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A new approach to the canonical s-process model

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Abstract. A new approach to the canonical s-process model is proposed. It is based on an optimized superposition of s-process events at different temperatures and neutron densities which aims at reproducing the solar system abundances as precisely as possible. An iterative procedure enables us to assign unambiguously to each event contributing to the solar s-abundance curve a statistical weight which in turn determines the distribution of neutron exposures, temperatures and neutron densities responsible for the production of the s-elements. It is shown that the abundance predictions of the multi-event model are in good agreement with those of the widely used exponential model, at least when a restricted range of thermodynamic conditions is considered. When enlarging the range of thermodynamic conditions in which the s-process is allowed to develop, a larger set of nuclei appear to be produced in solar quantity by the s-process. The impact of the astrophysical and nuclear physics uncertainties on the residual r-abundance distribution representative of the solar system is analyzed.

Key words: nucleosynthesis; nuclear reactions – stars: abundances – solar system: general – Sun: abundances

1. Introduction

For the last decades, an extremely intense amount of work has been devoted to the slow neutron-capture process (or s-process) of nucleosynthesis called to explain the origin of about half of the elements heavier than iron observed in nature (e.g Seeger et al. 1965; Clayton & Ward 1974; Käppeler et al. 1989). Although the modelling of the s-process still faces some problems–especially concerning the exact identification of the astrophysical sites in which it might develop–our understanding of the nuclear mechanisms responsible for the production of the s-nuclei can be regarded as very satisfactory, at least in comparison with the other important nucleosynthetic process susceptible to produce elements heavier than iron, namely the rapid neutron-capture process (or r-process). One of the major reasons of this success consists in the remarkable effort performed in experimental and theoretical nuclear physics to determine as reliably as possible the nuclear quantities of importance to the s-process nucleosynthesis. Most of the nuclei involved in the s-process have been studied in the laboratory, and a large number of their properties are known experimentally. Some specific nuclear uncertainties obviously remain, because of the special thermodynamic conditions found in stellar environment which cannot be reproduced in terrestrial laboratories. As regards the astrophysical modelling, the situation is unfortunately much more cumbersome. The so-called realistic s-process models aim at describing through consistent stellar models the burning phases where the astrophysical conditions required for the s-process to take place are fulfilled. Even though the observation of the radioactive Tc in stellar envelopes clearly proves that the s-process takes place during hydrostatic burning phases of a star, it remains difficult to explain the origin of the large neutron concentrations required to produce s-elements. At the present time, two nuclear reactions are suggested as possible neutron sources, i.e $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$. These reactions could be responsible for a large production of neutrons during given burning phases, namely the core He-burning of massive stars ($M \geq 10\ M_\odot$) (e.g Langer et al. 1989; Prantzos et al. 1990; Baraffe et al. 1992) and the shell He-burning during the thermal AGB instabilities–well-known as thermal pulses–of low and intermediate mass stars ($M \leq 10\ M_\odot$) (e.g Malaney & Boothroyd 1987; Holowell & Iben 1989; Straniero et al. 1995). Even though the core He-burning has proved its ability to produce the lightest s-elements (i.e $70 \lesssim A \lesssim 90$), the astrophysical models underlying the thermal pulse scenario (believed to be responsible for the production of the $A > 90$ s-elements) are still quite uncertain, in particular in the description of the mechanisms that could be at the origin of the neutron production (e.g Lattanzio 1989; Frost & Lattanzio 1995). For this reason, the models are often artificially parametrized in order to increase the neutron concentration (e.g. Busso et al. 1992).

In parallel to the realistic models exploring the s-process sites, fully parametric models free of all astrophysical constraints have been introduced in order to estimate the ability of the s-process to produce the various heavy elements in solar quantity, and consequently to decompose the solar abundances

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of heavy elements into the s-, r-, and p-components[1]. The most popular of these parametric models, well-known as the classical s-process model, is based on the original canonical model of Burbidge et al. (1957) and was first successfully developed by Clayton et al. (1961). The canonical model assumes that some stellar material composed of iron nuclei only is subjected to neutron densities and temperatures that remain constant over the whole time scale of the neutron irradiation, and are in addition low enough for the β-decays of unstable nuclei to be faster than the neutron captures. Under such conditions, the change in the abundance N of a given element i along the s-process path can be expressed as

$$\frac{dN_i}{d\tau} = \langle\sigma\rangle_{i-1} N_{i-1} - \langle\sigma\rangle_i N_i \ , \tag{1}$$

where $\langle\sigma\rangle$ is the Maxwellian-averaged neutron capture cross section and $\tau = \int_0^t N_n v_T dt$ is the time-integrated neutron exposure (v_T is the most probable relative neutron-nucleus velocity at the temperature T, and N_n is the neutron density). Rapidly, it turned out that the solar system s-abundances could not be explained as resulting from one given neutron exposure. Two main improvements were then introduced to the original model to give birth to the most-widely used form of the classical model. First, branching points, i.e. unstable isotopes for which the radioactive decay half-life is comparable with the time scale against neutron captures, were taken explicitly into account allowing for a possible competition between β-decays and (n,γ) reactions (Ward et al. 1976; Ward & Newman 1978). Second, the solar s-element composition was assumed to be the result of a superposition of different distributions of neutron exposures (Clayton et al. 1961; Clayton & Rassbach 1967). The solar s-abundance distribution clearly indicates that the stronger the neutron irradiation the less probable it becomes. In particular, Clayton et al. (1961) showed that an exponential or power law could efficiently be used to describe mathematically the neutron exposure distribution. The exponentially decreasing distribution has been greatly encouraged by Ulrich's (1973) interpretation as being the possible result of succeeding irradiations in identical thermal pulses (with a constant mixing fraction between the succeeding pulses) during the stellar AGB phase. The exponential model has been very successful in reproducing the solar system s-abundance distribution by considering the superposition of three exponential distributions: the weak component essentially responsible for the production of the $70 \leq A \leq 90$ s-nuclei, the main component for the $90 \leq A \leq 204$ isotopes and the strong component for the Pb and Bi elements (e.g Käppeler et al. 1989). Each of these distributions is typically expressed as

$$\rho(\tau) = \frac{fN_{56}(0)}{\tau_0} \exp(-\tau/\tau_0) \ , \tag{2}$$

[1] In addition to the neutron-capture s- and r-processes, another nucleosynthetic process (the p-process) is invoked to explain the origin of a large number of proton-rich isotopes heavier than iron which cannot be synthesized by the s- and r-processes. Details on the p-process nucleosynthesis can be found in Rayet et al. (1995).

