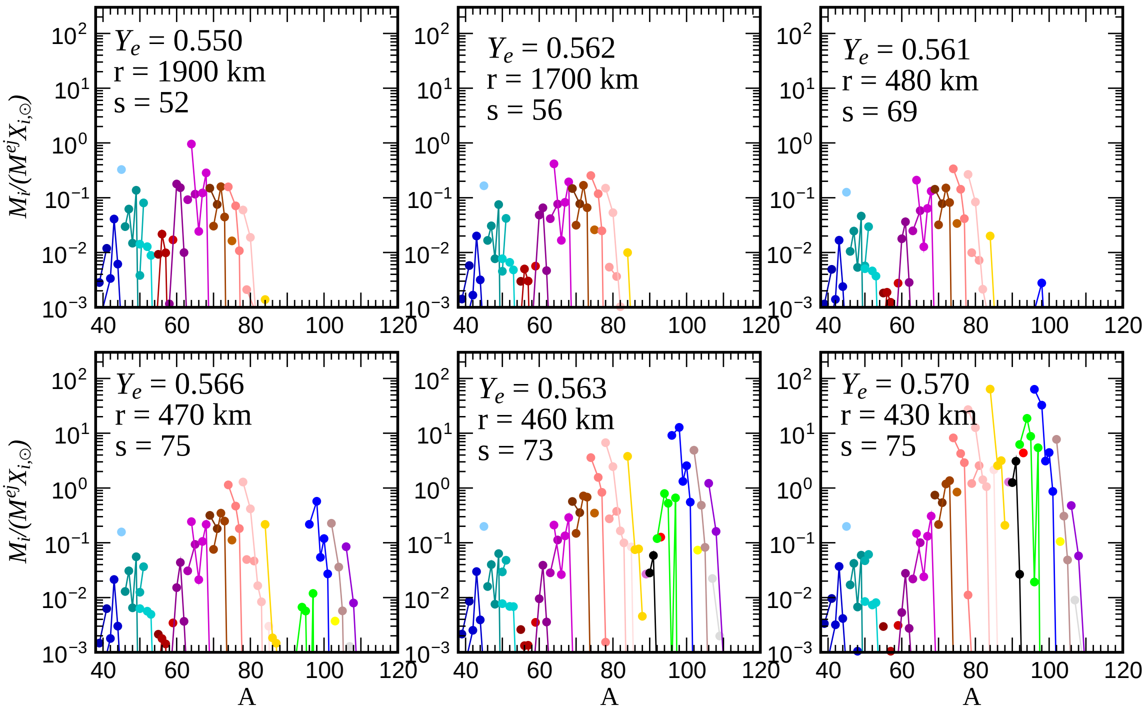

Figure 1: Production factors for six hydrodynamical trajectories corresponding to the early proton rich wind obtained in the explosion of a 15 $M_\odot$ star [8]. In each panel the radius, entropy and Y_e values of matter when the temperature reaches 3 GK are shown.

experimental work in this region should clarify this issue. However, this could be a feature of the νp-process. In this case, it is interesting to notice that previous studies have shown that ^{92}Mo can be produced in slightly neutron-rich ejecta with $Y_e \approx 0.47$–0.49 [17, 20]. A recent study [21] has shown that a combination of proton-rich and slightly neutron-rich ejecta produces all light p-process nuclei. Certainly, much work needs to be done in order to understand the transition from proton-rich to neutron-rich matter in consistent supernovae simulations and its dependence with stellar mass.

3. The role of fission in the r-process

The r-process is responsible for the synthesis of at least half of the elements heavier than Fe. It is associated with explosive scenarios where large neutron densities are achieved allowing for the series of neutron captures and beta decays that constitutes the r-process [7, 22]. The r-process requires the knowledge of masses and beta-decays for thousands of extremely neutron-rich nuclei reaching even the neutron-drip line. Moreover, in order to synthesize the heavy long-lived actinides, U and Th, large neutron to seed ratios are required ($\sim$ 100) allowing to reach nuclei that decay by fission. Fission can be induced by different processes: spontaneous fission, neutron induced fission, beta-delayed fission and, if the r-process occurs under strong neutrino fluxes, neutrino-induced fission. The role of fission in the r-process has been the subject of many studies in the past (see ref. [23] and references therein), however, often only a subset of fission-inducing reactions was considered and a rather simplistic description of fission yields was used. It should be emphasized that, if fission really plays a role in determining the final abundances of the r-process, one needs not only fission rates but equally important are realistic fission yields as they determine the final abundances. Our goal has been to improve this situation by putting together a full set of fission rates including all possible fission reactions listed above. We use the Thomas-Fermi fission barriers of reference [24] which accurately reproduce the isospin dependence of saddle-point masses [25]. The neutron-induced fission rates are from reference [23]. Beta-delayed fission rates are determined based on the FRDM beta-decay rates [26] using an approximate strength distribution for each decay build on the neutron-emission probabilities[1]. The spontaneous fission rates are determined by a regression fit of experimental data [27] to the Thomas-Fermi fission barriers. For each fissioning nucleus the fission yields are determined using the statistical code ABLA [28, 29]. The fission yields change from nucleus to nucleus and in a given nucleus depend on the excitation energy at which fission is induced.

