

*Letter to the Editor***The synthesis of the light Mo and Ru isotopes: how now, no need for an exotic solution?**V. Costa^{1,2,3}, M. Rayet³, R.A. Zappalà¹, and M. Arnould³¹ Dipartimento di Fisica e Astronomia dell'Università degli studi di Catania, Italy² INFN-LNS, Catania, Italy³ Université Libre de Bruxelles, Institut d'Astronomie et d'Astrophysique, Belgium

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Abstract. The most detailed calculations of the p-process call for its development in the O/Ne layers of Type II supernovae. In spite of their overall success in reproducing the solar system content of p-nuclides, they suggest a significant underproduction of the light Mo and Ru isotopes. On grounds of a model for the explosion of a $25 M_{\odot}$ star with solar metallicity, we demonstrate that this failure might just be related to the uncertainties left in the rate of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ neutron producing reaction. The latter indeed have a direct impact on the distribution of the s-process seeds for the p-process.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: supernovae: general – solar system: general

1. Introduction

The most successful p-process models available to-date call for the synthesis of the stable neutron-deficient nuclides heavier than Fe in the O/Ne layers of Type II supernovae (SNII) (Rayet et al. 1995, hereafter RAHPN). In spite of their many virtues in reproducing the solar-system p-nuclide abundance distribution, they however suffer from some shortcomings. One of them concerns their persistent underproduction of the light Mo (^{92}Mo , ^{94}Mo) and Ru (^{96}Ru , ^{98}Ru) p-isotopes. Some have tried to remedy this situation with exotic solutions, calling in particular for accreting neutron stars or black holes (e.g. Schatz et al. 1998). The level of the contribution of such sites to the solar system content of the nuclides of concern here is quite impossible to assess in any reliable way. In contrast, it has been emphasized many times over the last decade that the problem might just be due to some misrepresentation of the production in the He-burning core of massive stars of the s-nuclide seeds for the p-process (e.g. Arnould et al. 1998).

The aim of this Letter is to scrutinize the latter, ‘non-exotic’, solution in a quantitative way by duly taking into account the uncertainties that still affect the rate of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction, as they appear in the NACRE compilation of reaction

rates (Angulo et al. 1999). Clearly, these uncertainties in the key neutron producer in conditions obtained during central He burning in massive stars have a direct impact on the predicted abundances of the s-nuclide seeds for the p-process, as already analyzed quantitatively by Meynet & Arnould (1993). Another potential embarrassment of the p-process predictions identified by RAHPN is a SNII overproduction of oxygen relative to the p-nuclides. We show that this problem might be cured along with the one of the underproduction of the light Mo and Ru isotopes if the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate is modified adequately within a range permitted by the NACRE compilation. For the sake of illustration, we just discuss here the case of a $25 M_{\odot}$ solar metallicity ($Z = Z_{\odot}$) star. A more complete study dealing in particular with a set of stars with different masses and metallicities, and analyzing the impact of the uncertainties in the rates of a variety of reactions, is currently under way.

The adopted input physics is briefly described in Sect. 2, and some results are presented in Sect. 3. Conclusions are drawn in Sect. 4.

2. Input physics

The calculations reported here are based on a model for a Z_{\odot} $8 M_{\odot}$ helium star already considered by RAHPN. It corresponds to a main sequence mass of about $25 M_{\odot}$ and is evolved from the beginning of core helium burning to the supernova explosion. Details about this model can be found in Hashimoto (1995), and are summarized in RAHPN. As in RAHPN, 20 O/Ne-rich layers with explosion temperatures peaking in the $(1.8\text{--}3.3)\times 10^9$ K range are selected as the P-Process Layers (PPLs). Their total mass is approximately $0.58 M_{\odot}$. The deepest PPL is located at a mass of about $1.94 M_{\odot}$, which is far enough from the mass cut for all the nuclides produced in this region to be ejected during the explosion.

