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ASTRONOMY AND ASTROPHYSICS

The s-process efficiency in massive stars

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Abstract. The s-process is studied in the He burning core of a $M_\alpha = 8\,M_\odot$ He star using temperature and density profiles obtained with a standard stellar evolution model and an updated nuclear network. We discuss in detail the s-process efficiency for metallicities $Z/Z_\odot$ ranging between 1 and 10^{-3} in the light of recent nuclear data. We show that ^{16}O acts as a powerful neutron poison at low Z although its effect on the s-process yields is still subject to large uncertainties due to our imperfect knowledge of some nuclear reaction rates and of the galactic evolution of nuclei which determine the neutron economy of the s-process.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: interiors – Galaxy: abundances

1. Introduction

It is generallly admitted that shell He burning episodes in AGB stars are responsible for the synthesis of the $A \gtrsim 90$ s-nuclei (Gallino et al. 1998; Goriely & Mowlavi 1999) while massive stars ($M > 10M_\odot$) are assumed to produce most of the s-nuclei with $70 \lesssim A \lesssim 90$ during their central helium burning phase. As first suggested by Cameron (1960), helium rich material is enriched in ^{14}N by the CNO cycle during the previous H burning phase, and ^{22}Ne is rapidly produced, during helium burning, by the reaction chain $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\mathrm{e}^+\nu_\mathrm{e})^{18}\mathrm{O}\ (\alpha,\gamma)^{22}\mathrm{Ne}$, leading to the release of neutrons by the reaction $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$. It was shown by Peters (1968) that this neutron source could trigger an s-process in the central He burning of massive stars but it was later realized that this process, requiring relatively high temperatures, is efficient only for the largest stellar masses and was also limited by the large number of neutron captures on lighter nuclei which act therefore as a poison for the s-process (e.g. Lamb et al. 1977; see also Prantzos et al. 1990, hereafter PHN, for a thourough discussion of these points)

More specifically, ^{25}Mg, made in the above mentioned neutron producing reaction, has a very large neutron capture cross section and is usually considered to be the most active of these neutron poisons (a smaller but not negligible number of neutrons are also captured by the neutron source ^{22}Ne itself). We observe for example that the amount of neutrons captured by ^{25}Mg alone is comparable to the amount of captures by all nuclei with $A \geq 56$. On the other hand, the main products of helium burning, ^{12}C and ^{16}O, must also be considered as potential neutron poisons, their very large abundance compensating for their small neutron capture cross sections. However, their influence on the s-process yields is far from being clear since this influence depends very sensitively on two opposite effects. First, neutrons captured by either ^{12}C or ^{16}O can be re-emitted (*recycled*) by the reactions $^{13}\mathrm{C}\,(\alpha\,,\mathrm{n})\,^{16}\mathrm{O}$ or $^{17}\mathrm{O}\,(\alpha\,,\mathrm{n})\,^{20}\mathrm{Ne}$, respectively, which limit the poisonous effect of those nuclei. Second, as metallicity decreases, the relative importance of neutron captures on ^{12}C and ^{16}O increases with respect to neutron captures (or emissions) by nuclei which are *secondary*, i.e. whose abundances scale with metallicity. As a result, even a small loss of neutrons, due to an imperfect recycling of the neutrons absorbed by the *primary* nuclei ^{12}C or ^{16}O, may significantly reduce the number of neutrons available for the s-process (PHN, Nagai et al. 1998).

The balance between neutron emissions and captures (the "neutron economy") depends quite sensitively on the many reaction rates involved in this balance and is considered in most papers on the s-process in massive stars, the problem of the primary neutron poisons being more specifically addressed in relation with low metallicity stars (see e.g. PHN, Raiteri et al. 1992; Baraffe et al. 1992). However, if neutron poisoning is implicitly included in the calculations, a clear understanding of this effect is largely missing. For example the recycling of the neutrons captured by ^{12}C is completely overlooked in PHN and the partial recycling of neutrons captured by ^{16}O is only briefly discussed in Baraffe et al. (1992). On the other hand many important nuclear quantities involved in the neutron economy have been repeatedly changing in recent years, and a more systematic investigation of the neutron economy with updated reaction rates is desirable. An important motivation for this updating is a measurement of the neutron capture cross section on ^{16}O by Igashira et al. (1995) giving a neutron capture rate which is significantly larger than previously thought.

We remark here that in the massive star s-process the abundance of the neutron source, ^{22}Ne, is determined by the amount of ^{14}N initially present in the helium core, which is obtained as an end product of the hydrogen burning phase. On the opposite the available amount of ^{13}C, the main neutron source in the models of thermally pulsing AGB stars, is very uncertain and is still

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largely treated in these models as a free parameter. The contribution of massive stars to the s-process being free from such an arbitrariness, a careful examination of the nuclear physics data to be used in the s-process calculations makes sense in this case. We have also to mention that the contributions to the s-process of further burning phases are not well known yet. If central carbon and shell helium burnings are not expected to be important in this context (Arcoragi et al. 1991), carbon shell burning might have a larger effect on the shaping of the s-nuclei abundances in massive stars (The et al. 1999). The various contributions of those phases will be examined in a subsequent work.

We present in this paper a discussion of the s-process nucleosynthesis which takes place in the central He burning phase of a 8 $M_{\odot}$ helium star using a detailed stellar evolution model which is described in Sect. 2.1. Prescriptions for the initial abundances in relation with assumed values of the metallicity are given in Sect. 2.2 and the relevant nuclear physics input is considered in detail in Sect. 2.3. A discussion of s-process abundances obtained in solar metallicity stars is presented in Sect. 3 in relation with the nuclear physics data used in this and in previous works. In Sect. 4 we calculate the s-process efficiency for stars of metallicity smaller than solar, and different enrichments (w.r.t. solar) in heavy and in light elements, focusing the discussion on the respective roles of neutron source, neutron poison and seed nuclei as well as on different reaction rates of importance. Consequences for the galactic enrichment in s-nuclei are briefly discussed in the conclusions.

2. Input physics

2.1. Evolutionary model and reaction network

The evolution of massive helium stars ($2.6\,M_{\odot} \leq M_{\alpha} \leq 8\,M_{\odot}$) up to the presupernova stage has been described in full detail by Nomoto and Hashimoto (1988) and by Hashimoto (1995) who extended the calculations up to $M_{\alpha} = 32\,M_{\odot}$ and discussed the influence of the $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ reaction rate on the evolutionary sequences. We focus in this paper to the case of a helium star of mass $M_{\alpha} = 8 M_{\odot}$. A helium core of this mass would result from the hydrogen burning of a star with an initial mass of $\approx 25 \mathrm{M}_{\odot}$ if convection stability is determined by the Schwarzschild criterion (see e.g. The et al. 1999).

