Analysis of 26 barium stars^{★,★★,★★★}

II. Contributions of *s*-, *r*-, and *p*-processes in the production of heavy elements

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ABSTRACT

Context. Barium stars show enhanced abundances for the slow neutron capture (*s*-process) heavy elements, so they are suitable objects for studying *s*-process elements.

Aims. The aim of this work is to quantify the contributions of the *s*-, *r*-, and *p*-processes for the total abundance of heavy elements from abundances derived for a sample of 26 barium stars. The abundance ratios between these processes and neutron exposures were studied.

Methods. The abundances of the sample stars were compared to those of normal stars, thus identifying the fraction relative to the main component of the *s*-process.

Results. The fittings of the σN curves (neutron-capture cross-section times abundance, plotted against atomic mass number) for the sample stars suggest that the material from the companion asymptotic giant branch star had approximately the solar isotopic composition as concerns fractions of abundances relative to the *s*-process main component. The abundance ratios of heavy elements, *hs*, *ls*, and *s* and the computed neutron exposure are similar to those of post-AGB stars. For some sample stars, an exponential neutron exposure fits the observed data well, whereas a single neutron exposure provides a better fit for others.

Conclusions. The comparison of barium and AGB stars supports the hypothesis of binarity for the barium star formation. Abundances of *r*-elements that are part of the *s*-process path in barium stars are usually higher than those in normal stars, so barium stars also seemed to be enriched in *r*-elements, although to a lower degree than *s*-elements. No dependence on luminosity classes was found in the abundance-ratio behaviour among the dwarfs and giants of the sample of barium stars.

Key words. nuclear reactions, nucleosynthesis, abundances – stars: abundances

1. Introduction

Nucleosynthesis of elements has benefitted from the dispute between George Gamow and Fred Hoyle in explaining how the known chemical elements were formed (Alpher et al. 1948; Hoyle 1946). Since then, our knowledge of primordial and stellar nucleosynthesis has greatly improved. Burbidge et al. (1957, B²FH) based their work on solar abundances and defined eight nucleosynthetic processes in stars that would be responsible for the formation of the chemical elements. Wallerstein et al. (1997) present a review of B²FH, including recent and accurate experimental results and observations, where they show that some processes defined by B²FH have been confirmed, others redefined, and new processes not known by B²FH have been included in the list.

Three of the eight processes defined by B²FH are the focus of the present work: the *s*-, *r*-, and *p*-processes. We present the abundance ratios between these processes and abundance distribution for a number of heavy elements in a sample of barium stars. The abundance determination for the sample stars was described in Allen & Barbuy (2006, Paper I hereafter).

The abundance ratios for the best representatives of *s*- and *r*-processes provide clues to the formation and evolution of the Galaxy, since each of them is related to a different formation site, including stars of different characteristics and evolutionary stages. As an example, Mashonkina et al. (2003) estimate the timescale for the thick disk and halo formation based on the abundance ratios of [Eu/Ba], [Mg/Fe], and [Eu/Fe] and on the calculations of chemical evolution by Travaglio et al. (1999). Burris et al. (2000) conclude from abundances of metal-poor giant stars that the contributions of *s*-processes can be seen at metallicities as low as [Fe/H] = −2.75, and they are present in stars of [Fe/H] > −2.3, indicating that the *s*-process acts at lower metallicities than predicted by previous works.

Considering the scenario of barium star formation through enriched material transfer from a companion AGB star, it is worth comparing abundances of AGBs and barium stars. Such study can provide clues to the enrichment of barium stars in heavy elements, given that they should conserve the surface characteristics of AGB stars.

This work intends to address the following questions:

1. What are the *s*-element abundances of normal stars?

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** Full Tables 2 and 6 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via

<http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/454/917>

*** Figures 18 to 21 and Tables 4, 5, 7 and 8 are only available in electronic form at <http://www.edpsciences.org>

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2. Considering the hypothesis of the transfer of material enriched in carbon and s -elements from a more evolved companion for barium star formation, is it possible to estimate from observed abundances which proportions these elements are received?

3. What is the isotopic composition of the material received? Is it possible to consider the solar system mix?

4. How is the σN curve behaviour for barium stars?

5. What kind of neutron exposures were involved in the nucleosynthesis of the transferred material?

This paper is organised as follows. Section 2 is a brief description of atmospheric parameters and of the abundance determination carried out in Paper I; Sect. 3 briefly explains the s -, r -, and p -processes; Sect. 4 shows the contributions of s -, r -, and p -processes in normal stars compared to barium stars; Sect. 5 evaluates two kinds of neutron exposures and shows ratios involving s , hs , and ls . In Sect. 6 conclusions are drawn.

2. Atmospheric parameters and abundance calculations

The observations, atmospheric parameters, and abundance calculations have already been described in detail in Paper I. Here, we outline only the more important steps.

Photometric data were taken in several runs at the ZEISS 60 cm telescope at the LNA (*Laboratório Nacional de Astrofísica*) and from the literature. Optical spectra were obtained at the 1.52 m telescope at ESO, La Silla, using the Fiber Fed Extended Range Optical Spectrograph (FEROS) (Kaufer et al. 2000). A set of atmospheric parameters (temperature, surface gravity, metallicities, and microturbulent velocity) was obtained in an iterative way.

Photospheric 1D models were extracted from the NMARCS grid (Plez et al. 1992) for gravities $\log g < 3.3$, and from Edvardsson et al. (1993) for less evolved stars, with $\log g \geq 3.3$. The LTE abundance analysis and the spectrum synthesis calculations were performed using the codes by Spite (1967, and subsequent improvements in the past thirty years), described in Cayrel et al. (1991) and Barbuy et al. (2003). Line lists and respective parameters are given in Paper I.

3. s -, r -, and p -processes

Several important references describe the s -, r -, and p -processes in detail: B²FH, Meyer (1994), and Wallerstein et al. (1997) for a more general description; Käppeler et al. (1989), Busso et al. (1999), Lugaro et al. (2003), Lamb et al. (1977), and Raiteri et al. (1993) for the s -process; Woosley & Hoffman (1992), Wanajo et al. (2003), and Argast et al. (2004) for the r -process; Rayet et al. (1995) and Goriely et al. (2005) for the p -process, among others.

Typical s -elements are mainly produced by the s -process, but a smaller fraction of their abundance is due to the r -process. Analogously, the major production of r -elements is due to the r -process with a smaller contribution from s -process. Beyond these main processes, the p -process contributes with a small fraction of heavy elements production, as shown in Fig. 1 of Meyer (1994).

In the s -process, neutrons are captured by seed nuclei, which are the iron-peak elements, on a long timescale relative to β decay, denominated “ s ” (*slow*) by B²FH. This process has been subdivided into three components according to the site and the nucleosynthetic products: main, weak, and strong.

The s -process main component is responsible for many nuclides in the range of atomic mass $63 \leq A \leq 209$. Abundance peaks can be observed near $A = 90$, 138, and 208. In the classical analysis (Käppeler et al. 1989) the element formation through the s -process occurs in a chain, starting with the seed nucleus ^{56}Fe . Following this analysis, it is possible to obtain an expression for the σN , where σ is the neutron capture cross-section and N the abundances due to the s -process only for each nuclide. This expression involves the mean distribution of neutron exposure τ_0 , the abundance fraction of ^{56}Fe required as seed to s -process G , and the solar abundance of ^{56}Fe $N_{56}^{\odot}$,

$$\sigma_k N_k = \frac{GN_{56}^{\odot}}{\tau_0} \prod_{i=56}^k \left(1 + \frac{1}{\tau_0 \sigma_i}\right)^{-1} \quad (1)$$

where k is the atomic mass number.