where $fN_{56}(0)$ is the initial solar fraction of ^{56}Fe that has been irradiated and τ_0 the characteristic exposure of the distribution. Although important efforts have been made to improve the description of the nuclear physics input of relevance for the s-process, the impact of the assumptions made in the exponential model is seldom discussed. In particular, the effect of the adopted mathematical form of the exposure distribution on the s-abundance predictions is not known. Moreover, it should be recalled that the solar system r-process abundances are commonly derived from the observed solar values by subtracting the possible nucleosynthetic contribution of the s-process. A slight modification of the s-process abundance predictions could therefore have a large influence on the production of some r-nuclei. For example, about 90% of the solar abundance of ^{140}Ce is predicted to be produced by the classical s-process. The remaining 10% of the solar abundance are therefore ascribed to the r-process. However, a small change in the s-process parameter, such as deviations from the theoretical exponential form could slightly increase the s-contribution, and consequently make the r-process contribution negligible.

In order to test the reliability of the classical model, we have developed a new s-process model based on the superposition of a large number of canonical astrophysical events taking place at different temperatures and neutron densities. The resulting multi-event s-process model is described in Sect. 2 and compared with the predictions of the classical model. The new features introduced by the multi-event model are shown in Sect. 3 to have an important impact on the s- and r-process nucleosynthesis if a large range of thermodynamic conditions is considered. Finally, in Sect. 4, the uncertainties related to the astrophysical modelling (as introduced in Sect. 3) and to the imprecision in the nuclear reaction rates are studied in more detail. In particular, their impact on the residual r-abundance distribution is discussed. It should be mentioned that the main aim of this paper is to present the multi-event model as a new possible approach to the parametrized canonical s-process nucleosynthesis, and to study its implication on the calculated r-abundances representative of the solar system. For this reason, the detailed analysis of the production of each nuclear species is postponed to a future work.

2. The canonical multi-event s-process

In a similar way to that developed in the r-process modelling (Bouquelle et al. 1996; Goriely & Arnould 1996), it is possible to define a canonical multi-event s-process as a superposition of a large number of astrophysical events taking place in different thermodynamic conditions. Each canonical event is characterized by a given neutron irradiation on the ^{56}Fe seed nuclei during a time t at a constant temperature T and a constant neutron density N_n. After the time t, the neutron density is assumed to fall off to zero instantaneously. The combination of s-process events that provides the best fit to the solar abundances can then be derived with the aid of an iterative inversion procedure that has been applied to astronomical inverse problems (Lucy 1974), but also parametric r-process calculations (Bouquelle et al. 1996; Goriely & Arnould 1996). The observed solar abundance $N^{\odot}_{Z,A}$ of a nuclide (Z, A) is approximated by the weighted superposition of the abundances resulting from a given astrophysical event $n(Z, A; T, N_n, t)$ (always normalized such that $\sum_{Z,A} n = 1$),

$$N^{\odot}_{Z,A} \simeq \sum_{T,N_n,t} n(Z, A; T, N_n, t)\ \Phi(T, N_n, t)\ , \tag{3}$$

where $\Phi(T, N_n, t)$ represents the statistical weight of the event (T, N_n, t). The recursion relation

$$\Phi^{(r+1)}(T, N_n, t) \;=\; \Phi^{(r)}(T, N_n, t) \sum_{Z,A} \frac{N^{\odot}_{Z,A}}{N^{(r)}_{Z,A}} \times\ n(Z, A; T, N_n, t) \tag{4}$$

is used in order to obtain an "improved" $(r + 1)$th estimate of $\Phi(T, N_n, t)$ from the rth iteration $\Phi^{(r)}$. $N^{(r)}_{Z,A}$ is defined by

$$N^{(r)}_{Z,A} = \sum_{T,N_n,t} n(Z, A; T, N_n, t)\ \Phi^{(r)}(T, N_n, t)\ . \tag{5}$$

The iteration procedure starts with a uniform distribution of initial weights $\Phi^{(0)}(T, N_n, t)$ (i.e. all events have initially the same weight) and converges after several iterations to a "best-fit" abundance curve $N_{Z,A}$. The corresponding weight profile $\Phi(T, N_n, t)$ allows us to analyze the most contributing events to the synthesis of each fitted element.

In contrast to the usually adopted exponential model which assumes a superposition of exponentially decreasing exposures, the multi-event model makes no hypothesis concerning any particular predefined exposure distribution. By considering a set of astrophysically plausible events, an optimized s-abundance curve can be derived by the iterative inversion method, along with the corresponding exposure distribution. For each event, a full network calculation including 640 nuclei between Cr and Po is solved to derive the abundances. The latest experimental neutron capture cross sections are used (Bao & Käppeler 1987; Beer et al. 1992; Wisshak et al. 1996; Beer et al. 1997 and references therein). When not available, the cross sections are calculated within the statistical Hauser-Feshbach model based on a recent microscopic estimate of nuclear level densities (Goriely 1996), and nuclear structure properties (Aboussir et al. 1995). Note that the Hauser-Feshbach calculation is also used systematically to deduce from the laboratory neutron capture cross sections the stellar rates by allowing for the possible thermalization of low-lying states in the target nucleus. Nevertheless, the non-thermalization of the isomeric state in ^{85}Kr and ^{180}Ta, as well as the thermalization of ^{115}In and ^{176}Lu at temperatures exceeding $T_8 \simeq 2.5$[2] and $T_8 \simeq 3$, respectively, are introduced explicitly in the reaction network (Käppeler et al. 1989; Nemeth et al. 1994). The β-decay and electron capture rates in stellar conditions are taken from Takahashi & Yokoi (1987). The (n, α) and (γ, α) reactions on the Bi and Po isotopes (as well as ^{146}Sm) are also included.