At helium ignition, a convective core develops from the stellar centre, reaches a maximum extension of 5.66 $M_{\odot}$ (use being made of the Schwarzschild criterion) and then recesses, on a total time of $\sim 766\,10^3$ years. A total number of 146 mass zones is found necessary to describe the convective core at its maximum extension. A limited nuclear reaction network including the 3α, $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ and $^{16}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ reactions as well as the $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\mathrm{e}^{+}\nu_{\mathrm{e}})^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ reaction chain is used to calculate the nuclear energy production rate and the evolution of the main species. The initial composition consists of $^{4}\mathrm{He}$ and $^{14}\mathrm{N}$ only, with X(^{4}He)=0.988 and X(^{14}N)=0.012. The temperatures and densities obtained for each zone as a function of time are then used to calculate the s-process nucleosynthesis with a more complete network containing in particular the neutron capture reactions and all the heavy elements as described below and in Sect. 2.3. This "post-processing" procedure presupposes that our stellar model is not as different from the one which would be obtained with the full network as to change sensitively the s-process nucleosynthesis. We also stress that the same stellar model has been used here to calculate the nucleosynthesis for different choices of reaction rates and for different initial metallicities. The uncertainties in the calculated s-process abundances resulting from those various forms of inconsistency are expected to be smaller than variations coming from the uncertainties in nuclear reaction rates which are discussed in this paper. In support of this assumption we performed the following numerical experiment. We considered two different evolutionary sequences, one using the $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ reaction rate of Caughlan and Fowler (1988) and the other one taking that rate from Caughlan et al. (1985), which leads to slightly smaller densities and temperatures and to a longer evolution time. However, the s-process abundances calculated with the 1988 value of the $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ rate using, consistently, the evolutionary sequence obtained with the same rate and, inconsistently, the one obtained with the 1985 rate, turn out to be almost identical.

The s-process reaction network involves 472 nuclei and 834 reactions. The corresponding system of differential equations is transformed according to the two-step linearization procedure of Wagoner (1969) and the resulting algebraic systems are solved by a pseudo-Gaussian elimination technique adapted for the treatment of sparse matrices (Prantzos et al. 1987). To simulate convective mixing, all nuclei, except neutrons, are distributed homogeneously over the whole convective core and react with other species with temperature averaged rates since the time scales for charged particle induced reactions are larger than the convective mixing time scale. For neutron induced reactions, which have time scales of the order of 10^{-4} s, a different neutron density is calculated in each mass zone and a mass averaged neutron capture probability per target nucleus is then used in the nucleosynthesis equations. A more detailed description of those solving techniques can be found in Prantzos et al.(1987).

2.2. Stellar metallicities and initial abundances

Observations of metal poor stars spanning a large range of ages and of locations in our Galaxy show that the abundances of chemical elements did not increase in the same proportions everywhere in the Galaxy and at every time of its history (Pagel & Tautvaišienė 1995). Since we want to study the s-process in stars of non solar metallicities, the initial composition of our model helium stars should reflect the broad features of this evolution.

Spectroscopic data are now available for determining the photospheric abundances of a large variety of elements, from light to iron peak nuclei, as well as for elements produced in the s- and/or r-process (see e.g. Pagel & Tautvaišienė 1997). However the situation depicted by those rapidly accumulating data is far too detailed for our purpose in this work and we limit ourselves to the consideration of the observed differences in the evolution of two abundant elements, Fe and O, which are most often used to define stellar metallicities.

The abundance of iron is related to the amount of nuclei available for the s-process nucleosynthesis, or *seed* nuclei. On the other hand, oxygen can be considered as representative of the amount of CNO nuclei initially present in the star. During hydrogen burning, oxygen and carbon are essentially transformed into ^{14}N, the progenitor of ^{22}Ne which is the main neutron provider (see Introduction), so that oxygen is a measure of the neutron *source* abundance.

The abundance ratio of Fe with respect to O (as well as w.r.t. other α-elements) is found in low metallicity stars to be smaller than the corresponding solar ratio, with a flat plateau [Fe/O]≈ -0.4 for [Fe/H]$\lesssim -1$ (Pagel & Tautvaišienė 1995) [1]. This observation is very schematically explained by the fact that the Galaxy has been enriched in oxygen early in its history by short-lived massive stars exploding as type II supernovae (SNII), while a large quantity of Fe is later produced in the explosion of slowly evolving low and intermediate mass stars in binary system (type Ia supernovae), increasing the Fe/O ratio to the present, solar system, value. There is however a considerable scatter in the observed values of [Fe/O] and we consider in this work two limiting cases which have been considered in PHN:

1) Case A: [Fe/O]=0 at all metallicities, i.e. Fe and O evolve similarly with time up to the present epoch, and

2) Case B: [Fe/O]=0.42 [O/H], i.e. [Fe/O] increases continuously with metallicity.

Case A is not supported by present observations of low metallicity stars but is considered here as in PHN to illustrate the case of a constant *seed/source* ratio. Case B also appears to be an extreme case, corresponding to a very low *seed/source* ratio at small metallicities. Such a large depletion of Fe at low metallicities is only exceptionally observed. We mention here that a recent abundance analysis of 23 metal-poor unevolved halo stars by Israelian et al. (1998) leads to [Fe/O]≈ 0.45[O/H] in the $-3.0 <$[Fe/H]< -0.3 metallicity range, which is very close to our case B.

In the following, we denote Z the abundance of O with respect to hydrogen at a given galactic time and $Z_\odot$ the corresponding solar value. According to the above discussion, the initial Fe mass fraction in our considered helium stars is given (neglecting the slight variations of $X(\mathrm{H})$) by:

1) $X(\mathrm{Fe})/X(\mathrm{Fe})_\odot = (Z/Z_\odot)$ (case A)

2) $X(\mathrm{Fe})/X(\mathrm{Fe})_\odot = (Z/Z_\odot)^{1.42}$ (case B).

Next we assume that all ^{12}C and ^{16}O nuclei have been transformed into ^{14}N during the H burning phase so that, for solar metallicity, we take $X(^{14}\mathrm{N}) = \sum_{\mathrm{CNO}} \mathrm{X}_\odot = 0.0137$. This value is slightly overestimated if compared to the ^{14}N abundance found inside hydrogen exhausted cores at the end of hydrogen burning (as an example, $X(14) = 0.012$ in The et al. 1999) and would have the effect to overestimate slightly the s-process abundances obtained in our calculations. At metallicities smaller than solar, we decide to scale $X(^{14}\mathrm{N})$ with Z, i.e. to take $X(^{14}\mathrm{N}) = (\mathrm{Z}/\mathrm{Z}_\odot) \times 0.0137$. This is of course an extreme simplification which neglects the metallicity dependence of hydrogen burning conditions.