For the solar system, the corresponding curve from classical analysis represents the abundances of s -process nuclei for $A > 90$ very well. For lighter nuclides, this line appears below the empirical data, suggesting another form of synthesis of s -process nuclides in stars, with the first one called the main component and the second, the weak component. The good agreement between the classical model and the observed data of this curve for the solar system represents an interesting characteristic of the s -process, taking the large number of nuclides between Fe and Bi into account.

The s -process main component is believed to occur during the thermal pulses – asymptotic giant branch (TP-AGB) phase of intermediate or low mass stars. In this phase, the star consists of an inert CO core and the He and H burning shells. The region between the two shells is the so-called He intershell, where neutrons released by the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction during the interpulse period and by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction during the convective thermal pulse are captured by iron-peak nuclei.

The s -process weak component is responsible for part of the abundance of nuclides with atomic mass in the range $23 \leq A \leq 90$ (Lamb et al. 1977; Raiteri et al. 1993). The nucleosynthetic site is probably the core helium burning of stars with masses $\geq 10 M_{\odot}$, where temperature is high enough for the main neutron source to be the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction. Neutron density is low compared to the main component.

The s -process strong component was postulated in order to provide part of the Pb abundance (see Käppeler et al. 1989). However, according to Busso et al. (1999), it is possible to explain the ^{208}Pb galactic abundance without it.

The r -process occurs in an environment that is rich in neutrons, where several of them are captured by nuclides on a short timescale compared to β decay, and for this reason, this process was denominated as “ r ” (*rapid*) by B²FH. In this case, the neutron density is higher than for the s -process. Sites that favour such high neutron density are the final stages of massive stars such as core collapse supernovae (SN II, Ib, Ic) (Wasserburg & Qian 2000; Qian 2000, 2001) or those involving neutron stars (Woosley & Hoffman 1992; Meyer 1994; Freiburghaus et al. 1999; Rosswog et al. 1999, 2000).

The fact that r -elements are observed in very metal-poor stars suggests that these elements were produced in supernovae events resulting from the evolution of the first massive stars in the Galaxy (Snedden et al. 1996, 2003; Hill et al. 2002; Cowan et al. 2002; Ishimaru et al. 2004; Honda et al. 2004). Despite the promise of these scenarios, some difficulties have been found; for instance, Wanajo et al. (2001) show that to reproduce a solar abundance of r -elements, proto neutron stars must have $2 M_{\odot}$ and 10 km of radius, characteristics not observed so far.

Fig. 1. $\log \epsilon(X)$ vs. atmospheric parameters ($[\text{Fe}/\text{H}]$, T_{eff} , $\log g$) for normal stars. Symbols indicate different references: open squares: Gratton & Sneden (1994); open circles: Burris et al. (2000); open triangles: Tomkin & Lambert (1999); filled triangles: Jehin et al. (1999); crosses: Edvardsson et al. (1993) and Woolf et al. (1995); filled squares: Smith et al. (2000); open pentagon Mashonkina & Gehren (2001). Uncertainties were taken from the respective references; otherwise, the values of ± 0.1 for $[\text{Fe}/\text{H}]$ and ± 0.05 for $\log \epsilon(X)$ were used. These values were also attributed to Jehin et al. (1999), given that their uncertainties seem underestimated.

The p -process forms nuclei rich in protons. Some s - or r -nuclei, where s - and r -processes were blocked, capture protons with γ emission (p, γ). The p -nuclei may also be synthesised by photodesintegration (γ, n) of a pre-existing nucleus rich in neutrons (especially s -nuclei), followed by possible cascades of (γ, p) and/or (γ, α) reactions.

The p -process site should be rich in hydrogen, with proton density $\geq 10^2 \text{ g/cm}^3$, at temperatures of $T = 2-3 \times 10^9 \text{ K}$. This process site is most likely related to SN II, according to Arnould (1976), Woosley & Howard (1978, and references therein), Arnould et al. (1992), and Rayet et al. (1993) or the explosion of a moderately massive white dwarf due to the accretion of He-rich matter (Goriely et al. 2005, and references therein). A quantitative study of the p -process is presented in Rayet et al. (1995).

4. Abundance distribution for s -, r -, and p -processes

4.1. s -, r -, and p -processes in normal stars

One way to quantify the enrichment of s -elements in barium stars is to compare their abundances with normal stars. For the s -, r -, and p -elements, the total abundance for the element can

be described by the sum of the abundances corresponding to the three nucleosynthetic processes, taking into account all contributing isotopes “ i ”:

$$\epsilon(X) = \sum_i \epsilon_s^i + \sum_i \epsilon_r^i + \sum_i \epsilon_p^i.$$

In order to quantify the contribution of each process to the total abundance of several heavy elements in normal stars, an extensive set of stars from the literature was used. Peculiar stars were withdrawn from these samples in order to obtain more reliable results. Figures 1 and 2 show the behaviour of the abundances ($\log \epsilon(X)$) of several heavy elements as a function of atmospheric parameters (T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$). It is clear from these figures that $\log \epsilon(X)$ vs. $[\text{Fe}/\text{H}]$ is a linear correlation ($\log \epsilon_{\text{nor}}(X) = A[\text{Fe}/\text{H}] + B$), while $\log \epsilon(X)$ vs. T_{eff} and $\log g$ are not. Results of least-square fittings for $\log \epsilon(X)$ vs. $[\text{Fe}/\text{H}]$ are shown in Table 1.

From $\log \epsilon(X)$ vs. $[\text{Fe}/\text{H}]$ fittings, it is possible to determine the total abundance of a certain element in a normal star of a given metallicity. The first line of Table 2 shows $\log \epsilon_{\text{nor}}(X)$ obtained directly from fittings for normal stars with metallicities corresponding to the barium star, indicated in the

Fig. 2. Same as Fig. 1 for other elements.

Table 1. Results obtained from least-square fitting of $\log \epsilon_{\text{nor}}(X)$ vs. $[\text{Fe}/\text{H}]$ of normal stars: $\log \epsilon_{\text{nor}}(X) = A[\text{Fe}/\text{H}] + B$; “cov” is the covariance between A and B ; “d.o.f.” is the number of degrees of freedom.

X	A	B	χ^2_{red}	cov (10^{-4})	d.o.f.
Sr	1.013 ± 0.024	2.908 ± 0.021	1.197	4.18	82
Y	1.112 ± 0.016	2.239 ± 0.013	1.002	1.58	160
Zr	0.939 ± 0.019	2.625 ± 0.015	1.385	2.06	66
Mo	0.970 ± 0.212	1.895 ± 0.342	1.472	715.2	7
Ba	0.992 ± 0.014	2.095 ± 0.011	1.978	1.07	214
La	1.190 ± 0.031	1.377 ± 0.039	4.891	10.91	47
Ce	1.009 ± 0.047	1.500 ± 0.047	0.923	20.20	34
Pr	0.867 ± 0.048	0.748 ± 0.050	1.180	19.99	13
Nd	0.950 ± 0.019	1.460 ± 0.017	1.635	2.46	99
Sm	0.811 ± 0.045	0.951 ± 0.045	1.407	18.76	34
Eu	0.783 ± 0.019	0.581 ± 0.015	1.263	2.20	165
Dy	0.840 ± 0.031	1.080 ± 0.044	4.312	11.70	22

header. Data for molybdenum are rarely available in the literature in the same metallicity range as the present sample, and for this reason the least-square fitting was done using data derived for the globular cluster ω Centauri by Smith et al. (2000), with results shown in Col. 2 of Table 3. In order to verify the reliability of these results, Mo abundances were calculated through $\log \epsilon_{\text{nor}}(\text{Mo}) = \log \epsilon_{\odot}(\text{Mo}) + [\text{Fe}/\text{H}] + [\text{Mo}/\text{Fe}]$, considering $[\text{Mo}/\text{Fe}] = 0$, and results are shown in Col. 3 of Table 3.