For a given set of nuclear physics data, two degrees of freedom appear in the multi-event approach, namely the range of allowed thermodynamic conditions (such as the temperature, the neutron density and the irradiation time) and the set of nuclei the inversion method is supposed to fit (or equivalently the set of nuclei the s-process is expected to produce). With respect to the set of nuclei the s-process should produce in solar abundances, it seems obvious to consider in a first instance the s-only nuclei which cannot be produced by any other known nucleosynthetic process. In addition to the s-only isotopes, we also include ^{208}Pb (predicted to be produced by the strong s-process component) and ^{86}Kr (largely produced by the s-process). As regards the p-contribution to the solar abundance of the s-isotopes, no correction is taken into account in contrast to the usual practice in the classical approach. Our first aim is indeed to study the s-process efficiency to produce heavy nuclei independently from other nucleosynthetic processes. Moreover, some uncertainties still affect the astrophysical, as well as nuclear physics description of the p-process, and it remains difficult to determine safely the exact isotopic p-contribution to the solar system content. Note that we define in the present work a p-nucleus as a nucleus potentially synthesized by realistic p-process models, such as Rayet et al. (1995), and not as a proton-rich isotope bypassed or largely underproduced by the classical s-process (as usually done). The inability of the p-process to produce some nuclei like ^{152}Gd or ^{164}Er leads us to include them in the set of fitted nuclei. The resulting set made of 34 nuclei is called set I. The solar abundances, as well as the decomposition of the solar abundances into s- and r-components (as predicted by the classical model) are taken from Palme & Beer (1993). It should be noted that three specific elements still raise severe problems. These are the non-observable Kr, Xe and the ill-detectable Hg. Since neither meteoritic analyses, nor solar observations are available for these elements, their abundances are so far estimated through interpolation methods with neighbouring isotopes or more lately through theoretical systematics based on the classical s-process model. This latter determination is used in the compilation of Palme & Beer (1993) and is also considered here for comparison with the classical model.

As regards the astrophysical conditions in which the s-process events are allowed to take place, we first consider temperatures in the $2.5 \leq T_8 \leq 3.5$ range and neutron densities in the $7.5 \leq \log N_n[\mathrm{cm}^{-3}] \leq 9.0$ range, as suggested by classical calculations (Käppeler et al. 1989). Each of the 35 (T_8, N_n) events evenly distributed in grid steps of 0.25 in T_8 and $\log N_n[\mathrm{cm}^{-3}]$ are assumed to take place at 40 different irradiation times corresponding to 40 evenly distributed values of n_{cap} in the $5 \leq n_{cap} \leq 150$ range, where

$$n_{cap}(t) = \sum_{Z,A} A\ N_{Z,A}(t) - \sum_{Z,A} A\ N_{Z,A}(t = 0) \tag{6}$$

is the number of neutrons captured by the seed nuclei during the irradiation time t. An electron density $N_e = 10^{27}$ cm^{-3} characteristic of the AGB He-burning phase is taken to estimate the electron capture rates and assumed to be the same for all

[2] where T_8 is the temperature expressed in 10^8K

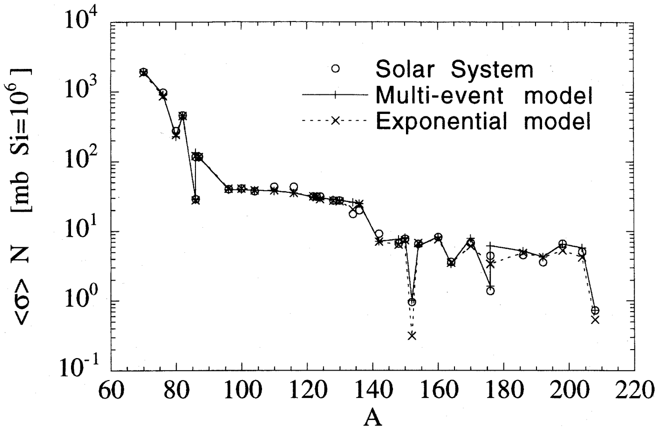

Fig. 1. Fit to the solar system (Palme & Beer 1993) abundances of the s-only isotopes obtained with the multi-event model. The abundance scale corresponds to $\langle\sigma\rangle N_{Z,A}$, where $\langle\sigma\rangle$ is the Maxwellian-averaged neutron capture cross section of (Z, A) at kT=30 keV. The predictions of the exponential model of Palme & Beer (1993) are given for comparison.

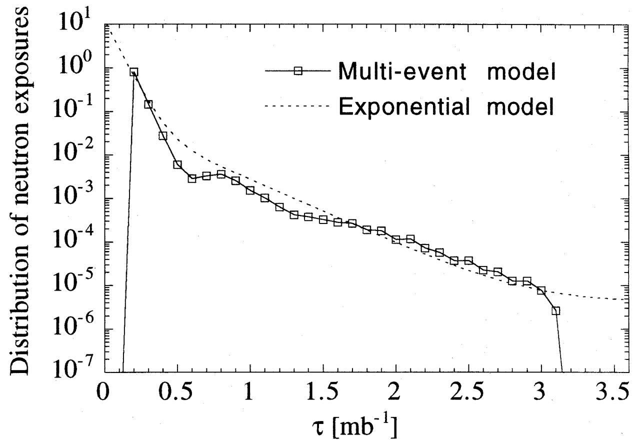

Fig. 2. Distribution of the neutron exposures τ characterizing the events involved in the abundance fit of Fig. 1. The analytical exposure distribution predicted by the exponential model of Beer et al. (1997) is also shown for comparison.