The initial abundances of ^{14}N and ^{56}Fe being fixed, the initial abundance distribution for the other nuclei is defined as follows. The only other nucleus in the $4 < A < 20$ mass range which is given a non-zero initial abundance is ^{13}C, for which we take the solar value scaled by $Z/Z_\odot$, in order to check a possible contribution of the $^{13}\mathrm{C}\,(\alpha\,,\mathrm{n})\,^{16}\mathrm{O}$ neutron source to the s-process. Although the abundances of several nuclides with mass ≥ 20 are modified during core H burning, we also adopt a solar distribution scaled by $Z/Z_\odot$ in the $20 \leq A \leq 30$ mass range. Similarly, for $A > 30$ we take solar initial abundances scaled by $Z/Z_\odot$ in case A and by $(Z/Z_\odot)^{1.42}$ in case B. Note that for a given choice of the *source* (^{14}N) and *seed* ($A \geq 56$) abundances, variations of that somewhat arbitrarily defined distribution should not change our results, the other abundances of interest for the s-process being built up during helium burning itself.

2.3. Nuclear physics input

If not otherwise specified reaction rates involving charged projectiles are taken from Caughlan and Fowler (1988) (hereafter CF88) while the neutron capture rates come from the compilation of Beer et al. (1992) which takes their temperature dependence into account. The temperature and density dependent rates for β-decays and electron captures are given by Takahashi and Yokoi (1987), except for the β-decay rate of ^{79}Se for which we adopt the results of Klay and Käppeler (1988). However, in several cases of importance more recent determinations of reaction rates are used as explained in the following.

First, for the main neutron producing reaction $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$, we use the rate given by Drotleff et al. (1993) which differs sensibly from CF88: it is smaller than CF88 by a factor 0.18 at $T_6 = 200$ ($T_6 = T/10^6$ K) but becomes larger for $T_6 > 250$ when the reaction is the most effective, being 2.3 times larger than CF88 at $T_6 = 300$. For another important reaction, $^{22}\mathrm{Ne}\,(\alpha\,,\gamma)\,^{26}\mathrm{Mg}$, we use data given by Wolke et al. (1989) who provide only lower and upper values of the rate. We adopt here for the central value the geometrical mean of those two limits, which again differs from CF88 by a factor which increases from 0.56 to 9.8 in the $T_6 = 200$–300 temperature range. Those data, along with CF88 for the other charged particle reactions, represent our "standard" choice. This choice is corroborated by the recent European Nuclear Astrophysics Compilation of Reaction Rates (NACRE) which has become available in the course of this work (Angulo et al. 1999). The NACRE rate for $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ is practically the same as in Drotleff et al. (1993), and for $^{22}\mathrm{Ne}\,(\alpha\,,\gamma)\,^{26}\mathrm{Mg}$ it differs only slightly from our choice (being larger than our rate by a factor 1.7 at $T_6 = 200$ and smaller by the same factor at $T_6 = 300$). In contrast the "tentative" value for the $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ rate proposed by Käppeler et al. (1994) on the basis of Giesen et al. (1993) data appears to be larger than NACRE results by a factor 20–2 on the T_6 =200–300 range. For $^{22}\mathrm{Ne}\,(\alpha\,,\gamma)\,^{26}\mathrm{Mg}$,

[1] We use the usual spectroscopic notation [A/B]= log[A/B]$_{star}$-log[A/B]$_\odot$

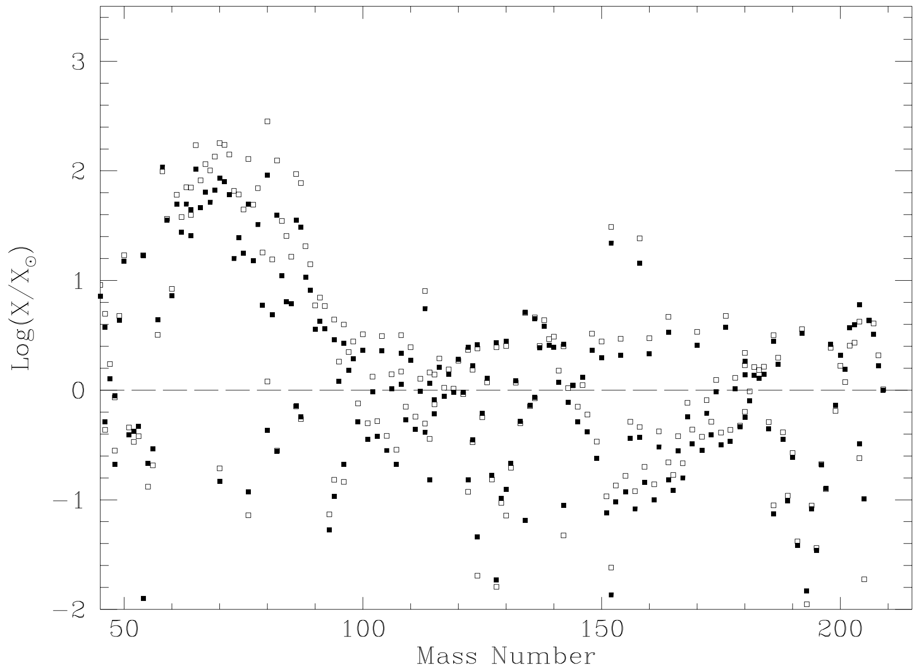

Fig. 1. Logarithm of the overabundances obtained at the end of central He burning in a $8\,M_{\odot}$ star with $Z = Z_{\odot}$. Open squares: our standard choice of reaction rates. Full squares: NACRE reaction rates. The dashed line shows the level of initial abundances.

Käppeler et al. (1994) rate is roughly two times smaller than NACRE. It is not the purpose of this paper to comment on the reasons for those discrepancies. Let us note however that NACRE and Käppeler et al. (1994) agree fairly well on the lower limits of both rates and that the relatively large value of the $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ rate suggested by Käppeler et al. (1994) lie well within the uncertainty due to the possible contributions of low lying resonances in $^{26}\mathrm{Mg}$.