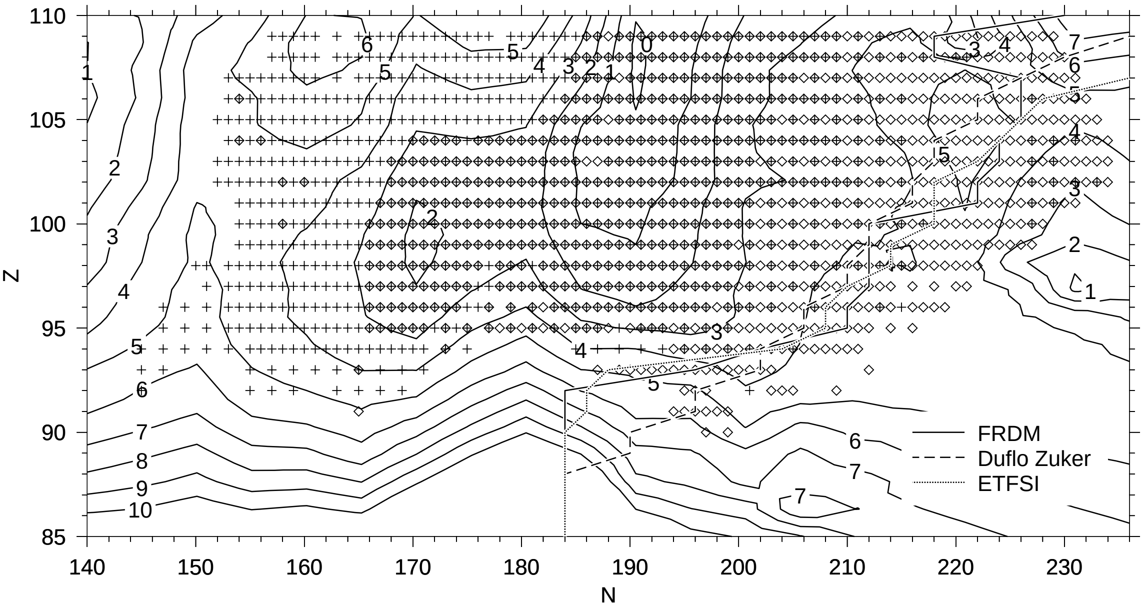

Figure 2: Region of the nuclear chart where fission takes place during the r-process. The contour lines represent the Thomas-Fermi fission barrier heights in MeV. Crosses show the nuclei for which neutron-induced fission dominates over (n,γ). Diamonds show the nuclei for which the spontaneous fission or beta-delayed fission operates in a time scale smaller than 1 second. The lines show the location for which negative neutron separation energies are found in different mass models (FRDM [30], ETFSI [31] and Duflo-Zuker [32]).

Figure 2 shows the region where fission takes place during the r-process. When the r-process reaches nuclei with $Z \sim 85$–90 matter accumulates at the magic neutron number $N = 184$ that plays a similar role as the standard waiting points at $N = 82$ and 126. Nuclei in this mass range have large fission barriers so that fission is only possible once matter moves beyond $N = 184$. The amount of matter that is able to proceed beyond this point depends of the magnitude of the $N = 184$ shell gap. The Duflo-Zuker [32] mass model shows the weakest shell gap, while masses based on the ETFSI model [31] show the stronger shell gap; the FRDM model [30] is somewhat

[1] `http://t16web.lanl.gov/Moller/publications/tpnff.dat`

in between. Once matter has passed $N = 184$, neutron-induced fission takes place in the region $Z \sim 90$–95 and $N \sim 190$. Once fission occurs, the main consequence is that neutrons are mainly captured by fissioning nuclei that have a larger net capture rate (difference between the capture and its inverse process). Once a neutron induces a fission the fissioning nucleus emits around 2–4 neutrons during the fission process. But a larger amount of neutrons is produced by the decay of the fission products which have a Z/A ratio similar to the fissioning nucleus so that they are located closer to the neutron-drip line than the r-process path. Thus, the fission products will decay either by photodissociation, (γ, n), or beta decays (mainly by beta-delayed neutron emission) to the r-process path, emitting of order 8 neutrons per fragment. This implies that each neutron-induced fission event produces around 20 neutrons.