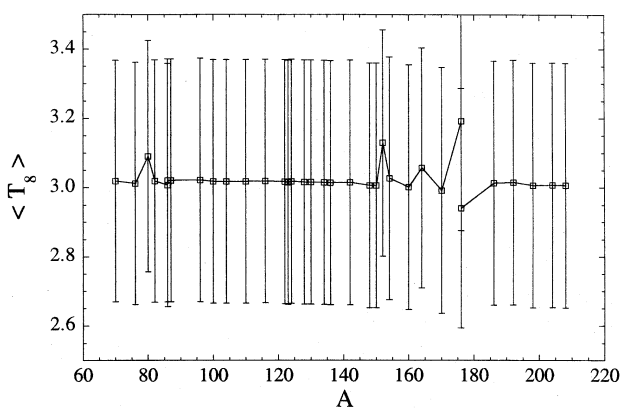

Fig. 3. Average temperature characterizing the s-process events responsible for the production of each element in Fig. 1. The error bars indicate the corresponding root mean square deviation as defined in the text.

the events. The resulting range of thermodynamic conditions is called range I.

Fig. 1 shows that an excellent fit to the solar system abundances of the s-only nuclei can be obtained with the multi-event model. The multi-event predictions are also in good agreement with the exponential model predictions of Palme & Beer (1993). In particular, both models show the same discrepancies with respect to the solar observations, for example a 20% underabundance of ^{116}Sn or ^{142}Nd, and an overabundance of elements like Ba or Pt. The thermodynamic conditions leading to the abundance distribution of Fig. 1 can be characterized by a distribution of neutron exposures as in the case of the exponential model. Such a distribution is shown in Fig. 2, and compared with the analytical form of Beer et al. (1997). Once again, both models are in qualitatively good agreement.

The statistical distribution of the s-process events responsible for the quasi-solar distribution in Fig. 1 can also provide an estimate of the most representative T and N_n required to produce each of the fitted isotopes. In particular, we can define for each fitted nucleus a characteristic average temperature

$$\langle T\rangle_{Z,A} = \sum_{T,N_n,t} \Phi(T,N_n,t)\ \frac{n(Z,A;T,N_n,t)}{N_{Z,A}}\ T \quad , \qquad (7)$$

and a mean square deviation from this average temperature

$$\omega_T^2 = \sum_{T,N_n,t} \Phi(T,N_n,t)\ \frac{n(Z,A;T,N_n,t)}{N_{Z,A}}\ [T-\langle T\rangle_{Z,A}]^2. \qquad (8)$$

Similar expressions define the characteristic neutron density responsible for the production of each fitted isotope. The average temperatures and neutron densities responsible for the calculated abundances of Fig. 1 are shown in Figs. 3 and 4. The error bars indicate the corresponding root mean square deviation ω given by Eq. 8. The s-abundances of Fig. 1 are seen to be relatively insensitive to the temperature and neutron density of the s-process events (ω_T and ω_{N_n} covering the entire interval of conditions included in range I). However, this is not the case for the abundances of ^{80}Kr, ^{152}Gd, ^{176}Lu and ^{176}Hf which are sensitively affected by the thermodynamic conditions (because of the existence of branching points).

In order to analyze the production of the non s-only isotopes, the residual abundances of the r-nuclei are calculated within the multi-event model and compared with the exponential model predictions in Fig. 5. Non-negligible deviations can be seen for $A \lesssim 90$ and $A \gtrsim 204$ nuclei. This result is to be expected, because of the difficulty of the exponential model reliably to determine the characteristic neutron exposures of the weak and strong components. As regards the solar r-abundances in the $90 \lesssim A \lesssim 204$ range, both models globally predict the same abundance distribution, although some small differences are observed for the s-dominant $A \simeq 120$, $A \simeq 140$ and $A \simeq 180$ nuclei.

The multi-event s-process developed here also predicts an s-contribution to the production of the p-nucleus ^{180}Ta, which appears to be produced exactly in solar quantity through the β-decay branching at ^{179}Hf (Takahashi & Yokoi 1987). It should be mentioned that the p-process is also able to produce ^{180}Ta in solar quantity as shown by Rayet et al. (1995), but that both results are bound to the crucial assumption that the isomeric state of ^{180}Ta is not in equilibrium with its ground state. If both states were in equilibrium in the considered stellar conditions, ^{180}Ta would not survive. On the other hand, the s-contribution to the other p-nuclei is completely negligible, reaching a maximum of a few percent of their solar values for the ^{115}Sn and ^{180}W isotopes.

The multi-event s-process model presented so far is in relatively good agreement with the exponential model predictions. This comparison mainly aimed at proving the reliability and predictive power of the multi-event approach. As soon as the thermodynamic conditions are fixed and the set of fitted nuclei is defined, the iterative method rapidly converges to a unique solution. Some deviations between the multi-event and exponential models are unavoidable since neither the nuclear physics input (especially the calculated neutron capture rates), nor the reaction network treatment (especially at the branching points) are identical. In particular, the s-process events are now taken at different T and N_n. Finally, the most fundamental difference between both models lies in the hypothesis of a predefined exposure distribution existing in the classical approach, but abolished in the multi-event method. It should be recalled that in the multi-event model the exposure distribution shown in Fig. 2 is a direct result of the calculation, while in the exponential model it represents an input quantity usually made of 6 (or more) free parameters.