The p-process reaction network and its numerical solver are described by RAHPN. A series of their selected nuclear reaction rates are updated, however. In particular, the NACRE ‘adopted’ rates are used for charged particle captures by nuclei up to ^{28}Si . For heavier targets, the rates predicted by the Hauser-

Feshbach code MOST (Goriely 1997) are used, except for the experimentally-based neutron capture rates provided by Beer et al. (1992).¹

As already pointed out in Sect. 1, we turn our special attention to the impact of the uncertainties remaining in the rate of $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$. For temperatures of about $2\text{--}3 \times 10^8$ K at which the s-process typically develops during core He burning in massive stars (e.g. Rayet & Hashimoto 2000), the NACRE upper limit on this rate is 50–500 times larger than the ‘adopted’ value (see Angulo et al. 1999 for details). In order to quantify the consequences of this situation for the predicted abundance distribution of the s-nuclide seeds for the p-process, and ultimately for the p-nuclide yields themselves, we perform nucleosynthesis calculations for five different rates ranging from the NACRE adopted value to its upper limit. These rates, labelled R_i ($i=1$ to 5) in the following, are defined and displayed in Fig. 1.² They are used in the Z_{\odot} $25 M_{\odot}$ star referred to above to calculate the abundances of the s-process nuclides at the end of core He burning. The results are shown in Fig. 2 for the s-only nuclides. Use of R_1 leads to the classical ‘weak’ s-process component pattern (e.g. Rayet & Hashimoto 2000), exhibiting a decrease of the overproduction (with respect to solar) of the s-nuclides by a factor ranging from ≈ 100 to about unity when the mass number A increases from about 70 to 100. In the heavier mass range, the s-process ‘main component’ supposed to originate from low- or intermediate-mass stars takes over. This ‘canonical’ picture changes gradually with an increase of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate, more ^{22}Ne having time to burn, releasing more neutrons, before He exhaustion in the core. The direct result of this is a steady increase of the overproduction of heavier and heavier s-nuclides. For example, with the extreme R_5 rate, the overproduction factor increases from 10^3 to 10^4 for A varying from about 70 to 90, before decreasing to a value around unity for $A \approx 150$ only.

At first sight, it might be felt that the s-process abundance distributions obtained with large enough R_i values exhibit some unwanted or embarrassing features. One of these concerns the underproduction of the $A \approx 70\text{--}76$ s-nuclides relative to the $A \approx 80\text{--}90$ ones. Another one relates to the fact that a more or less substantial production of heavy s-nuclides (like in the Ba region) would screw up the pattern of the s-process main component ascribed to lower-mass stars. In our opinion, none of these predictions can really act as a deterrent to $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rates substantially in excess of R_1 . On the one hand, the absence of ab initio self-consistent calculations of the s-process in low- and intermediate mass stars does not allow at this time to predict the exact shape of the main s-process component which is classically assigned to these stars. As a consequence, a contribution

¹ The NACRE and MOST rates are available in the Brussels Nuclear Astrophysics Library (<http://www-astro.ulb.ac.be>)

² The calculations reported here were completed when we have been informed of new low-energy measurements of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ cross section (J.W. Hammer & M. Jaeger, private communication). Rate estimates based on these new data are not available yet. It seems, however, that the revised upper limit might range somewhere between R_4 and R_5

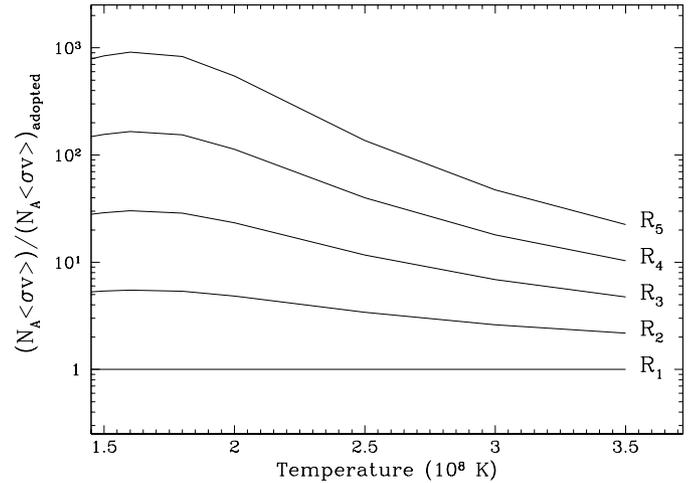


Fig. 1. The five $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rates R_i used in our calculations for temperatures of relevance for core He burning in massive stars. All rates are normalized to R_1 , which is the NACRE ‘adopted’ rate. R_5 corresponds to the NACRE upper values. R_3 , R_2 and R_4 are the geometrical means between R_1 and R_5 , R_1 and R_3 , and R_3 and R_5 , respectively (see also footnote 2)