The agreement between results from these two columns means that, according to the fitting, $[\text{Mo}/\text{Fe}] \approx 0$ at metallicities near solar. Data for Gd and Pb are also rare in the literature for normal stars in the range of metallicities of the present sample. For this reason, $\log \epsilon_{\text{nor}}(\text{Gd})$ and $\log \epsilon_{\text{nor}}(\text{Pb})$ were determined by considering $[\text{Gd}/\text{Fe}] = [\text{Pb}/\text{Fe}] = 0 \pm 0.05$, near the solar metallicity. Gadolinium is expected to behave like dysprosium given that both are produced mainly through the r -process in almost the same proportions (Arlandini et al. 1999). Columns 4 and 5 of Table 3 show $\log \epsilon_{\text{nor}}(\text{Dy})$ values determined by least-square fitting and by summing the star metallicity to the solar value, and Cols. 6 and 7 show $\log \epsilon_{\text{nor}}(\text{Gd})$ and $\log \epsilon_{\text{nor}}(\text{Pb})$.

Considering that the total abundance of an element is the sum of the contributions of s -, r -, and p -processes, one can write:

$$\epsilon_{\text{nor}}(X) = \epsilon_{\text{s}}(X)_{\text{nor}} + \epsilon_{\text{sw}}(X)_{\text{nor}} + \epsilon_{\text{st}}(X)_{\text{nor}} + \epsilon_{\text{r}}(X)_{\text{nor}} + \epsilon_{\text{p}}(X)_{\text{nor}} \quad (2)$$

where $\epsilon_{\text{s}}(X)_{\text{nor}}$, $\epsilon_{\text{sw}}(X)_{\text{nor}}$, and $\epsilon_{\text{st}}(X)_{\text{nor}}$ are, respectively, the contributions of main, weak, and strong components of s -process and $\epsilon_{\text{r}}(X)_{\text{nor}}$ and $\epsilon_{\text{p}}(X)_{\text{nor}}$ the r - and p -processes. Arlandini et al. (1999) provide detailed information about the s -process main component and r -process. According to Lugaro et al. (2003), around 50% of ^{86}Sr and ^{87}Sr in the solar system results from the s -process weak component; hence, the missing abundance that completes the total abundance in Arlandini et al. (1999) for these Sr isotopes was attributed to the weak component. Around 45% of ^{96}Zr abundance

Table 2. Abundances obtained from least-square fittings for normal stars with metallicities corresponding to our sample of barium stars. Each set of five lines corresponds to the normal star with the same metallicity as the barium star indicated in parenthesis. $\log \epsilon(X)$ corresponds to $\log \epsilon_{\text{nor}}(X)$ and $\epsilon_{s,r,p}(X)$ corresponds to $\epsilon_{s,r,p}(X)_{\text{nor}}$ from Eq. (2). $\epsilon_0(X)$ is from Eq. (6). The full table is only available in electronic form at the CDS.

	Sr	Y	Zr	Mo	Ba	La	Ce ...
	[Fe/H] = -0.06 (HD 749)						
$\log \epsilon(X)$	2.85 ± 0.18	2.17 ± 0.20	2.57 ± 0.17	1.84 ± 0.37	2.04 ± 0.18	1.31 ± 0.22	$1.44 \pm 0.19 \dots$
$\epsilon_s(X)$	594.4 ± 51.0	136.8 ± 63.2	307.4 ± 20.1	34.1 ± 29.2	87.7 ± 36.1	12.5 ± 6.3	$20.9 \pm 9.0 \dots$
$\epsilon_r(X)$	0.00 ± 0.00	11.9 ± 5.5	58.9 ± 23.0	17.9 ± 15.4	20.6 ± 8.5	7.7 ± 3.8	$6.5 \pm 2.8 \dots$
$\epsilon_p(X)$	109.0 ± 46.0	0.0 ± 0.0	4.1 ± 1.6	16.7 ± 14.3	0.2 ± 0.1	0.0 ± 0.0	$0.1 \pm 0.0 \dots$
$\epsilon_0(X)$	109.0 ± 46.0	11.9 ± 5.5	63.0 ± 24.6	34.6 ± 29.7	20.8 ± 8.6	7.7 ± 3.8	$6.6 \pm 2.8 \dots$
.	.	.	.	.	.	.	...
.	.	.	.	.	.	.	...

Table 3. Abundances [$\log \epsilon_{\text{nor}}(X)$] of Mo, Dy, Gd, and Pb for normal stars. Symbol “*” indicates that the column was obtained from a least-square fitting.

star	Mo*	Mo	Dy*	Dy	Gd	Pb
HD 749	1.84	1.86	1.03	1.14	1.06 ± 0.19	1.89 ± 0.20
HR 107	1.55	1.56	0.78	0.84	0.76 ± 0.07	1.59 ± 0.10
HD 5424	1.36	1.37	0.62	0.65	0.57 ± 0.19	1.40 ± 0.20
HD 8270	1.49	1.50	0.73	0.78	0.70 ± 0.07	1.53 ± 0.10
HD 12392	1.78	1.80	0.98	1.08	1.00 ± 0.19	1.83 ± 0.20
HD 13551	1.47	1.48	0.71	0.76	0.68 ± 0.07	1.51 ± 0.10
HD 22589	1.63	1.65	0.85	0.93	0.85 ± 0.07	1.68 ± 0.10
HD 27271	1.81	1.83	1.00	1.11	1.03 ± 0.19	1.86 ± 0.20
HD 48565	1.29	1.30	0.56	0.58	0.50 ± 0.07	1.33 ± 0.10
HD 76225	1.59	1.61	0.82	0.89	0.81 ± 0.07	1.64 ± 0.10
HD 87080	1.47	1.48	0.71	0.76	0.68 ± 0.07	1.51 ± 0.10
HD 89948	1.60	1.62	0.83	0.90	0.82 ± 0.07	1.65 ± 0.10
HD 92545	1.78	1.80	0.98	1.08	1.00 ± 0.07	1.83 ± 0.10
HD 106191	1.61	1.63	0.84	0.91	0.83 ± 0.07	1.66 ± 0.10
HD 107574	1.36	1.37	0.62	0.65	0.57 ± 0.07	1.40 ± 0.10
HD 116869	1.58	1.60	0.81	0.88	0.80 ± 0.19	1.63 ± 0.20
HD 123396	0.74	0.73	0.08	0.01	-0.07 ± 0.19	0.76 ± 0.20
HD 123585	1.43	1.44	0.68	0.72	0.64 ± 0.07	1.47 ± 0.10
HD 147609	1.46	1.47	0.70	0.75	0.67 ± 0.07	1.50 ± 0.10
HD 150862	1.80	1.82	1.00	1.10	1.02 ± 0.07	1.85 ± 0.10
HD 188985	1.60	1.62	0.83	0.90	0.82 ± 0.07	1.65 ± 0.10
HD 210709	1.86	1.88	1.05	1.16	1.08 ± 0.19	1.91 ± 0.20
HD 210910	1.54	1.55	0.77	0.83	0.75 ± 0.19	1.58 ± 0.20
HD 222349	1.28	1.29	0.55	0.57	0.49 ± 0.07	1.32 ± 0.10
BD+18 5215	1.38	1.39	0.63	0.67	0.59 ± 0.07	1.42 ± 0.10
HD 223938	1.56	1.57	0.79	0.85	0.77 ± 0.19	1.60 ± 0.20