3. Beyond the predictions of the classical model

The relatively good agreement between the classical multi-event models shown in the previous section is to be expected, since we restricted the s-events to thermodynamic conditions in a range predicted by the classical model, namely $T_8 \simeq 3$ and $N_n \simeq 10^8$ cm^{-3}. The results were also obtained by considering a set of fitted nuclei limited to the s-only nuclei. However, the iterative procedure detailed in Sect. 2 does not constrain the multi-event calculation to produce in solar quantity other isotopes than those included in the set of fitted nuclei. Therefore, the astrophysical events which do not significantly contribute to the production of s-only isotopes, but well to the production of other nuclei might not be picked up by the iterative procedure, so that the efficiency of the s-process to produce other nuclei than those included in set I has not been totally explored yet. To analyze to what extent a superposition of T- and N_n-dependent events could be responsible for the production of the s-only, as well as the s-dominant isotopes, we now extend the set of fitted nuclei by including the s-dominant isotopes in addition to the s-only. We define here a nucleus to be s-dominant if it is produced by more than 70% of its solar abundance by the multi-event

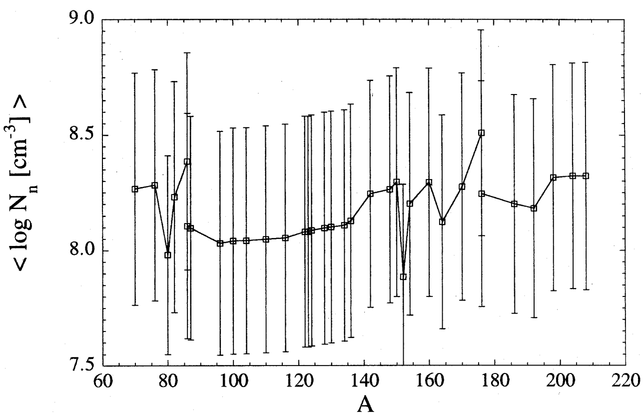

Fig. 4. Same as Fig. 3 for the $\langle \log N_n \rangle$ quantity.

calculation of Sect. 2. Note that we also regard here ^{115}Sn as an s-dominant nucleus. This new set is called set II.

To study the possibility of producing s-dominant isotopes, we consider in addition a larger range (called range II) of thermodynamic conditions, namely $1.5 \leq T_8 \leq 4.5$ and $7.0 \leq \log N_n[\mathrm{cm}^{-3}] \leq 11.0$. The 136 (T_8, N_n) events evenly distributed in grid steps of 0.5 in T_8 and 0.25 in $\log N_n[\mathrm{cm}^{-3}]$ are assumed once again to take place at 40 evenly distributed values of n_{cap} in the $5 \leq n_{cap} \leq 150$ range. Fig. 6 compares the solar abundances with the abundance distribution resulting from the best-fit superposition of such s-process events. The fit is more or less of the same quality as the one obtained in Fig. 1, although the introduction of s-dominant isotopes in set II slightly increases the discrepancies between the solar and calculated abundances of some s-only nuclei. On the contrary, the fit is better for some specific nuclei, such as ^{116}Sn, which is now produced at 90% of its solar abundance[3]. The only element overproduced (by a factor of 5) in such conditions is ^{180}Ta, because of the high temperatures included in range II. However, the possible establishment of an equilibrium between the isomeric and ground states at increasing temperatures would obviously destroy part of the produced ^{180}Ta.

The large range of thermodynamic conditions included in range II introduces a new degree of freedom in the s-process modelling in comparison with the classical exponential approach. The T- and N_n-dependent events are now clearly producing the s-only nuclei in solar quantity, as well as most of the s-dominant nuclei, including isotopes like ^{115}Sn. The distribution of neutron exposures responsible for the fit in Fig. 6 is shown in Fig. 7. It remains very similar to the previously obtained distribution of Fig. 2, and for this reason does not illustrate the new features introduced in this second multi-event calculation. Figs. 8 and 9 show the average temperatures and neutron densities that are required to produce each s-only and s-dominant isotope. In particular, it can be observed that the production of some specific elements is favoured by high temperatures and low neutron densities. This is the case of the s-only

[3] Note that no prior renormalization of the solar tin abundances has been considered in contrast to Beer et al. (1989) suggestion.

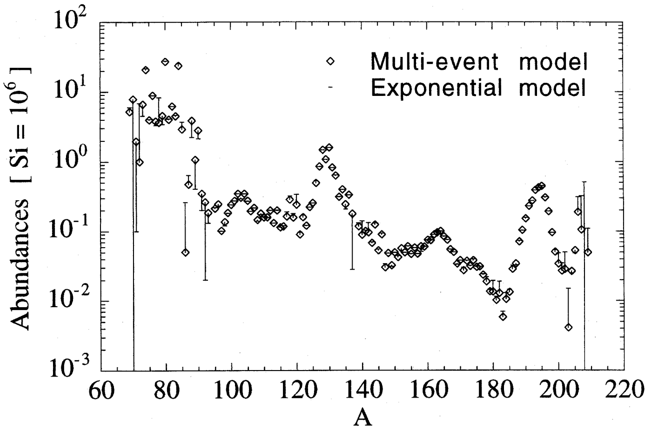

Fig. 5. Comparison of the solar system r-abundances predicted by the exponential model (Palme & Beer 1993) and the multi-event model. Both predictions are connected with a vertical line for the same isotope and normalized to the solar abundance of ^{130}Te.