Other charged particle induced reactions of interest for this study have been revised in NACRE. In particular, the recommended rate for $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ is larger in that compilation than in CF88 by a factor of ≈ 2, being very close again to the value given by Caughlan et al. (1985). The influence of this change on the s-process production is briefly discussed in the next section. It must be remarked that the NACRE value for the $^{4}\mathrm{He}\,(\alpha\alpha\,,\gamma)\,^{12}\mathrm{C}$ rate differs from CF88 by less than 15% over the $1 < T_8 < 10$ range, which includes all temperatures of interest for the s-process.

Since the most significant results of this paper concern the effect of neutron captures by light nuclei on the s-process efficiency, we focus our discussion on the (n,γ) rates for the main light neutron capturers. Although the temperature dependence of the rates is included in our calculations, we limit the present discussion to the values of σ_A, the maxwellian averaged cross section at $kT = 30$ keV for radiative neutron capture on a nucleus A. For neon, $\sigma_{20} = 1.4\,$mb and $\sigma_{22} = 0.9\,$mb, measured by Almeida and Käppeler (1983), are adopted in Bao & Käppeler (1987) but have been considerably reduced shortly afterwards by Winters and Macklin (1988) (to 119 and 240 μb respectively). In their compilation, Beer et al.(1992) use the (temperature dependent) rate obtained in Winters and Macklin's experiment for ^{20}Ne while for ^{22}Ne their rate is based on a still smaller cross section $\sigma_{22} = 60\,\mu$b measured by Beer et al. (1991). For ^{25}Mg, the value $\sigma_{25} = 6.5\,$mb obtained by Weigmann et al. (1976) has been adopted in all compilations up to and including Beer et al. (1992).

Interestingly the capture cross section on oxygen, σ_{16}, has steadily increased with time. The value $\sigma_{16} = 0.2\,\mu$b is quoted in Bao & Käppeler (1987), wheras $\sigma_{16} = 0.86\,\mu$b is recommended in Beer et al. (1992). Recently, Nagai et al. (1998) have pointed out the importance of the p-wave contributions to the neutron captures on nuclei with $A < 20$. In particular Igashira et al. (1995) found a very large capture cross section on ^{16}O, corresponding to $\sigma_{16} = 34 \pm 4\,\mu$b, 170 times Allen & Macklin's (1971) value used in Bao & Käppeler (1987). In Sect. 4 we compare s-process calculations obtained with the large rate and with this rate divided by 170. For the sake of conciseness we refer in the following to the former and to the latter choice as the "large" and "small" σ_{16}, although it must be reminded that in both cases the rates are temperature dependent, their dependence being given by Igashira et al. (1995). We note that Beer et al. (1992) already considered that $\sigma_{16} = 0.2\,\mu$b is unrealistically small and we use it in the following only to better demonstrate the poisoning effect of ^{16}O. Note that for the neutron captures on ^{12}C Bao & Käppeler (1987) quote a large value, $\sigma_{12} = 0.2\,$mb, while a recent experiment by Ohsaki et al. (1994) leads to the value $\sigma_{12} = 15.4\,\mu$b which is adopted here.

3. Some results for solar metallicity

We present in Fig. 1 the overabundances of nuclei in the $45 \leq A \leq 209$ range obtained for a 8 M$_{\odot}$ helium star with $Z = Z_{\odot}$. As expected ^{89}Y is the last nuclide to be significantly overproduced, the neutron irradiation obtained during the core He burning phase being too weak to noticeably increase the abundances of nuclei beyond that range[2]. Those overabundances are calculated with the 2 sets of rates for charged particle induced reactions described in Sect. 2.3, i.e. our standard case and the NACRE compilation (the same neutron capture rates, with the large σ_{16} for the results of Fig. 1, are used in both calculations). The observed differences on Fig. 1 result almost entirely from the larger value of the $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ rate (r_{12}) recommended in NACRE with respect to the CF88 value used in our standard case. The effect of the other relevant differences between the two sets (discussed in Sect. 2.3) have been examined by running calculations with NACRE rates except for r_{12}, taken from CF88. It appears that remaining differences between the abundances of the main s-process products are of a few percent with the small σ_{16} and range between 10 and 20% with the large one (as a general rule smaller overabundances are less stable than larger ones against changes in the various physics inputs).

As pointed out by Raiteri et al. (1991) a smaller r_{12} means less captures of ^{4}He on ^{12}C and more on ^{22}Ne, increasing the number of available neutrons and resulting in a stronger s-process (see also The et al. 1999). This effect is shown quantitatively in Table 1 which gives the overabundances of three typical s-only nuclei, the mass fraction of burnt $^{22}\mathrm{Ne}$ and the C/O ratio in the convective core at helium exhaustion for three different values of r_{12}: (a) NACRE "adopted", (b) NACRE "low" value, i.e. the lower limit of the rate estimated in Angulo et al. (1999) and (c) CF88 (our standard case). For each case the ratio of r_{12} to its CF88 value at $T = 3\,10^8$ K is shown. The increase of overabundances and of the fraction of burnt ^{22}Ne from cases (a) to (c) is clearly correlated to the decrease of r_{12} and to the correspondingly larger C/O ratios. Although NACRE "low" r_{12} is only some 15% larger than in CF88, non negligible differences persist between cases (b) and (c), showing that r_{12} is a rather critical quantity.

We also show in Table 1 the effect of neutron captures on ^{16}O. The abundances obtained with the small σ_{16} are displayed in italics for comparison with those in upright numbers calculated with the large σ_{16}. As expected the poisoning effect of ^{16}O is rather limited because most of the neutrons captured on ^{16}O are "recycled" by the reaction $^{17}\mathrm{O}\,(\alpha\,,\mathrm{n})\,^{20}\mathrm{Ne}$ (see also Travaglio et al. (1996) for a brief discussion of this effect with $\sigma_{16} = 34\,\mu$b for solar metallicity).

The overproduction pattern shown in Fig. 1 is in qualitative agreement with other calculations using comparable nuclear physics and astrophysical inputs (see e.g. PHN and Raiteri et al. 1991). Considering the six s-only nuclei in the $70 \le A < 90$ range ($^{70}\mathrm{Ge}$, $^{76}\mathrm{Se}$, $^{80}\mathrm{Kr}$, $^{82}\mathrm{Kr}$, $^{86}\mathrm{Sr}$, $^{87}\mathrm{Sr}$), five of them are coproduced within a factor 1.5, with an average overproduction factor of 121. The overproduction of ^{80}Kr is 2.3 times larger than the latter factor; a similar result is found in most other calculations, which is regarded as a difficulty for the s-process in massive stars (see e.g. PHN).