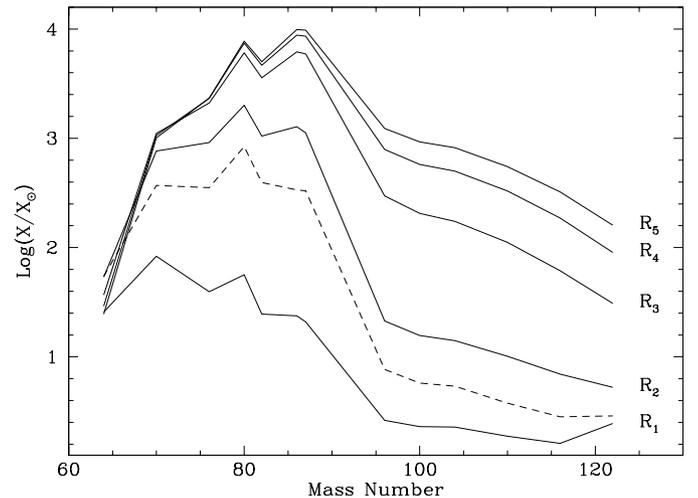


Fig. 2. Distribution of the abundances, normalized to solar values, of the s-only nuclides at the end of core He burning in the considered Z_{\odot} $25 M_{\odot}$ model star, for the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rates R_i ($i = 1$ to 5) defined in Fig. 1, all the other ingredients of the model being kept unchanged (see Rayet & Hashimoto 2000). The dashed line is the distribution adopted by RAHPN for their p-process calculations

to the main component by massive stars cannot be excluded, even if it may disturb some traditional views on the subject. On the other hand, the reduction of the light s-process nuclide production by massive stars could well be compensated by their increased synthesis by some low- or intermediate-mass stars when rates larger than R_1 are considered (Goriely & Mowlavi 2000). The classical ^{80}Kr overproduction problem found in the massive star s-process (e.g. Rayet & Hashimoto 2000) could also be eased with increased $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rates, as demonstrated by Fig. 2. For these same rates, note that ^{80}Kr is not overpro-

duced either in some of the calculations of Goriely & Mowlavi (2000) which predict high yields of the other light s-nuclides.

Fig. 2 also suggests that a discrepancy, if any, between the observed Ba overabundance in the SN1987A ejecta and the model predictions could be cured in a natural way by increasing the adopted $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate. The $[\text{Ba}/\text{Fe}]_{\text{SN}}/[\text{Ba}/\text{Fe}]_{\text{LMC}}$ ratio is observationally still quite uncertain, values between about 5 and 20 having been reported (e.g. Mazzali & Chugai 1995). Prantzos et al. (1988) have calculated lower values of 2.6 to 4.7 with the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate of Fowler et al. (1975). This rate is on average comparable to R_1 in the temperature range of relevance to the s-process. We have not conducted any new s-process calculation in a specific SN1987A progenitor model. Instead, some rough estimates based on the procedure of Prantzos et al. (1988) in which their adopted s-process Ba mass fraction is replaced by the one calculated for the model star adopted here have been made. Assuming that the LMC metallicity is one third of the solar one, we predict $[\text{Ba}/\text{Fe}]_{\text{SN}}/[\text{Ba}/\text{Fe}]_{\text{LMC}}$ ratios from 3 to 14 for rates increasing from R_1 to R_5 . Theory could thus account for quite substantial SN1987A Ba productions with high enough $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rates (compatible with the NACRE data).

As discussed by RAHPN, it is a fair approximation to adopt the s-process abundance distributions of Fig. 2 as seeds for the p-process. For the $A \leq 40$ species, the initial abundances in the PPLs are taken from the detailed stellar models. Although these models have been obtained with rates that may differ from the NACRE ones adopted here, this inconsistency is certainly not responsible for any intolerable distortion in the predicted s-process seeds or p-process yields.