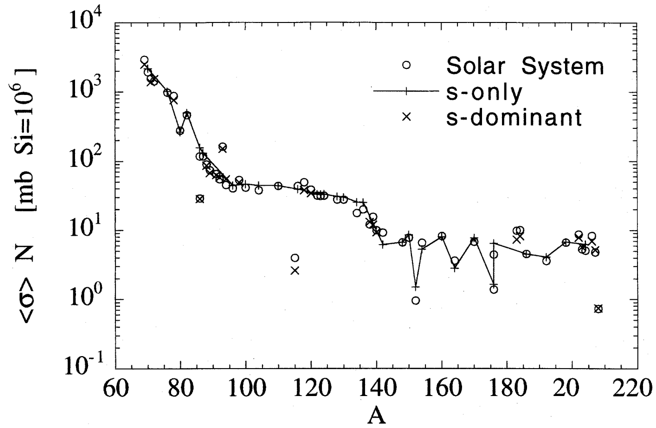

Fig. 6. Fit to the solar system abundances of the s-only and s-dominant nuclei (set II) obtained with the multi-event model when allowing the events to take place in the range II of thermodynamic conditions.

^{80}Kr, ^{152}Gd, ^{164}Er and ^{176}Lu, and the s-dominant ^{115}Sn, which is now produced in 70% of its solar abundance at $T_8 \gtrsim 3.5$ and $N_n \lesssim 5\ 10^7$ cm^{-3} (note that events with temperatures higher than $T_8 \simeq 4.5$ would largely produce ^{114}Sn and ^{115}Sn). On the other hand, most of the s-dominant nuclei of r-type can be produced by events characterized by neutron densities slightly higher than those responsible for the synthesis of the s-only isotopes.

The r-abundance distribution predicted by the multi-event s-process in the conditions II is displayed in Fig. 10, and compared with the predictions of the exponential model (Palme & Beer 1993). In this case, the residual solar abundance of a large number of r-nuclei appears to be reduced, especially in the $A \lesssim 90$ region and on both sides of the r-process peaks at $A \simeq 130$ and $A \simeq 195$. The Pb and Bi isotopes are also predicted to be potentially produced in a much greater proportion compared with the exponential model. The r-abundance pattern obtained with the multi-event model is also smoother than that of Palme & Beer (1993). However, it should be argued that the smooth character of the r-abundance curve is in no way a criterion justifying the quality of the model. The r-abundance distribution is governed by astrophysical conditions in which the r-process takes place, but also by nuclear physics properties of the neutron-rich nuclei produced. The latter, in particular, can be responsible for rapid abundance variations between neighbouring nuclei, and do not guarantee that the solar system r-abundance distribution should present a smooth behaviour with the atomic mass.

Finally, let us note that all the calculations have been performed at an average electron density $N_e = 10^{27}$ cm^{-3}, and that only the very sensitive abundances of ^{164}Er and ^{180}Ta are slightly affected by this assumption (a decrease of N_e by a factor of 5 would increase their calculated abundances by about 20%).

4. Uncertainties on the r-abundance distribution

As shown in the previous sections, the parametric s-process model plays an important role not only in trying to explain the nuclear mechanisms taking place during the s-process, but also in deriving the residual r-contribution to the solar system abundances. Many r-nuclei are dominantly produced by the r-process, and consequently their solar abundances are rather insensitive to the calculated s-contribution. Others can be significantly synthesized during the s-process, and their resulting residual solar abundances are this time highly dependent on all the astrophysical and nuclear physics uncertainties of the s-process modelling. The multi-event model described above emphasized the sensitivity of the solar r-abundance distribution to the astrophysical modelling of the s-process. In particular, allowing for a large range of thermodynamic conditions, the residual r-contribution to many s-dominant nuclei is drastically reduced. However, so far no uncertainties on the nuclear physics input of the model have been taken into account. These concern mainly the estimate of the neutron capture cross sections and β-decay rates. Although all the β-decay rates of relevance in the s-process modelling are known in terrestrial conditions, the contribution of thermally populated excited states, as well as atomic effects in the strongly ionised stellar plasma can drastically modify the laboratory value (Yokoi & Takahashi 1987). The calculated β-rates in stellar environments are subject to nuclear uncertainties which remain difficult to estimate. We therefore neglect this complication here.

The uncertainties on the experimental (n,γ) rates have been highly reduced recently reaching in some cases less than one or two percent. In these conditions, the imprecisions associated with the contribution of thermalized low-lying states in the target nucleus can become significant. It is for example the case of the (n,γ) reactions on the s-only isotopes ^{160}Dy, ^{164}Er, ^{170}Yb, ^{176}Hf and ^{187}Os, which have been experimentally determined within a few percent (Beer et al. 1992). The stellar cross sections are estimated to differ from the laboratory values by +10, 18, 16, 20 and 37%, respectively. These correction obviously tend

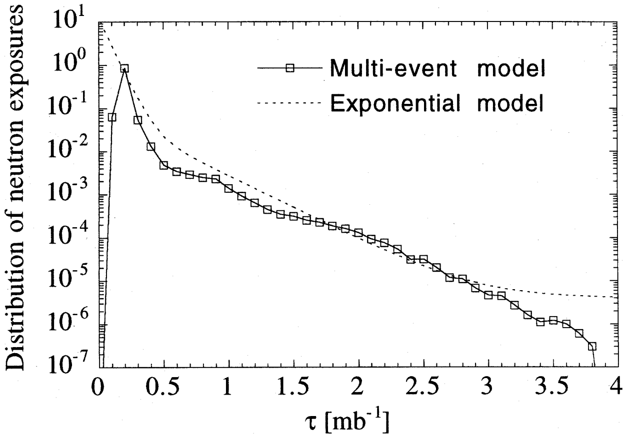

Fig. 7. Distribution of the neutron exposures τ characterizing the events involved in the abundance fit of Fig. 6. The analytical exposure distribution used by Beer et al. (1997) in the exponential model is also given for comparison.