[2] Note that only two nuclides are overproduced by more than a factor 10 beyond that mass, ^{152}Gd ($X/X_\odot = 32.3$), also reported in previous calculations (PHN, Raiteri et al. 1991) and ^{158}Dy ($X/X_\odot = 24.9$), which is actually a p-nucleus but gets here a small contribution due to the β^- instability of ^{157}Gd and of ^{158}Tb at high temperatures ($T_6 > 150$), triggering the reaction chain $^{157}\mathrm{Gd}(\beta^-)^{157}\mathrm{Tb}(\mathrm{n},\gamma)^{158}\mathrm{Tb}(\beta^-)^{158}\mathrm{Dy}$. To our knowledge a similar enhancement for ^{158}Dy has not been reported in other calculations

Table 1. Overabundances of 3 s-only nuclei obtained for three different choices the $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ rate, r_{12} (see text). Also shown are the fraction of burnt ^{22}Ne and the C/O ratio in the convective core at helium exhaustion. Upright figures refer to calculations with $\sigma_{16} = 34\,\mu$b, italics to $\sigma_{16} = 0.2\,\mu$b

r_{12}/CF88	(a) NACRE(adopted)	(b) NACRE(low)	(c) CF88
at $T = 3\,10^8$ K	1.92	1.16	1.00
^{70}Ge	85.5	136	180
	123	*178*	*204*
^{80}Kr	92.0	180	282
	154	*269*	*338*
^{86}Sr	35.6	65.3	93.5
	56.2	*99.5*	*114*
Fraction of	46%	54%	63%
burnt ^{22}Ne	*47%*	*55%*	*63%*
X(^{12}C)/X(^{16}O)	0.35	0.64	0.76

If a quantitative comparison of s-process abundance calculations may be confusing when they differ in both their nuclear physics and their astrophysical contents, we attempt here such a comparison between PHN and our results since the astrophysical conditions are almost identical in both cases. In PHN the average overproduction for the considered s-only nuclei but $^{80}\mathrm{Kr}$ amounts to 329 (with an additional enhancement of a factor 2.4 for $^{80}\mathrm{Kr}$). If we use the small σ_{16} value like is done in PHN, our average overproduction increases from 121 to 143, which is smaller than in PHN by a factor 2.3. This difference can be attributed essentially to the use of different rates for the neutron producing reaction $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ as well as for the competing reaction channel $^{22}\mathrm{Ne}\,(\alpha\,,\gamma)\,^{26}\mathrm{Mg}$ (those rates being taken from CF88 in PHN). Although our rate for the (α,n) channel is larger than the CF88 one by a factor 1–2.3 in the $T_6 = 250$–300 range, our s-process turns out to be weaker because we use a larger rate for the (α,γ) channel. In the $T_6 = 200$–300 range, the (α,n)/(α,γ) branching ratio is indeed larger in CF88 than in our case by a factor 3–4. If we artificially increase this ratio to the CF88 value by reducing the (α,γ) channel (and *not* changing the (α,n) one) our results agree with PHN. Let us note finally that ^{13}C is burnt very early in the formation of the convective core and, as expected, plays no role in the ensuing nucleosynthesis.

In conclusion, we remark that using the recommended NACRE rates instead of the CF88 compilation leads to a weaker s-process both as a result of an enhanced $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ rate and of a smaller (α,n)/(α,γ) branching ratio in the ^{22}Ne+α reaction. Note also that a increase of a factor ≈ 5 in the s-process production would probably result from the use of the ^{22}Ne+α reaction rates proposed by Käppeler et al. (1994), as shown by The et al. (1999). We refer to the latter reference for a discussion of other effects which may influence the amount of s-processing in massive stars.

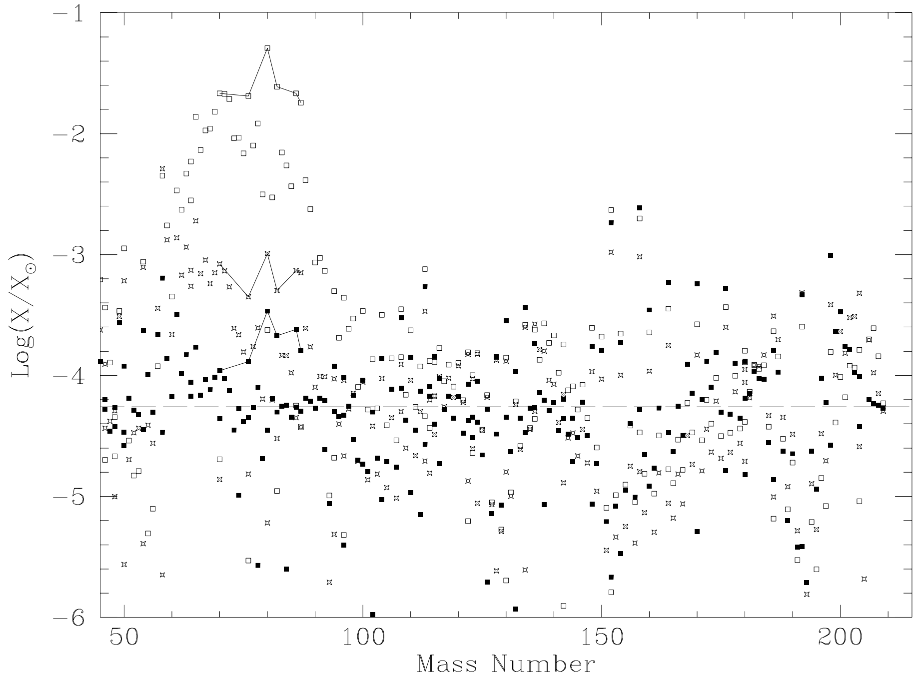

Fig. 2. Overabundances obtained at the end of core He burning for a metallicity $Z/Z_\odot = 10^{-3}$. The initial abundances of seed nuclei correspond to case B and are represented, relative to solar, by the dashed line. Open squares: $\sigma_{16} = 0.2\,\mu$b (Bao & Käppeler 1987); solid squares: $\sigma_{16} = 34\,\mu$b (Igashira et al. 1995); stars: idem with reduced ^{17}O $(\alpha\,,\gamma)\,^{21}$Ne rate. For clarity the six s-only nuclei referred to in the text (Sect. 3) are connected by straight lines

4. The neutron economy at various metallicities

The s-process efficiency, i.e. the enhancement of heavy element abundances during the s-process *with respect to their initial abundances* depends on the respective abundances of the neutron sources (in our case essentially ^{22}Ne), seed nuclei (with $A \gtrsim 56$) and neutron poisons, i.e. of the light nuclei which capture neutrons that are lost for the s-process nucleosynthesis. Potential poisons can be products of the helium burning (like ^{12}C, ^{16}O or ^{20}Ne) in which case their abundances do not depend on the initial metallicity of the star (they are called for this reason "primary"), or result from the transformation of a nucleus whose initial abundance in the star scales with metallicity. This is the case for ^{22}Ne or ^{25}Mg whose progenitor is ^{14}N (these poisons are referred to as "secondary").