3. Results and discussion

The various seed abundances of Fig. 2 are used to compute the production of the p-nuclides in the PPLs of the Z_{\odot} $25 M_{\odot}$ star considered here. As in RAHPN, the abundance of a p-nuclide i is characterized by its mean overproduction factor $\langle F_i \rangle = \langle X_i \rangle / X_{i,\odot}$, where $X_{i,\odot}$ is its solar mass fraction (Anders & Grevesse 1989), and

$$\langle X_i \rangle = \frac{1}{M_p} \sum_{n \geq 1} (X_{i,n} + X_{i,n-1})(M_n - M_{n-1})/2, \quad (1)$$

where $X_{i,n}$ is the mass fraction of isotope i at the mass coordinate M_n , $M_p = \sum_{n \geq 1} (M_n - M_{n-1})$ is the total mass of the PPLs, the sum running over all the PPLs (M_0 corresponds to the bottom layer). An overproduction factor averaged over all 35 p-nuclei is calculated as $F_0 = \sum_i \langle F_i \rangle / 35$, and is a measure of the global p-nuclide enrichment in the PPLs. So, if the computed p-nuclei abundance distribution were exactly solar, the normalized mean overproduction factor $\langle F_i \rangle / F_0$ would be equal to unity for all i .

Fig. 3 shows the normalised p-nuclide overproduction factors derived from the seed abundance distributions calculated with the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rates R_1 , R_3 and R_5 . Changes in the shape of the p-nuclide abundance distribution are clearly noticeable, at least for $A \lesssim 120$. The use of R_1 leads to a more or less

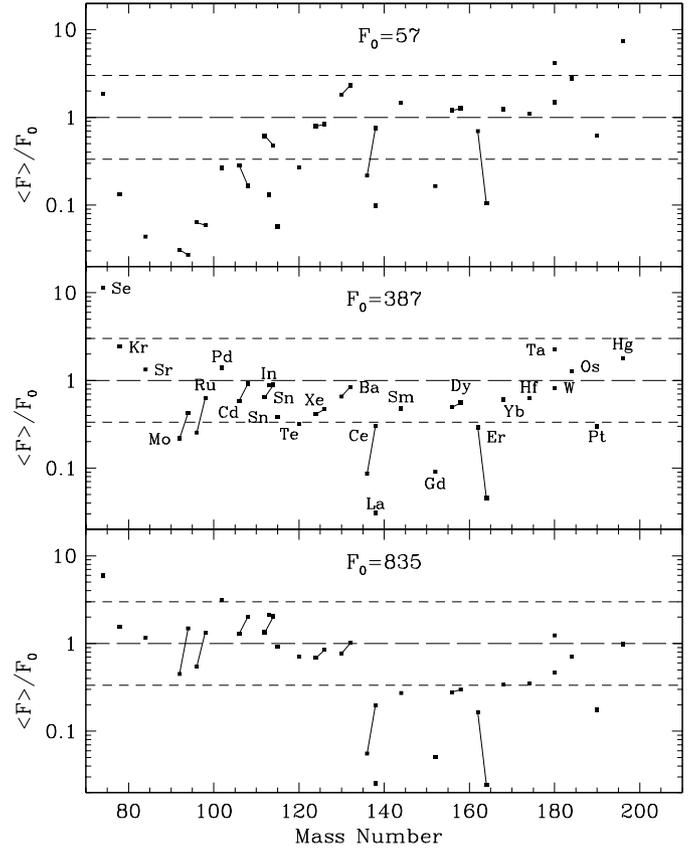


Fig. 3. Values of $\langle F_i \rangle / F_0$ and of F_0 derived from the seed abundances calculated with the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate R_1 (upper panel), R_3 (middle panel) and R_5 (lower panel). Lines connect different isotopes of the same element. The dotted horizontal lines delineate the $0.3 \leq \langle F_i \rangle / F_0 \leq 3$ range