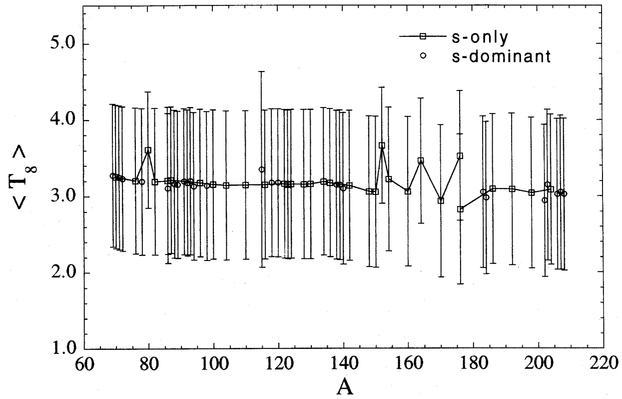

Fig. 8. Average temperatures characterizing the s-process events responsible for the production of each s-only and s-dominant isotopes in Fig. 6. The error bars indicate the corresponding root mean square deviation.

to decrease their s-abundances. Some 25 experimentally known (n,γ) reactions on s-dominant or r-dominant nuclides are also found to be affected within 10 to 40% by the specific conditions of stellar environments. These effects can modify some solar r-abundances. We reiterated the multi-event calculation of Sect. 2 (with range I and set I) making use of the laboratory (n,γ) cross sections and obtained a decrease of the predicted r-abundance of ^{119}Sn, ^{201}Hg and ^{203}Tl by 10–15% and an increase of the abundance of ^{169}Tm, ^{174}Yb, ^{177}Hf, ^{180}Hf, ^{182}W, ^{183}W and ^{184}W by 5 to 25%. Even though this thermalization factor only represents a correction of 10-20% on some reaction rates and residual r-abundances, it remains quite significant in comparison to the characteristic experimental errors prescribed in the literature.

In addition to such uncertainties plaguing the experimentally determined cross sections, theoretical estimates within the Hauser-Feshbach model are known to be reliable within a factor of 2 for nuclei close to the β-stability valley (Thielemann et al. 1986). Theoretical evaluations mainly concern unstable nuclei, and in particular the branching points which cannot be studied in the laboratory. In order to estimate the global impact of the nuclear uncertainties on top of the astrophysical ones already studied in Sect. 3, we consider now the multi-event calculations described in the previous sections when a random selection is made among the three possible values of the (n,γ) reaction rates, namely the quantity prescribed in the literature (or calculated), its upper and lower limit. The thermalization effects were systematically included as before, but not added to the experimental uncertainties at this stage. The same selected rates are used for all the events included in the superposition method. Such a procedure is performed 10 times with different selected rates in order to pick out a representative sampling. The resulting uncertainties on the calculated r-abundance distribution are illustrated in Fig. 11. In these conditions, it appears difficult to assign an accurate r-abundance to many $A \lesssim 100$ nuclei, as well as to ^{138}Ba, ^{140}Ce, ^{142}Ce, ^{182}W (or its long-lived progenitor ^{182}Hf), ^{202}Hg, ^{203}Tl, ^{207}Pb and ^{208}Pb. This feature is due to the almost total s-contribution to their solar system abundance, a small change in the astrophysical parameters or nuclear data leading to a large scatter in the residual r-contribution. The solar r-abundance of the $A \simeq 120$ nuclei also shows some possible variations, even though a renormalization of the solar Sn abundance (as suggested by Beer et al. 1989) would have a much stronger reduction effect (Wisshak et al. 1996). Since an overestimated meteoritic Sn abundance is not confirmed yet, this renormalization might not be justified at the present time. However, for unknown reasons the calculated ^{116}Sn abundance always remains 10% (Fig. 6) to 20% (Fig. 1) lower than the meteoritic value. If it was artificially increased to the solar value, the residual r-abundances of the ^{118}Sn, ^{119}Sn and ^{120}Sn would also be dramatically decreased. In these conditions, the uncertainties on the $A \simeq 120$ r-abundances (Fig. 11) are expected to be largely underestimated. The $A \simeq 180$ r-abundance dip is also rather pronounced in comparison with the predictions of the exponential model (see also Fig. 10). Such increased $A \simeq 120$ and $A \simeq 180$ pre-peak troughs in the solar system r-abundance curve–resulting from the nuclear and astrophysical uncertainties in the s-process modelling–can modify the interpretation given to the r-process origin of such nuclei, as already emphasized by Goriely (1997). Finally, the determination of the r-abundances in the Pb region remains problematic. The s-process is seen to be able to produce the Pb and Bi isotopes in large quantities. This result is obviously bound to the assumption that irradiations leading to values of n_{cap} as high as 150 (or $\tau \simeq 3.5$ mb^{-1}) are effectively found in astrophysical environments. Lower values would obviously give rise to a smaller s-contribution, and consequently to a larger r-component.

Finally, let us note that so far no uncertainties on the observed solar abundances have been taken into account in the determination of the residual r-abundances. Although most of the solar abundances are estimated within less than 10-20%, observational data are not available for Kr and Xe or show large

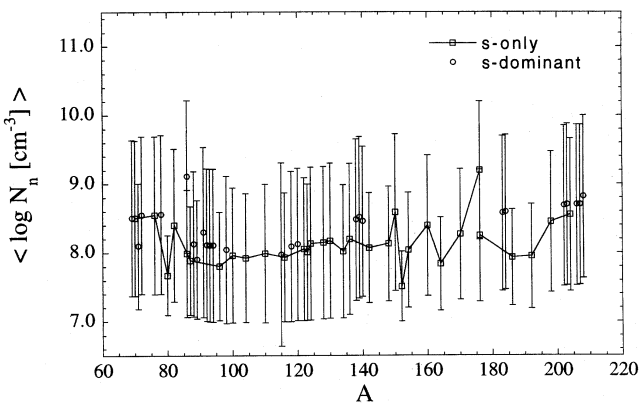

Fig. 9. Same as Fig. 8 for the average $\langle \log N_n \rangle$ quantity.