As seen in Sect. 2.3, experimental values of the neutron capture rates on light nuclei have been subject to many important revisions during the last decade. Some have decreased and nuclei which were considered as effective neutron poisons play now a negligible role, like ^{20}Ne or ^{22}Ne. On the other hand, a very large value of σ_{16} has been reported recently (Igashira et al. 1995) and the effect of the ^{16}O neutron poison has to be re-evaluated at different values of the metallicity. It has also been suggested (see e.g. PHN) that ^{12}C could have a poisoning effect due to its large abundance and a non-negligible capture cross section, $\sigma_{12} \approx 20\,\mu$b, even if the latter has been reduced by one order of magnitude from the Bao & Käppeler's (1987) value. It turns out however that all neutrons captured by ^{12}C are instantaneously re-emitted in the reaction ^{13}C $(\alpha\,,\mathrm{n})\,^{16}$O so that those captures do not significantly modify the neutron economy, for any considered value of the metallicity (variations of a few percent in the largest overabundances are observed at $Z/Z_\odot = 10^{-3}$ when σ_{12} is multiplied or divided by a factor 5). In the case of ^{16}O a similar recycling occurs through the reaction ^{17}O $(\alpha\,,\mathrm{n})\,^{20}$Ne but in this case the competing ^{17}O $(\alpha\,,\gamma)\,^{21}$Ne channel causes a fraction of the captured neutrons to be lost. Unfortunately, due to the lack of experimental knowledge on the (α,γ) channel, the branching ratio for those two reactions is quite uncertain: in CF88, $(\alpha,\gamma)/(\alpha,\mathrm{n}) \approx 0.1$ in the temperature range of interest, but microscopic calculations of both reaction rates (Descouvemont 1993) suggest that this ratio could be as small as 10^{-4}. Note that the ^{17}O $(\alpha\,,\mathrm{n})\,^{20}$Ne rate itself is predicted by Descouvemont (1993) to be only 1 to 10% of the CF88 value in the $10^8 < T < 10^9$ K range but such a low value is not supported by NACRE (see Sect. 2.3).

S-process calculations have been performed for different values of the initial metallicity: $Z/Z_\odot = 1,\ 10^{-1},\ 10^{-2},\ 10^{-3}$, the initial abundances being calculated for the two scenarios, case A and case B, according to the prescriptions of Sect. 2.2.

4.1. The poisoning effect of ^{16}O *versus metallicity*

As seen in Table 1 for solar metallicity, increasing the neutron capture cross section σ_{16} by a factor 170 only slightly reduces the s-process abundances, which suggests that the amount of neutrons *effectively* captured by ^{16}O (i.e. not recycled) remains small compared to the number of neutrons released by ^{22}Ne $(\alpha\,,\mathrm{n})\,^{25}$Mg. A closer look at that table also reveals that the effect of neutron poisoning becomes larger, going from Column (c) to Column (a), as the number of emitted neutrons (measured here by the fraction of burnt ^{22}Ne) decreases, so that the amount of neutrons captured on ^{16}O becomes comparatively more important.

We then calculate the s-process for $Z/Z_\odot = 10^{-3}$ and plot in Fig. 2 the s-process overabundances obtained with both the small and the large σ_{16}. The initial abundances correspond to case B of Sect. 2.2 and are represented on the $X/X_\odot$ scale by the horizontal dashed line. It appears clearly that at such a small metallicity, the increase of σ_{16} has a catastrophic consequence on the s-process production which decreases for $70 \le A < 90$ by more than two orders of magnitude. The $^{17}\mathrm{O}\,(\alpha\,,\mathrm{n})\,^{20}\mathrm{Ne}$ and $^{17}\mathrm{O}\,(\alpha\,,\gamma)\,^{21}\mathrm{Ne}$ rates are taken from CF88 but, as mentioned before, there is a considerable uncertainty on the latter reaction rate, so we also show the result of calculations using the large σ_{16} value and a reduced $^{17}\mathrm{O}\,(\alpha\,,\gamma)\,^{21}\mathrm{Ne}$ rate, given by 10^{-4} times the $^{17}\mathrm{O}\,(\alpha\,,\mathrm{n})\,^{20}\mathrm{Ne}$ rate, as predicted by Descouvemont (1993). As expected we obtain larger abundances, a smaller rate for $^{17}\mathrm{O}\,(\alpha\,,\gamma)\,^{21}\mathrm{Ne}$ meaning more efficient recycling, though a large poisoning effect remains present. We note also that at this low metallicity, the overproduction patterns for $A < 90$ nuclei obtained with the large σ_{16} value are totally different from the one obtained with the small σ_{16} or, for both values of σ_{16}, in the solar metallicity case. In fact with the large σ_{16} the neutron flux becomes so small that ^{58}Fe is the only nucleus to be enhanced by a factor of about 10. Note also that similar enhancements observed for heavier nuclei, among which the two nuclei mentioned in footnote 2, come essentially from temperature dependent β-decay processes and not from neutron captures.

Preliminary calculations show that the above conclusions remain qualitatively the same for helium cores of mass $M_\alpha = 6$ or 16 $M_\odot$. Quantitative results for an extended mass range will be given in a forthcoming paper.

The mechanism of partial neutron recycling is best understood by studying the "fluxes" of the main reactions which determine the neutron economy[3]. Table 2 presents those quantities for $Z = Z_\odot$ and $Z = 10^{-3} Z_\odot$ (initial abundances corresponding to case B of Sect. 2.2) at a central temperature of 2.5 10^8 K, for which the flux of the main neutron producing reaction ($^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$) is maximum. For each metallicity we use $\sigma_{16} = 0.2\,\mu$b (Column (a)) and $\sigma_{16} = 34\,\mu$b (Column (b)), and for the small Z we also consider the case (Column (c)) where the large σ_{16} is used together with the small ^{17}O(α,γ)/^{17}O(α,n) branching ratio (10^{-4}) predicted by Descouvemont (1993).