missing in Arlandini et al. was also attributed to the s -process weak component. A few nuclides are formed mainly through the p -process, and they are not in Arlandini et al. (1999), such as ^{138}La , $^{136,138}\text{Ce}$, ^{144}Sm , $^{156,158}\text{Dy}$ (Rayet et al. 1995). The total solar abundances adopted by Arlandini et al. (1999) were those from Anders & Grevesse (1989), and it is possible to deduce the abundance of each p-only nuclide. For nuclides that are partially p, the difference between the total abundance and the sum of s- and r-fractions from Arlandini et al. (1999) was computed, such as for ^{94}Mo , ^{142}Nd , $^{152,154}\text{Gd}$, and ^{160}Dy . The isotopes $^{142,150}\text{Nd}$ are missing in Rayet et al. (1995), however they were considered p-partial or p-only according to the missing of part or all in Arlandini et al. Once all abundance percentages were identified, it was possible to derive the abundance fractions of each process relative to the total abundance of an element, shown in Cols. 3–7 of Table 4. The total abundance of

each element, taking into account its n isotopes for normal stars, can be written as

$$\epsilon_{\text{nor}}(X) = \left(\sum_i^n g_s^i + \sum_i^n g_{\text{sw}}^i + \sum_i^n g_{\text{st}}^i + \sum_i^n g_r^i + \sum_i^n g_p^i \right) \epsilon_{\text{nor}}(X) \quad (3)$$

where g_s^i , g_{sw}^i , g_{st}^i , g_r^i , and g_p^i are fractions of total abundance relative to the three s -process components, r - and p -processes, respectively, for each isotope “ i ”.

The uncertainty on $\log \epsilon_{\text{nor}}(X)$ is calculated with

$$\sigma_{\log \epsilon_{\text{nor}}(X)} = \left([\text{Fe}/\text{H}]^2 \sigma_A^2 + A^2 \sigma_{[\text{Fe}/\text{H}]}^2 + \sigma_B^2 + 2[\text{Fe}/\text{H}] \text{cov}(A, B) \right)^{0.5} \quad (4)$$

where $\text{cov}(A, B)$ is the covariance between A and B . The uncertainties on abundances relative to s -, r -, and p -processes are given by

$$\sigma_{\epsilon_j} = \epsilon_j \sigma_{\log \epsilon_{\text{nor}}(X)} \ln 10 \quad (5)$$

where “ j ” corresponds to the process involved (s: main, sw: weak, st: strong, components of s -process, r: r -process, or p: p -process).

Finally, the sum of abundances from other processes except the s -process main component was computed, i.e., the sum of fractions sw, st, r, and p, indicated by subscript “o” and its uncertainty are

$$\epsilon_o(X) = \left(\sum_i^n g_{\text{sw}}^i + \sum_i^n g_{\text{st}}^i + \sum_i^n g_r^i + \sum_i^n g_p^i \right) \epsilon_{\text{nor}}(X) \quad (6)$$

and

$$\sigma_{\epsilon_o(X)} = \epsilon_o(X) \sigma_{\log \epsilon_{\text{nor}}(X)} \ln 10. \quad (7)$$

Lines 2, 3, and 4 of Table 2 show abundances due to the s -process main component, r - and p -process, respectively, and line 5 shows $\epsilon_0(X)$.

4.2. The s -, r -, and p -processes in barium stars

Barium stars are enriched in neutron capture elements, and the excess of heavy elements can be deduced from a comparison with normal stars of similar metallicities. If the excess is due to the s -process main component, one can consider that abundances due to other processes (r , p , and other s -process components) are similar to those of normal stars with the same metallicity, i.e., $\epsilon_r(X) = \epsilon_r(X)_{\text{nor}}$, $\epsilon_p(X) = \epsilon_p(X)_{\text{nor}}$, $\epsilon_{\text{sw}}(X) = \epsilon_{\text{sw}}(X)_{\text{nor}}$,

Table 6. Results relative to the s -, r -, and p -processes for barium stars. $\epsilon_s(X)$, $\epsilon_{sw}(X)$, and $\epsilon_{st}(X)$: abundance fractions of s -process main, weak, and strong components; $\epsilon_r(X)$ and $\epsilon_p(X)$: abundance fractions of r - and p -processes; σN and $\sigma N(\text{Si})$: cross-section times abundance fraction corresponding to the s -process main component taking the overabundance of barium stars into account on the usual scale and Si scale; $\epsilon_s(X)_{\text{nor}}$: abundance fractions of the s -process main component for normal stars; diff: $\epsilon_s(X) - \epsilon_s(X)_{\text{nor}}$; σN_{gs} : cross-section times abundance fraction corresponding to the s -process main component without the overabundance of barium stars. The full table is only available in electronic form at the CDS.

A	el	$\epsilon_s(X)$	$\sigma_{\epsilon_s(X)}$	$\epsilon_{sw}(X)$	$\epsilon_{st}(X)$	$\epsilon_r(X)$	$\sigma_{\epsilon_r(X)}$	$\epsilon_p(X)$	$\sigma_{\epsilon_p(X)}$	σN	$\sigma_{\sigma N}$	$\epsilon_s(X)_{\text{nor}}$	$\sigma_{\epsilon_s(X)_{\text{nor}}}$	diff	$\sigma N(\text{Si})$	$\sigma_{\sigma N(\text{Si})}$	σN_{gs}
HD 749																	
84	Sr	...	...	...	...	...	...	4.2	1.8	...	...	...	...	...	...	...	...
86	Sr	208.7	118.7	37 ± 16	...	...	...	...	...	13357	7621	32.80	13.85	175.89	0.373E+03	0.213E+03	0.324E+03
87	Sr	145.5	82.7	23 ± 9	...	...	...	...	...	13387	7635	22.87	9.66	122.64	0.374E+03	0.213E+03	0.325E+03
88	Sr	3427.1	1948.9	45 ± 19	...	...	...	...	...	21248	12127	538.70	227.51	2888.40	0.593E+03	0.339E+03	0.516E+03
89	Y	2260.2	994.0	...	...	11.9	5.5	...	...	42944	18935	136.79	63.17	2123.40	0.120E+04	0.529E+03	0.111E+04
90	Zr	4297.9	1992.2	...	...	53.0	20.7	...	...	90255	42711	137.63	53.75	4160.22	0.252E+04	0.119E+04	0.211E+04
91	Zr	1247.0	578.0	...	...	1.8	0.7	...	...	74821	36089	39.93	15.60	1207.09	0.209E+04	0.101E+04	0.175E+04
92	Zr	1854.7	859.7	...	...	4.2	1.6	...	...	61205	29325	59.39	23.20	1795.30	0.171E+04	0.820E+03	0.143E+04
94	Zr	2021.7	937.2	...	...	...	...	...	...	52565	24450	64.74	25.29	1956.98	0.147E+04	0.683E+03	0.123E+04
96	Zr	178.5	82.7	4.1 ± 1.6	...	...	...	...	...	1910	890	5.72	2.23	172.75	0.533E+02	0.249E+02	0.445E+02

and $\epsilon_{st}(X) = \epsilon_{st}(X)_{\text{nor}}$. In this way, $\epsilon_o(X)$ (line 5 of Table 2) was attributed to each barium star as the fraction corresponding to processes other than the s -process main component. The logarithmic mean abundances ($\log \epsilon(X)$) shown in Tables 16 and 17 of Paper I were used to compute the fractions corresponding to each process.