substantial underproduction of not only ^{92}Mo , ^{94}Mo , ^{96}Ru and ^{98}Ru , a ‘classical’ result in p-process studies (see RAHPN), but also of ^{78}Kr and ^{84}Sr , which was not predicted in previous calculations. This new feature directly relates to the larger abundances around $A \approx 80$ used by RAHPN (dashed curve in Fig. 2), in contrast to the much flatter seed distribution obtained with R_1 . This Kr-Sr-Mo-Ru trough is gradually reduced, and in fact essentially disappears, for $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rates of the order or in excess of R_3 . This situation is most clearly illustrated by Fig. 4. In these very same conditions, $\langle F_i \rangle / F_0$ for ^{113}In and ^{115}Sn comes much closer to unity as well. It has to be noticed that this situation does not result from a stronger production of these two nuclides by the p-process, but instead from their increased initial abundances associated with a more efficient s-process when going from R_1 to R_5 . In contrast, the $\langle F_i \rangle / F_0$ pattern does not depend on the adopted $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate for $A \gtrsim 140$. This is expected from a mere inspection of the s-nuclide seed distributions displayed in Fig. 2. In particular, ^{152}Gd and ^{164}Er remain underproduced. This cannot be considered as an embarrassment as these two nuclides can emerge from the s-process in low- or intermediate-mass stars.

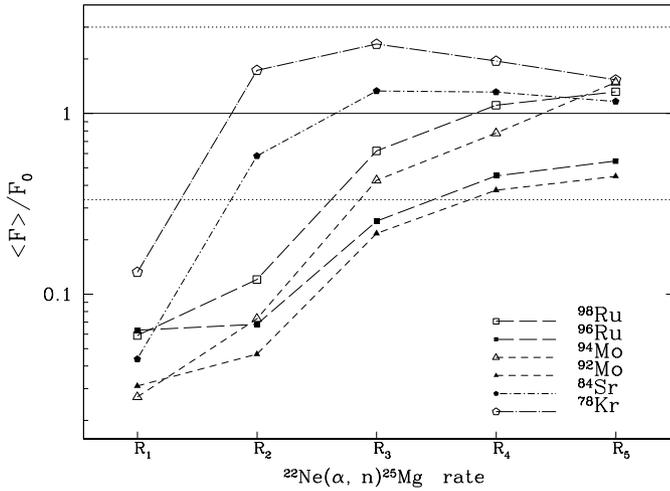


Fig. 4. Values of the normalized overproduction factors of the Kr, Sr, Mo and Ru p-isotopes as a function of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate

In addition, the overall efficiency of the p-nuclide production substantially increases with increasing ^{22}Ne burning rates. More specifically, F_0 is multiplied by a factor of about 15 when going from R_1 to R_5 . This could largely ease, and even solve, the problem of the relative underproduction of the p-nuclides with respect to oxygen identified by RAHPN. For their considered $25 M_{\odot}$ model star calculated with the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate from Caughlan et al. (1985), they obtain $F_0 = 130$ and report a value of 4.4 for the ratio of the oxygen to p-process yields. This value would come close to unity for $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rates in the vicinity of R_3 - R_4 , as the p-nuclides would be about 3 to 6 times more produced than in RAHPN.

4. Conclusions

This Letter makes plausible that the long-standing puzzle of the underproduction with respect to solar of the p-isotopes of Mo and Ru in SNI explosions could be quite naturally solved by just assuming an increase of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate over its ‘nominal’ value. More specifically, this could be achieved by multiplying the NACRE ‘adopted’ rate by factors of about 10 to 50 in the temperature range at which the s-process typically develops during core He burning in massive stars. These factors are well within the uncertainties reported by NACRE. As an important bonus, this increased rate would also largely avoid (i) the underproduction of ^{78}Kr and of ^{84}Sr which we predict

here for the first time to be concomitant to the light Mo and Ru one, (ii) the too low production of ^{113}In and ^{115}Sn , and (iii) the overall underproduction of the p-nuclides with respect to oxygen noted by RAHPN. In direct relation with an increased $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate, more s-process Ba could also be ejected by SNI events. Our predictions comfortably overlap the range of Ba overabundances reported for SN1987.

This array of pleasing features has of course not to be viewed as a proof of the validity of the assumption that the true $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate is higher than usually thought. It may just be a hint that there might be ways around exotic solutions. This conclusion applies at least if one relies on the simplistic (and the only ones to be available for our purpose) supernova models used here and in previous p-process calculations (see RAHPN et references therein), as well as in a myriad of other explosive nucleosynthesis calculations.

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