The number of "lost" neutrons (in s^{-1} g^{-1}) is given by δ, the difference of fluxes between the $^{16}\mathrm{O}\,(\mathrm{n}\,,\gamma)\,^{17}\mathrm{O}$ and $^{17}\mathrm{O}\,(\alpha\,,\mathrm{n})\,^{20}\mathrm{Ne}$ reactions. It is seen that δ is negligible with respect to the $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ flux for $Z = Z_\odot$ so that the poisoning effect of ^{16}O is very small in this case. On the other hand, in the low metallicity case δ becomes comparable to the $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ flux, which scales with Z, and for $\sigma_{16} = 34\,\mu$b it is even larger, so that the neutron flux is totally exhausted and almost no s-process synthesis is left. As seen in Column (c), a smaller ^{17}O (α,γ)/^{17}O(α,n) branching ratio increases neutron recycling, corresponding to a smaller δ. In this case however, the comparison of δ with the flux of $^{17}\mathrm{O}\,(\alpha\,,\gamma)\,^{21}\mathrm{Ne}$ shows that this reaction is not responsible for the total loss of neutrons as it is in cases (a) and (b) where its rate is about 10^3 times larger. This explains why the overabundances obtained in case (c) are still affected by neutron captures on ^{16}O, having values intermediate between case (a) and case (b).

[3] We define the flux of a reaction i(j,k)l as the number of events per second and per gram of matter, i.e. $n_j Y_i N_\mathrm{A} \langle\sigma v\rangle_{ij\to kl}$

Table 2. The reaction fluxes for a central temperature of 2.5 10^8 K are shown for two values of the metallicity and reaction rates as follows: (a) $\sigma_{16} = 0.2\,\mu$b; (b) $\sigma_{16} = 34\,\mu$b; (c) idem with (α,γ)/(α,n)=10^{-4} (see text). Figures in brackets are exponents of 10

	$Z = Z_\odot$		$Z = 10^{-3}\,Z_\odot$ (case B)		
	(a)	(b)	(a)	(b)	(c)
$^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})$	1.42 (8)	1.41 (8)	1.45 (5)	1.46 (5)	1.46 (5)
$^{16}\mathrm{O}\,(\mathrm{n}\,,\gamma)$	4.46 (5)	7.29 (7)	4.17 (5)	2.51 (6)	2.64 (7)
$^{17}\mathrm{O}\,(\alpha\,,\mathrm{n})$	4.17 (5)	6.74 (7)	3.88 (5)	2.32 (6)	2.64 (7)
δ	2.9 (4)	5.4 (6)	2.8 (4)	1.8 (5)	6.0 (4)
$^{17}\mathrm{O}\,(\alpha\,,\gamma)$	3.21 (4)	5.20 (6)	2.99 (4)	1.79 (5)	2.64 (3)
$^{20}\mathrm{Ne}\,(\mathrm{n}\,,\gamma)$	5.14 (5)	7.95 (5)	1.15 (4)	2.06 (3)	6.87 (4)
$^{22}\mathrm{Ne}\,(\mathrm{n}\,,\gamma)$	3.55 (6)	3.43 (6)	3.31 (3)	1.17 (2)	1.24 (3)
$^{25}\mathrm{Mg}\,(\mathrm{n}\,,\gamma)$	5.15 (7)	5.00 (7)	4.65 (4)	2.05 (3)	2.02 (4)

The last three lines of Table 2 show how the three other important light neutron poisons, $^{20,22}\mathrm{Ne}$ and $^{25}\mathrm{Mg}$ compete with ^{16}O in limiting the neutron flux available for the s-process. For the small σ_{16} cross section (Column (a)), captures on Ne and Mg dominate captures on oxygen (taking account of the recycling effect, i.e. comparing their flux to δ), for $Z = 10^{-3}\,Z_\odot$ as well as for $Z = Z_\odot$. In both cases captures on Ne and Mg absorb about half of the neutrons emitted by $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$. For the large σ_{16} (Column (b)) one has a similar situation at solar metallicity but an opposite one at $Z = 10^{-3}\,Z_\odot$, where practically all neutrons are lost following their capture by ^{16}O.

4.2. The s-process efficiency

The s-process efficiency can be related, through a given chemical evolution model, to the rate of galactic enrichment in that s-nucleus. It is expected to decrease with metallicity since the effect of the ^{16}O primary poison becomes more important when the abundance of *source* nuclei decreases. On the other hand it may possibly increase with decreasing metallicity if the *source/seed* ratio increases, in a scenario where the seed nuclei ($A \ge 56$) abundances decrease faster than Z, i.e. faster than the abundance of the *source* nucleus ^{14}N. In order to disentangle those two effects we describe here the s-process efficiencies calculated for the six representative s-only nuclei considered in Sect. 3 with the two metallicity scenarios defined in Sect. 2.2 as case A and case B.

In case A the *source/seed* ratio is constant with Z and the efficiency can only decrease, when neutron losses due to captures on oxygen become important with respect to neutron production. Fig. 3 shows this effect by comparison of the efficiencies obtained for $Z = 1$, 0.1, 0.01 and 0.001. When σ_{16} is small (Fig. 3a), captures on ^{16}O do not affect the s-process efficiency before Z reaches $10^{-3}\,Z_\odot$, when the efficiency drops by a factor ≈ 4. For the large σ_{16} (Fig. 3b) the efficiency is reduced by a factor ≈ 3 already for $Z = 0.1\,Z_\odot$. In case B (Fig. 4), the

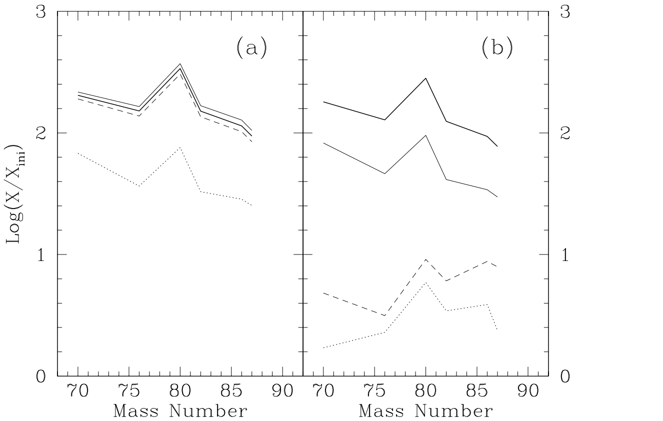

Fig. 3a and b. The s-process efficiency, $X/X_{\rm ini}$ for 6 s-only nuclei in the $70 \leq A < 90$ range: **a** with $\sigma_{16} = 0.2\,\mu$b (Bao & Käppeler 1987) and **b** with $\sigma_{16} = 34\,\mu$b (Igashira et al. 1995). Initial abundances are for case A (Sect. 2.2) and different values of $Z/Z_\odot$: 1 (thick solid line), 10^{-1} (thin solid line), 10^{-2} (dashed line) and 10^{-3} (dotted line)

efficiency behaves quite differently for the two values of σ_{16}: for small σ_{16} it increases by more than one order of magnitude from $Z/Z_\odot = 1$ to $Z/Z_\odot = 0.01$ because of the increasing *source/seed* ratio. The efficiency starts decreasing only for $Z = 10^{-3}\,Z_\odot$ but remains larger than it is for solar metallicity despite the oxygen poisoning effect. On the other hand, for large σ_{16} (Fig. 4b) the efficiency is only slightly increased for $Z/Z_\odot = 0.1$ but for smaller metallicities neutron poisoning outweighs the source/seed effect and the efficiency decreases as in case A.