The abundance fraction corresponding to the s -process main component of an element is

$$\epsilon_s(X) = \epsilon(X) - \epsilon_o(X). \quad (8)$$

Table 5 shows abundances relative to the s -process main component calculated with Eq. (8). In order to characterise the overabundance of neutron capture elements in barium stars, $\epsilon_s(X)$ values were compared to $\epsilon_s(X)_{\text{nor}}$ from Table 2, which is the fraction relative to the s -process main component in a normal star of same metallicity. Table 5 also shows the percentages $\epsilon_s(X)/\epsilon_s(X)_{\text{nor}} \times 100$. The r -elements, Sm, Eu, Gd, and Dy, also show large overabundances, similar to those of s -elements in some cases.

Normal stars are expected to have lower abundances of heavy elements than barium stars ($\epsilon_{\text{nor}}(X) < \epsilon(X)$); however, for some elements in some stars, abundances in barium stars obtained for the present sample were much lower than those of normal stars. This is the case of Mo (HD 27271, HD 116869, HD 123396, HD 210709, HD 210910, HD 223938), Eu (HR 107), Gd (HD 210709), Dy (HD 89948), and Pb (HD 22589, HD 210910). It is not clear why these barium stars show such low abundances for these elements. For these cases, the Eq. (8) does not apply, and there is no $\epsilon_s(X)$ for them (Table 5).

After computing the abundance relative to the s -process main component for an element in barium stars using Eq. (8), the abundance of each isotope and for each process can be determined with

$$\epsilon_s^i(X) = f_s^i \epsilon_s(X); \quad \sigma_{\epsilon_s^i(X)} = f_s^i \sigma_{\epsilon_s(X)} \quad (9)$$

$$\epsilon_{sw}^i(X) = f_{sw}^i \epsilon_{sw}(X); \quad \sigma_{\epsilon_{sw}^i(X)} = f_{sw}^i \sigma_{\epsilon_{sw}(X)} \quad (10)$$

$$\epsilon_{st}^i(X) = f_{st}^i \epsilon_{st}(X); \quad \sigma_{\epsilon_{st}^i(X)} = f_{st}^i \sigma_{\epsilon_{st}(X)} \quad (11)$$

$$\epsilon_r^i(X) = f_r^i \epsilon_r(X); \quad \sigma_{\epsilon_r^i(X)} = f_r^i \sigma_{\epsilon_r(X)} \quad (12)$$

$$\epsilon_p^i(X) = f_p^i \epsilon_p(X); \quad \sigma_{\epsilon_p^i(X)} = f_p^i \sigma_{\epsilon_p(X)} \quad (13)$$

where f_s^i , f_{sw}^i , f_{st}^i , f_r^i , and f_p^i are the abundance fractions of the corresponding isotope “ i ”, respectively, of the three s -process components, the r - and p -processes relative to total abundance of the involved process, shown in Cols. 8 to 12 of Table 4. The total abundance can be described by the equation

$$\epsilon(X) = \sum_i^n f_s^i \epsilon_s(X) + \sum_i^n f_{sw}^i \epsilon_{sw}(X) + \sum_i^n f_{st}^i \epsilon_{st}(X) + \sum_i^n f_r^i \epsilon_r(X) + \sum_i^n f_p^i \epsilon_p(X). \quad (14)$$

Abundances relative to the s -process main component for each nuclide of the sample barium stars are shown in Col. 3 of Table 6, and for normal stars in Col. 13. The difference between these two columns is shown in Col. 15.

Some elements of Table 2 are formed in larger amounts through the r -process. They are Eu (94.2%), Gd (84.54%), Dy (84.8%), and Sm (67.4%), according to Arlandini et al. (1999). For these elements, barium stars are expected to have abundance values closer to normal stars than for s -elements. It can be verified that this supposition is valid for Eu by comparing data from Tables 16 and 17 of Paper I to those from Table 2. Figure 3 shows the behaviour of $\log \epsilon_{\text{nor}}(X)$ of normal stars calculated by least-square fitting with $\log \epsilon(X)$ of barium stars, and Fig. 4 shows the behaviour of $\log \epsilon(X)$ for barium stars with $\log \epsilon_o(X)$. It is important to point out that Figs. 3 to 10, the elements were arranged in increasing order of the contribution by the s -process main component, following Arlandini et al. (1999), Eu, Gd, Dy, Sm, Pb, Pr, Mo, Nd, La, Ce, Ba, Zr, Sr, and Y. Behaviours tend to be approximately constant; however, Eu data are very close to a straight line with tangent = 1, differently from the other elements. The larger the distance of the data from tangent = 1, the larger the abundance of barium stars compared to normal stars. If the fraction corresponding to the s -process main component is withdrawn as in Fig. 4, the behaviours of Eu, Gd, and Dy are almost unaltered relative to Fig. 3; however, the change in ordinates due to the missing abundance is remarkable for the other elements.

Figure 5 shows the behaviour of $\log \epsilon_s(X)$ with $\log \epsilon_s(X)_{\text{nor}}$, which are the abundance fractions of the s -process main

Fig. 3. Total abundances of heavy elements for the barium ($\log \epsilon(X)$) and normal ($\log \epsilon_{\text{nor}}(X)$) stars with the same metallicities. Solid lines indicate $\log \epsilon_{\text{nor}}(X) = \log \epsilon(X)$.

Fig. 4. Abundance fraction of heavy elements due to all processes except the s -process main component ($\log \epsilon_0(X)$) vs. total abundance of barium stars ($\log \epsilon(X)$). Solid lines indicate $\log \epsilon_0(X) = \log \epsilon(X)$.

component of barium stars (Eq. (8)) and normal stars of the same metallicity, respectively. Unlike in Fig. 4, the changes in ordinates due to the missing fraction r in Eu, Gd, and Dy abundances in Fig. 5 are remarkable in comparison with Fig. 3. Figure 5 shows similar differences from tangent = 1 as in Figs. 3 and 4, making it clear that the fraction s of the abundance of barium stars leads their behaviour. The difference between the maximum and minimum values of the abundance fraction corresponding to the s -process main component of normal stars is $\Delta \log \epsilon_s(X)_{\text{nor}} \approx 1$ in the range of metallicities of the sample stars. For barium stars this difference is larger, $\Delta \log \epsilon_s(X) \approx 2$.

According to Fig. 6, the abundance relative to the s -process main component of heavy elements is essentially independent of $[\text{Fe}/\text{H}]$ for the present sample of barium stars.

Fig. 5. Abundances corresponding to the s -process main component for heavy elements of barium stars ($\log \epsilon_s(X)$) vs. normal stars ($\log \epsilon_s(X)_{\text{nor}}$) with the same metallicities. Solid lines indicate $\log \epsilon_s(X)_{\text{nor}} = \log \epsilon_s(X)$.

Fig. 6. $\log \epsilon_s(X)$ vs. $[\text{Fe}/\text{H}]$, where $\log \epsilon_s(X)$ are the abundances corresponding to the s -process main component of heavy elements in barium stars.