Once neutrons are exhausted the matter accumulated at $N = 184$ beta-decays producing neutrons by beta-delayed neutron emission. These neutrons induce new fissions in the region $Z \sim 95$, $N \sim 175$ that is fed by beta-decays and produce more neutrons self-enhancing the neutron-induced fission rate by a mechanism similar to a chain reaction. The net result is that neutron-induced fission dominates over beta-delayed or spontaneous fission as it can operate in time scales of less than a ms for neutron densities above 10^{18} cm^{-3}.

The above qualitative arguments which show the role of fission during the r-process are independent of the fission barriers used. (See for example figure 2 of reference [33] where a figure similar to our figure 2 is shown based on the ETFSI fission barriers [34].) To get a more quantitative understanding, we have carried out fully dynamical calculations that resemble the conditions expected in the high-entropy bubble resulting in a core-collapse supernova explosion. Early calculations [35] failed to produce the large entropies required for a successful r-process [36]. However, recent calculations indicate that the high entropies required by the r-process can be attained [37] (see also the contributions of A. Burrows and A. Arcones). In our calculations, we assume an adiabatic expansion of the matter, as described in reference [38], but using a realistic equation of state [39]. We adjust the entropy to produce large enough neutron-to-seed ratios to study the effect of fission. We notice that the neutron-to-seed ratio does not only depends on entropy, but also on neutron-richness and expansion time scale [36].

Figure 3 shows the results of our calculations for three different mass models. While the FRDM and Duflo-Zuker mass models show a similar trend with increasing neutron-to-seed ratio, the ETFSI-Q mass model is clearly different. This difference is due to the fact that the ETFSI-Q mass has a quenched shell gap for $N = 82$ and $N = 126$, while the other two mass models show strong shell gaps even close to the drip line. In the ETFSI-Q mass model the $N = 82$ waiting point is practically absent for the conditions of figure 3. This allows all matter to pass through $N = 82$, incorporating most neutrons in heavy nuclei and leaving a few free neutrons to induce fission events. In the other two models, a smaller amount of matter passes the $N = 82$ and $N = 126$ waiting points. Once this matter reaches the fissioning region a large abundance of neutrons is still present that creates new neutrons by fission allowing the r-process to last for a longer time and produce a larger fraction of fission fragments. This explains why the FRDM and Duflo-Zuker mass models produce larger amounts of matter in the range $A = 130$–190, and implies that the shell structure at $N = 82$ is essential for determining the role of fission in the r-process. Calculations with mass models with strong shell gaps yield final abundances that are practically independent of the conditions once the neutron-to-seed ratio is large enough. This seems to be consistent with metal-poor star observations that show a universal abundance distribution of elements heavier than $Z = 56$ [1].