5. Conclusions

Although the s-process in the central He burning of massive stars is relatively well understood in terms of the stellar models involved (in contrast to the s-process in pulsating AGB stars) remaining uncertainties in some key nuclear reactions still preclude precise estimates of the s-process yields. We have shown in particular that ^{16}O progressively emerges as a very effective neutron poison (even supplanting ^{25}Mg) as metallicity decreases, the poisoning effect depending dramatically on σ_{16}.

A summary of the situation is depicted in Fig. 5 which shows how the s-process efficiency evolves with the increasing values of σ_{16} which have come out of experimental determinations. The value $\sigma_{16} = 2\,\mu$b was used by Baraffe et al. (1992)[4] who already pointed out an important poisoning effect at low metallicities due to this large cross section. This effect is shown in Fig. 5a for $Z = 10^{-3}\,Z_\odot$ (case B), where each increase of σ_{16} produces a substantial decrease of the efficiency, an additional decrease by a factor 3 resulting from the increase of σ_{16} from 2μb (Baraffe et al. 1992) to the new determination $\sigma_{16} = 32\mu$b by Igashira et al. (1995). In contrast, for $Z = 0.1\,Z_\odot$ (Fig. 5b) there is no perceptible decrease of the efficiency due to neutron poisoning effects except when σ_{16} gets its largest value, for reasons that have been explained in detail in Sect. 4.1.

[4] This value is quoted in Baraffe et al. 1992 from an unpublished work by Beer and Voß. It is mentioned in Beer et al. (1992) but the value $0.86\,\mu$b is the one which is recommended in the latter paper

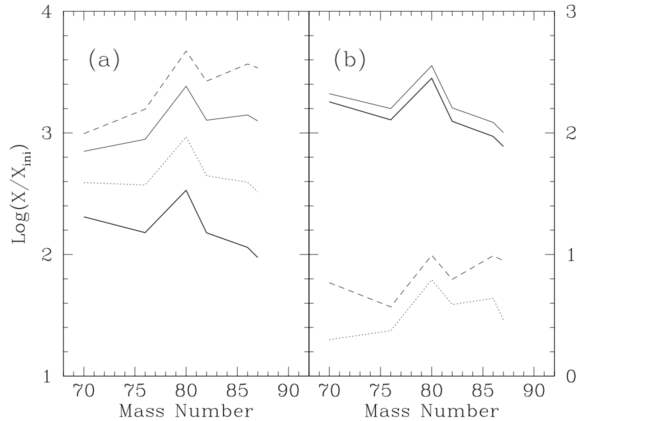

Fig. 4a and b. The same as Fig. 3 but for initial abundances given according to the prescription of case B (Sect. 2.2). Note the shift in the vertical scales between **a** and **b**

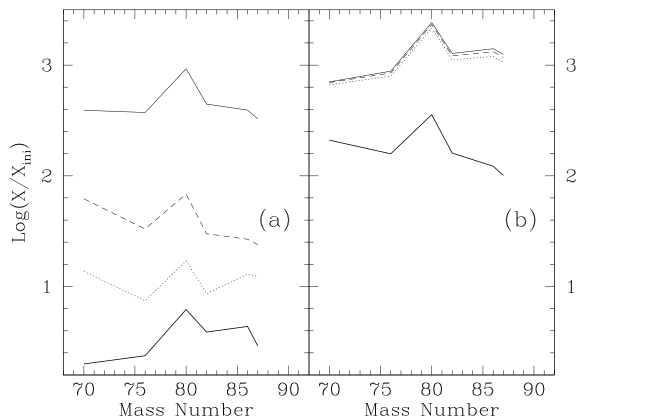

Fig. 5a and b. The s-process efficiency for the different experimental determinations of σ_{16} [solid line, $\sigma_{16} = 0.2\,\mu$b (Bao & Käppeler 1987); dashed line, $\sigma_{16} = 0.86\,\mu$b (Beer et al. 1992); dotted line, $\sigma_{16} = 2\,\mu$b (quoted in Baraffe et al. 1992); thick solid line, $\sigma_{16} = 34\,\mu$b (Igashira et al. 1995)] and for two different metallicities (in case B): **a** $Z = 10^{-3}\,Z_\odot$ and **b** $Z = 10^{-1}\,Z_\odot$

Unfortunately the s-process efficiency also depends on the very uncertain branching ratio between the (α,γ) and (α,n) reactions on ^{17}O. The value we use in Fig. 5 for this ratio (≈ 0.1) is probably an upper limit but we have shown that even with the small value 10^{-4} the neutron recycling is not complete and the poisoning effect is still quite strong at $Z = 10^{-3}\,Z_\odot$. On the other hand, the efficiency of the neutron source does not only depend on the absolute value of the $^{22}{\rm Ne}\,(\alpha\,,{\rm n})\,^{25}{\rm Mg}$ reaction rate but is also conditioned by the branching between this reaction and the radiative channel $^{22}{\rm Ne}\,(\alpha\,,\gamma)\,^{26}{\rm Mg}$, which again is still subject to large uncertainties.

As already stressed in PHN, another important cause of uncertainty comes from the source/seed ratio or, equivalently, from [O/Fe], a quantity which is far from being well and uniquely determined when one goes back into the Galaxy's past. Clearly the effects discussed in this paper as well as the related uncertainties must be dealt with in any reliable model for the galactic evolution of s-nuclei abundances.

Similar calculations are now being performed for different stellar masses, covering the range $3.3 \leq M_\alpha/M_\odot \leq 32$, in order to reach more quantitative conclusions. Later phases of evolution of massive stars, particularly shell carbon burning, may also contribute to the production of s-nuclei. Such contributions are not well understood yet and have also to be (re-)examined.

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