4.3. Abundance ratios involving s - and r -processes

The r -process is related to the final stages of evolution of massive stars ($M > 8 M_{\odot}$), whereas the s -process main component occurs in AGB stars of low ($1-3 M_{\odot}$) or intermediate ($4-8 M_{\odot}$) masses. The timescale for stars to reach the SN II ($t < 10^8$ yr) stage is less than that for stars to reach the AGB phase ($t > 10^8$ yr); therefore, the first heavy elements ejected in the interstellar medium of the Galaxy, which is observed in very metal-poor stars, are expected to be mainly due to the r -process (Truran et al. 2002). The products of nucleosynthesis of AGB stars to the interstellar medium, particularly the s -process main component appeared later.

Fig. 7. $\log \epsilon(X)$ vs. $[\text{Fe}/\text{H}]$ for present sample of barium stars and post-AGBs from Reyniers et al. (2004) and van Winckel & Reyniers (2000). Filled symbols indicate barium stars; squares: $\log g \geq 3.7$; triangles: $2.4 < \log g < 3.7$; circles: $\log g \leq 2.4$. Open circles are post-AGBs.

It is usual to investigate the starting point of the s -process contribution by analyzing the $[\text{Eu}/\text{Ba}]$ abundance ratio, since they are, respectively, the best representatives of the r - and s -processes. Figure 6 from Burris et al. (2000) shows the behaviour of Ba relative to Eu for normal stars of metallicities $-3 < [\text{Fe}/\text{H}] < +0.5$. From the moment that the s -process starts to produce Ba, an increase in its abundance relative to Eu can be seen, since the s -process is responsible for $\sim 81\%$ of its production, according to Arlandini et al. (1999).

Figure 7 shows $\log \epsilon(X)$ vs. $[\text{Fe}/\text{H}]$ for barium stars from the present sample and post-AGB stars from Reyniers et al. (2004) and van Winckel & Reyniers (2000). Abundances of post-AGBs are larger or similar to those of barium stars, except for Sm in one star. This is expected considering that barium stars were enriched by an AGB companion.

Figure 8 shows $\log \epsilon(\text{Eu})$ vs. $\log \epsilon(X)$, where X are heavy elements other than Eu for the present sample of barium stars and stars from the literature. From Nd to Y, for which the s -process contribution is larger, barium stars and post-AGBs are clearly overabundant, located on the high abundance end.

In the Ba panel of Fig. 8, the lowest values of $\log \epsilon(\text{Eu})$ corresponding to normal stars are close to the upper line where $[\text{Ba}/\text{Eu}] = -0.70$, representing Ba production only by r -process (Mashonkina et al. 2003). As $\log \epsilon(\text{Eu})$ increases, data become closer to the lower line, where data are compatible with $[\text{Ba}/\text{Eu}]$ values for the solar ratio. Both barium and post-AGB stars values are very different from the solar ratio line.

In Fig. 9, the r -process fraction of Eu abundance $[\log(0.942\epsilon(\text{Eu}))]$ correlates with the s -process main component abundance fraction of other elements in barium stars. In Fig. 10, the r -process fraction of Eu is plotted against fractions of r -process of other elements, for the data given in Table 2. In the second, the correlation is linear with no dispersion, indicating that the s -process main component contribution causes a scatter in earlier figures. This linear correlation in Fig. 10 is expected, given that only the r part of the abundances for all involved elements were used. Strontium was not included in this

figure because it does not have an r -process contribution (see Table 4).

Table 7 and Fig. 11 show $[\text{X}/\text{Eu}]$ vs. $[\text{Fe}/\text{H}]$ for barium and post-AGB stars. The star HD 210910 shows lower values of $[\text{X}/\text{Eu}]$ for Y, Zr, Ba, La, Ce, Nd, Pr, and Pb, reaching negative values for $[\text{Zr}/\text{Eu}] = -0.18$. The value of $[\text{Sr}/\text{Eu}]$ is low for the star HD 123396, $[\text{Sr}/\text{Eu}] = -0.1$. This result is expected from Fig. 13 of Paper I, which shows that the stars HD 123396 and HD 210910 present the lowest values of $[\text{SrII}/\text{Fe}]$ and $[\text{ZrII}/\text{Fe}]$, respectively, and their $[\text{Eu}/\text{Fe}] = 0.50$ and 0.54 , thus very close. For other stars, $[\text{X}/\text{Eu}]$ is in the range of $0 \leq [\text{X}/\text{Eu}] \leq 1.3$. The post-AGBs are also mainly in this range, the lowest value being $[\text{Zr}/\text{Eu}] = -0.01$. For all elements, $[\text{X}/\text{Eu}]$ vs. $[\text{Fe}/\text{H}]$ is approximately constant in the range of metallicities of the sample stars.

For Mo, which has a contribution of 49.76% of the s -process main component, 26.18% of the r -process and 24.06% of the p -process, $[\text{Mo}/\text{Eu}]$ are mainly in the range $-0.4 < [\text{Mo}/\text{Eu}] < 0.6$. Relative to Ba, the values are lower, in the range $-1.5 \leq [\text{Mo}/\text{Ba}] \leq -0.35$. Regarding the ratios involving Pr, that has 49% of the contribution from the s -process main component and 51% from the r -process, data are mainly in the ranges $-1.01 \leq [\text{Pr}/\text{Ba}] \leq -0.04$ and $0.12 \leq [\text{Pr}/\text{Eu}] \leq 0.92$. There is no r -process contribution in the Pb abundance, according to Arlandini et al. (1999), while 46% of the contribution comes from s -process main component and 54% has been attributed in previous work to the s -process strong component. Data are in the ranges $-1.03 \leq [\text{Pb}/\text{Ba}] \leq 0.07$ and $-0.58 \leq [\text{Pb}/\text{Eu}] \leq 0.86$. Abundances of Pb obtained for barium stars are usually higher than those of Mo, which are higher than those of Pr, and the same is true for solar abundances. Only for 5 stars the Mo abundance is higher than those of Pb and for one star Pr abundance is higher than that of Mo. However, the $[\text{X}/\text{Fe}]$ values are such that the values of $[\text{Mo}/\text{Ba}, \text{Eu}]$ are usually lower than $[\text{Pr}, \text{Pb}/\text{Ba}, \text{Eu}]$. As a consequence, the range for Mo involves lower values in Fig. 11.

Elements formed mainly by the s -process main component can be divided into two groups: light s -elements around the magic neutron number 50 and heavy s -elements around the magic neutron number 82. In this work, Sr, Y, Zr were included in light s -elements and Ba, La, Ce, Nd in the heavy s -elements groups. For these elements, the s -process main component contribution is larger than 50% according to Arlandini et al. (1999). It is worth emphasising that Sm is rather an r -element because its s -process contribution is less than 30%, while the r -process contributes with 67.4% of its production. The presence of light s -elements in very metal-poor stars cannot be explained entirely by an r -process contribution. For instance, there is no production of Sr by the r -process, as shown in Table 4, and it is observed in the most metal-poor stars. Another nucleosynthetic process related to massive stars is needed in order to explain such observed abundances. Figure 9, from Burris et al. (2000), shows an increasing trend of $[\text{Sr}/\text{Ba}]$ toward lower metallicities $[\text{Fe}/\text{H}] < -1$. It has been suggested that beyond the observational uncertainties, another nucleosynthesis source would explain the increasing $[\text{Sr}/\text{Ba}]$ at lower metallicities, and this source could be the s -process weak component. According to Table 4, 14.9% of the solar abundance of Sr comes from the s -process weak component and 0.56% from the p -process. At metallicities as low as $[\text{Fe}/\text{H}] < -3$, the Sr production is expected to be low, given that the s -process weak component is secondary and that in such environment there is a lack of pre-existing seed nuclei.