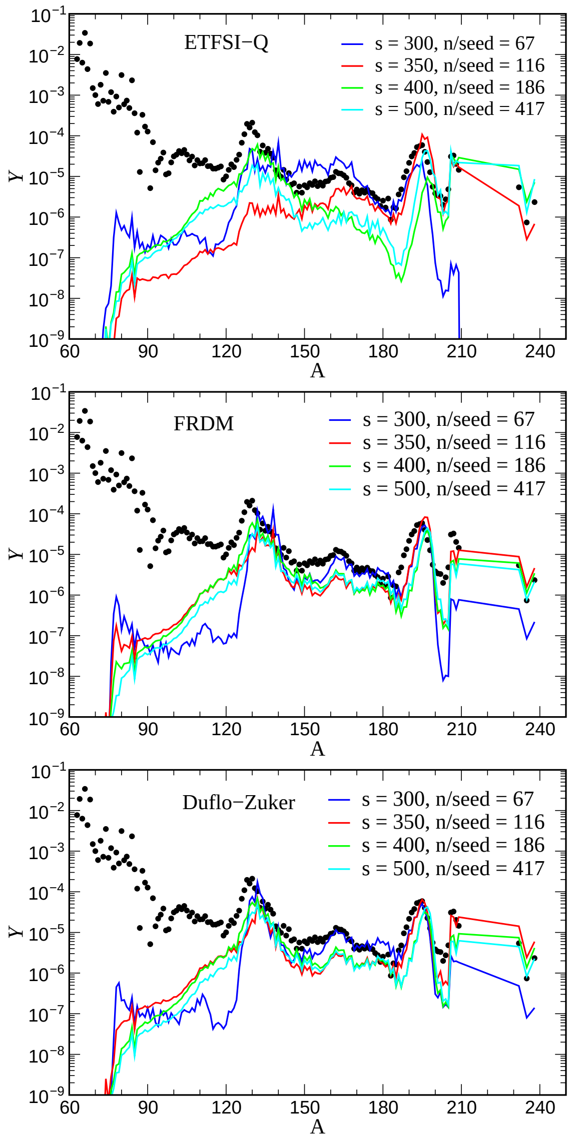

Figure 3: Final r-process abundances (at 1.6 Gy) obtained in several adiabatic expansions using different mass models (FRDM [30], ETFSI-Q [40] and Duflo-Zuker [32]). All the calculation are done for a constant expansion velocity of 4500 km (corresponding to a dynamical time scale of 50 ms). The product ρr^3 is keep constant during the expansion and the temperature is determined from the equation of state under the condition of constant entropy. The curves are labeled according to the entropy and neutron to seed ratio ($n/seed$) resulting after the alpha-rich freeze-out. The solid circles correspond to a scaled solar r-process abundance distribution [41].

Our calculations also show that neutron-induced fission is the major fission process. For example for the calculations with neutron-to-seed ratio 186, the percentage of final abundance that has undergone neutron-induced fission is 36%, beta-delayed fission 3% and neutrino-induced fission 0.3%. With increasing neutron-to-seed ratio all the percentages increase but the relative proportions remain practically constant.

The detection of Th and U in several metal-poor stars [1] opens the possibility of using the decay of this elements to estimate the age of the oldest stars in the galaxy and hence put limits in the age of the Galaxy and the Universe that are independent of the cosmological model used [42]. These age estimates need reliable predictions of the Th and U abundances resulting from the r-process. Figure 3 shows that the absolute amount of Th and U produced depends of the conditions under which the r-process takes place. This variations imply that the Th/Eu ratio cannot be used as a chronometer [43]. However, the ratio U/Th is much less sensitive to the detailed conditions as these nuclei are produced by alpha decays originating in a similar mass range [44, 45]. Using the mean value of the three calculations with largest entropy shown in figure 3 we obtain a U/Th ratio of 0.63 ± 0.02 for the FRDM mass model and of 0.59 ± 0.05 for the Duflo-Zuker mass model. Taking the average of both ratios we determine an age of 16.0 ± 2.4 Gyr for the metal-poor star CS 31082-001 [43] and of 13.4 ± 6.9 Gyr for BD +17°3248 [46].

Another interesting issue is the possibility of producing superheavy elements in the r-process. In our calculations we produce nuclei with mass numbers reaching $A = 320$ however during the beta decay to the stability all these nuclei fission resulting in no production of superheavy elements. Future work is required to explore the sensitivity of the potential production of superheavies by the r-process to different fission barriers.

4. Conclusions

The study of the nucleosynthesis processes responsible for the production of medium and intermediate elements and their relationship to supernovae constitutes a challenge to astronomers, astrophysicists and nuclear physicists. Our current understanding is driven by high-resolution spectroscopic observations of metal-poor stars that aim to probe individual nucleosynthesis events. At the same time progress in the modeling of core-collapse supernovae has improved our knowledge of explosive nucleosynthesis in supernovae. In particular the presence of proton-rich ejecta has open the way to find a solution to the long-standing problem of the origin of light p-process nuclei. Further progress will come from advances in the modeling of the supernovae explosion mechanism and from improved knowledge of the properties of the involved nuclei to be studied at future radioactive-ion beam facilities. These facilities will also open the door to the study many of the nuclei involved in r-process nucleosynthesis, in particular the nuclei located near the $N = 82$ waiting point that are important in determining the role of fission in the r-process. They will also provide valuable data needed to constrain theoretical models to allow for more reliable extrapolations to the region of the nuclear chart where fission takes place during r-process nucleosynthesis.

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