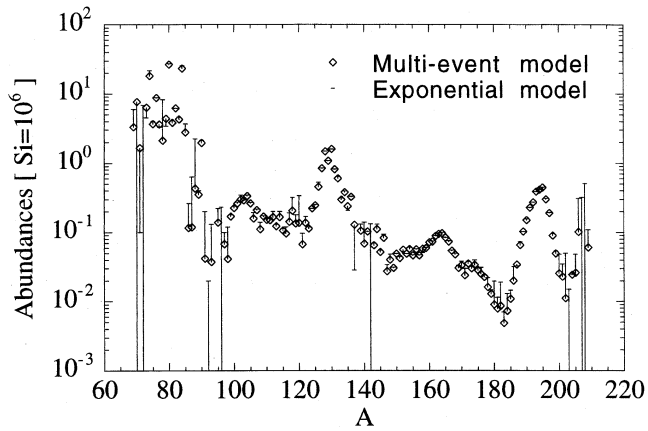

Fig. 10. Comparison of the solar system r-abundances predicted by the exponential model (Palme & Beer 1993) and the multi-event model (with range II and set II). Both predictions are connected with a vertical line for the same isotope and normalized to the solar abundance of ^{130}Te.

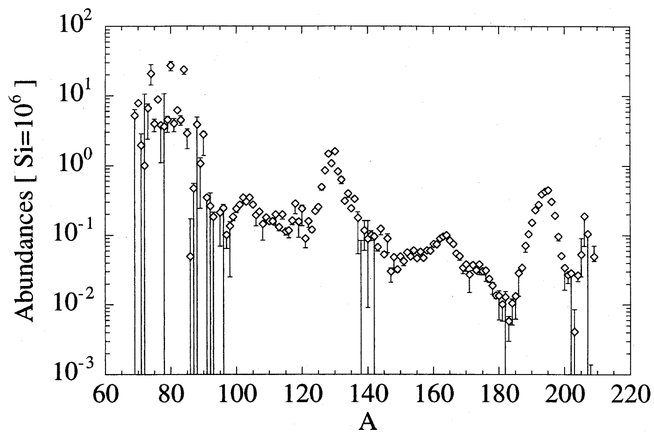

Fig. 11. The solar system r-abundances predicted by the multi-event model with range I and set I. The error bars illustrate the sensitivity of the calculated abundances to the astrophysical conditions (determined by a multi-event calculation with range II and set II) and to the nuclear physics uncertainties on the neutron capture rates.

scatters for Hg. The impact of such uncertainties on the solar r-abundance distribution remains to be studied in detail.

5. Conclusion

Even though much effort has been devoted in the past to improve the experimental determination of the various nuclear data relevant to the s-process nucleosynthesis, little has been done to go beyond the original classical model of Clayton et al. (1961), at least in the framework of the parametric approach. The exponential model is and will remain an excellent tool for a good understanding of the different nuclear mechanisms taking place during the s-process. However, even its most refined version is bound to the fundamental assumption of a predefined mathematical form of the neutron exposure distribution, and is not sensitive to the different thermodynamic conditions in which the s-process might develop. Unfortunately, the impact of the mathematically suitable exponential expression on the final s- and r-abundances have never been analyzed in detail. Since Ulrich (1973) linked the exponential form of the exposure distribution to the possible succession of neutron irradiations inside thermal pulses of AGB stars, the exponential model is quite often considered as the ultimate solution of the parametric s-process calculations.

An alternative method to the canonical model is developed in order to estimate the impact of the astrophysical modelling on the s- and r-abundance distribution. This approach has been successfully applied to parametric r-process calculations, and is shown to give also excellent predictions in the case of the s-process nucleosynthesis. It is based on an optimized superposition of s-process events at different temperatures and neutron densities which reproduces the solar system s-content as precisely as possible. Each event is assigned a statistical weight which corresponds to its relative contribution to the final abundance distribution. The various elements produced by the s-process are strongly correlated through their nuclear physics properties, so that the superposition of a large number of events does not represent an unphysical solution of purely mathematical origin. It is shown in Sect. 2 that considering thermodynamic conditions in the same range as predicted by the exponential model, very similar s-abundance predictions are obtained. In particular, the abundance of the s-only nuclei presents the same type of deviations from the solar value as in the classical approach, which can be interpreted as resulting from either nuclear physics or astrophysics deficiencies of the model. In order to study the impact of the astrophysical modelling, the multi-event calculations have been reiterated with an enlarged range of thermodynamic conditions. In this case, it is found that an even larger set of nuclei, including s-only and s-dominant nuclei, can be produced in solar quantity by the s-process. The consequence of such calculations on the solar system r-abundance distribution is relatively striking, especially if the remaining uncertainties on the neutron capture rates are included.

The new multi-event approach of the s-process developed in the present paper is therefore believed to be an interesting tool to study the s-process nucleosynthesis. It presents new features in comparison with the exponential model. In particular, it allows for the superposition of s-process events at different temperatures and neutron densities. More refinements of the multi-event model are obviously possible. After inclusion of uncertainties on β-decay rates and solar abundances, a final decomposition of solar abundances into s-, r- and p-components with their resulting error bars is to be provided. The effects associated with time-dependent profiles of the neutron density can also be studied, for example by the explicit introduction of neutron sources– $^{13}C\,(\alpha\,,n)\,^{16}O$ or $^{22}Ne\,(\alpha\,,n)\,^{25}Mg$ in a given range of temperatures and densities. Hopefully, the multi-event model of the s-process will help us to improve our understanding of the nucleosynthesis of the elements heavier than iron by enabling a more accurate decomposition of the solar abundances into the s-, r- and p-contributions, and by opening new perspectives in that direction.

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