Abundance ratios of light s -elements relative to Ba are shown in Table 7 and Fig. 11. In the range of metallicities

Fig. 8. $\log \epsilon(\text{Eu})$ vs. $\log \epsilon(X)$ for normal, post-AGB, and barium stars. Normal stars from the literature are represented by symbols as in Fig. 1. Starred squares are the present sample of barium stars. Starred triangles are post-AGB from Reyniers et al. (2004) and van Winckel & Reyniers (2000). Solid lines in the Ba panel represent r-only production of Ba (upper line) and solar $[\text{Ba}/\text{Eu}]$ (lower line).

studied, the ratios are approximately constant in the ranges $-1 \leq [\text{Sr}/\text{Ba}] \leq 0.1$, $-0.75 \leq [\text{Y}/\text{Ba}] \leq 0.05$, and $-0.80 \leq [\text{Zr}/\text{Ba}] \leq 0.30$. The AGB stars are included in the same range for $[\text{Zr}/\text{Ba}]$, while for $[\text{Y}/\text{Ba}]$ two of them show higher values, 0.25 and 0.66. Figure 9, from Burris et al. (2000), shows a dispersion around $[\text{Fe}/\text{H}] \approx -1$ with $-0.55 \leq [\text{Sr}/\text{Ba}] \leq 0.1$, similar to the present sample of barium stars.

5. Neutron exposures

5.1. Theoretical predictions of Malaney (1987)

The s -element nucleosynthesis depends on the neutron exposure to which the seed nuclei were submitted inside the AGB star. Considering the scenario of material transfer for the barium star formation, it is reasonable to expect that the abundance patterns

of barium stars show signatures of the neutron exposure during the occurrence of the s -process in the AGB companion.

Models trying to reproduce the resulting abundances of the s -process were presented by Cowley & Downs (1980), who calculated theoretical abundances by using exact solutions from Clayton & Ward (1974) for models of exponential distribution and the approximate solution from Clayton et al. (1961) for a model of single exposure.

Malaney (1987a) presented theoretical predictions of abundances from the s -process starting on iron seeds, considering single neutron exposure for several values of τ_0 and neutron density $n_n = 10^8 \text{ cm}^{-3}$. Malaney (1987b) also provides theoretical predictions, but considering an exponential neutron distribution for several values of τ_0 and two different values of neutron density, 10^8 cm^{-3} and 10^{12} cm^{-3} .

Fig. 9. $\log \epsilon_r(\text{Eu})$ vs. $\log \epsilon_s(X)$, where $\log \epsilon_r(\text{Eu})$ is the abundance fraction due to r -process for Eu and $\log \epsilon_s(X)$ is that due to s -process main component for other heavy elements in barium stars.

Fig. 10. $\log \epsilon_r(\text{Eu})$ vs. $\log \epsilon_r(X)$, where $\log \epsilon_r(\text{Eu})$ and $\log \epsilon_r(X)$ are the abundance fractions due to r -process for Eu and other heavy elements in barium stars, respectively.

Abundances resulting from theoretical predictions are usually normalised for $\log \epsilon_c(\text{Sr}) = 20$. Tomkin & Lambert (1983) provide an expression to transform observational data to this scale

$$\epsilon_c(X) = C(y - 1)\epsilon_o(X) \quad (15)$$

where y is the relative abundance between barium and normal stars of same metallicity

$$\log y = \log \epsilon(X) - \log \epsilon_{\text{nor}}(X)$$

where $\log \epsilon(X)$ of barium stars are those from Tables 16 and 17 of Paper I and $\log \epsilon_{\text{nor}}(X)$ are those from Table 2. The value of C for each star is known by setting $\log \epsilon_c(\text{Sr}) = 20$.

Fig. 11. Abundance ratios involving s - and r -processes, light and heavy s -elements. Uncertainties indicated are the highest values of Table 7 for each panel. Symbols are the same as in Fig. 7.

In order to check the fit, Cowley & Downs (1980) used an expression largely used in the literature (e.g. van Winckel & Reyniers 2000; Pereira & Junqueira 2003). There

$$S^2 = \frac{1}{N} \sum_{i=1}^N \frac{(O_i - P_i)^2}{\sigma_i^2} \quad (16)$$

where O_i are abundances $\log \epsilon_c(X)$ for each element “ i ”, P_i are theoretical predictions, N is the number of elements, and σ is the uncertainty on $\log \epsilon_c(X)$ calculated by

$$\sigma_{\log \epsilon_c} = \sqrt{\sigma_{\log C}^2 + \frac{\sigma_{\log y}^2}{(1 - 10^{-\log y})^2} + \sigma_{\log \epsilon_o(X)}^2} \quad (17)$$

with

$$\sigma_{\log y} = \sqrt{\sigma_{\log \epsilon(X)}^2 + \sigma_{\log \epsilon_{\text{nor}}(X)}^2} \quad (18)$$

and the uncertainty on C

$$\sigma_{\log C} = \sqrt{\frac{\sigma_{\log y}^2}{(1 - 10^{-\log y})^2} + \sigma_{\log \epsilon_o(\text{Sr})}^2} \quad (19)$$

where y represents Sr, considering $\sigma_{\log \epsilon_c(\text{Sr})} = 0$.

The best fit between theoretical predictions and observational data corresponds to the lowest value of S^2 , where S^2 was calculated for all P values from Malaney (1987a) and Malaney (1987b) tables. Table 8 shows the best fittings of S^2 and τ_o for each table in Malaney. Figures 12 to 15 show the best fittings obtained for each present sample of barium star, showing the values of τ_o and neutron density n_n , in Cols. 8 and 9 of Table 8.

For some elements of some barium stars, the differences between abundances of barium and normal stars were too small, although $\epsilon_{\text{nor}}(X) < \epsilon(X)$. This is the case for Mo (HD 749), Eu (HD 89948, HD 116869, HD 210709), and Gd (HD 22589). In these cases, the uncertainty on $\log \epsilon_c(X)$ is too large, decreasing the quality of the fit. They were withdrawn before using Eq. (16), and are easily seen in Figs. 12 to 15 due their discrepant

Fig. 12. Fittings of observed data to theoretical predictions by Malaney (1987a,b).

Fig. 14. Same as Fig. 12 for 6 other sample stars.

Fig. 13. Same as Fig. 12 for 6 other sample stars.

values with respect to theoretical predictions, and there are no error bars for them. Except for such cases, there is good agreement between observed and theoretical data shown in Figs. 12 to 15. For most stars, the best fit was that for which theoretical predictions consider an exponential neutron exposure distribution, with neutron density 10^{12} cm^{-3} for 5 stars and 10^8 cm^{-3} for 14 stars. For 7 stars, the best fit was found for a single neutron exposure and neutron density 10^8 cm^{-3} . This result is curious since the exponential neutron exposure distribution is better accepted in the literature. However, Busso et al. (1999) suggest that *s*-process is a result of a number of single exposures instead of an exponential distribution. Pereira & Junqueira (2003) also obtained a single exposure and neutron density 10^8 cm^{-3} as the best fit for 2 barium stars. One of them, HD 87080 for which they

Fig. 15. Same as Fig. 12 for 8 other sample stars.

found $\tau = 1.0$, is in common with the present sample, for which we found a best fit with an exponential distribution of $\tau = 0.6$ and neutron density 10^8 cm^{-3} . The reason for this difference is unclear. The metallicities adopted were very close (see Tables 9 and 11 from Paper I); however, values of $\log \epsilon_c(X)$ in this work are usually higher than those from Pereira & Junqueira (2003). Least-square fittings were used here to compute abundances of normal stars (Eq. (15)), while Pereira & Junqueira (2003) use the sum of solar abundance with star metallicity as a reference.

5.2. The σN curve

Another way to evaluate the neutron exposure nature is through σN curves. For such, the cross-section values (σ_c (30 keV), Col. 13 of Table 4) and abundances related to the *s*-process main

Fig. 16. Example of the fit of parameters G and τ_0 for the barium star HD 123585. Open symbols correspond to the use of $\frac{\partial \chi}{\partial G} = 0$ and filled symbols, $\frac{\partial \chi}{\partial \tau_0} = 0$. From left to right the plot is zoomed in order to visualise the crossing of the two functions better.

component of each nuclide (from Eq. (9)) are needed. Results of the σN curve for each barium star are shown in Col. 11 of Table 6.

The uncertainty on σN is given by the expression

$$\sigma_{\sigma N} = \sigma_c \epsilon_s(X) \sqrt{\left(\frac{\sigma_{\epsilon s}}{\epsilon_s}\right)^2 + \left(\frac{\sigma_{\sigma c}}{\sigma_c}\right)^2}. \quad (20)$$

In the literature, σN is found in Si scale, where $\epsilon(\text{Si}) = 10^6$. Anders & Grevesse (1989) provide the following relation between the Si scale and the scale where $\log \epsilon(X) = \log(n_x/n_H) + 12$:

$$\epsilon(X)_{\text{Si}} = 10^{\log \epsilon(X) - x} \quad (21)$$

where $x = 1.554 \pm 0.020$, and the uncertainty is

$$\sigma_{\epsilon \text{Si}} = \epsilon(X)_{\text{Si}} \sqrt{(\ln 10 \sigma_{\log \epsilon \text{Si}})^2 + \sigma_x^2}. \quad (22)$$

To compute abundances relative to the s -process main component in the Si scale, it is necessary to transform abundances of normal stars to this scale. Then the distribution relative to each process on the Si scale is done in the same way as for the usual scales. Column 16 of Table 6 shows the results of $\sigma N = \sigma_c \epsilon_s(X)_{\text{Si}}$ for the nuclides of barium stars.

For comparison purposes, the distribution of abundance in several nucleosynthetic processes were also done. The total abundance of the element of a barium star was distributed in solar proportions, with fractions corresponding to s -, r -, and p -processes, shown in Cols. 3 to 7 in Table 4. Results for this σN curve are shown in Col. 18 of Table 6, and they are represented by open symbols in Figs. 18 to 21. These results are lower than others because the overabundance derived from the s -process is neglected.

A theoretical σN curve is calculated with Eq. (1), where two parameters (τ_0 and G) must be determined by fitting observed data. A robust statistics was used, which, in this work, consists in finding values of G and τ_0 that simultaneously minimise the sum of absolute deviations represented by

$$\chi = \sum |f(x_k) - y_k|,$$

where $f(x_k)$ is the theoretical value calculated with Eq. (1) and y_k is the value calculated directly for σN by using observed data. Data very far from the curve were neglected. Figure 16 shows the functions that minimise χ relative to each parameter. The

crossing point of these functions provides the values of G and τ_0 that minimise both functions simultaneously. More details on this procedure are found in Allen & Horvath (2000). Table 8 shows results of the fittings and their $\chi_{\text{red}} = \chi/(n - 2)$, where n is the number of data, representing the goodness of fits.

The method was tested for the Sun by using data from Arlandini et al. (1999). The resulting line from the fitting is shown in Fig. 17, in which $\tau_0 = 0.345 \pm 0.005 \text{ mb}^{-1}$ and $G = 0.043 \pm 0.002\%$. Figure 19b from Käppeler et al. (1989) shows their solar σN curve, resulting in $\tau_0 = 0.30 \pm 0.01 \text{ mb}^{-1}$ and $G = 0.043 \pm 0.002\%$. Figures 18 to 21 show that the uncertainties, represented by error bars, are very large for barium stars, so they were neglected in computing the quality of the fit. Branching and the too discrepant data were also neglected.

For the present sample, theoretical σN curves fit the observed data very well, as shown in Figs. 18 to 21. This confirms that the solar isotopic composition is adequate for barium stars and that the transfer of enriched material keeps approximately the solar proportions of each nuclide. In order to build the theoretical curve, one considers that abundances of all elements heavier than iron are null at the beginning of the neutron capture chain. This supposition becomes less reasonable as the metallicity increases. Furthermore, the fit creates more than one difficulty: a) there is a lack of elements along the curve due to the difficulty in finding lines in the spectrum, thereby preventing a higher quality of the fit between theoretical and observed curves; b) barium star data show a large dispersion; c) branching values were not considered; d) the numerical solution of Eq. (1) is difficult, given that two parameters to be fitted appear in non linear form in the equation. The good agreement between theoretical and observed curves is interesting, taking all assumptions and difficulties found in their building into account.

5.3. The s -process indices

One way to relate light and heavy s -elements is through hs and ls indices, defined as the mean of the abundances of light and heavy elements, respectively. According to Sect. 4.3, Sr, Y, and Zr were included in ls , and Ba, La, Ce, and Nd were included in hs . For the s index, all these heavy and light s -elements were considered. In the case of missing abundances, such an element was excluded from the index. Figure 22 and Table 9 show $[hs/ls]$, $[ls/Fe]$, $[hs/Fe]$, and $[s/Fe]$ vs. $[Fe/H]$, with $[hs/ls] = [hs/Fe] - [ls/Fe]$. Uncertainties on $[s/Fe]$, $[ls/Fe]$, and $[hs/Fe]$ have to take

Fig. 17. Solar σN curve. Abundances related to s -process main component were taken from Arlandini et al. (1999).

Fig. 22. $[hs/ls]$, $[ls/fe]$, $[hs/fe]$, and $[s/fe]$ vs. $[Fe/H]$. Filled symbols indicate barium stars, as in Fig. 7; open circles are post-AGBs; crosses are data from Junqueira & Pereira (2001); open squares are data from Luck & Bond (1991); open triangles are data from North et al. (1994). The uncertainties indicated are the higher values shown in Table 9.

into account the contribution of the uncertainties on abundances of each element included in the index.

A behaviour of $[hs/ls]$ as a function of τ_o can be inferred from the slope of the σN curve. The larger τ_o , the smaller the slope, and, at the same time, a smaller slope means larger abundance of heavy s -elements located at the right end of the curve. The conclusion is that the larger τ_o , the larger $[hs/ls]$, as shown in Fig. 17 of Wallerstein et al. (1997). This is reasonable considering that the chain of formation of s -elements cannot go far if the neutron flux is low.

During the third dredge-up, a given amount of protons is introduced into the intershell, a region composed of helium located between helium and hydrogen burning shells. These protons are captured by ^{12}C and form ^{13}C through the reaction $^{12}\text{C}(p, \gamma)^{13}\text{N}(\beta^+ \nu)^{13}\text{C}$ or ^{14}N through $^{13}\text{C}(p, \gamma)^{14}\text{N}$, creating the ^{13}C pocket. If the thermal pulse is independent of metallicity, protons are introduced into the intershell in the same amounts for higher or lower metallicities. It means that the neutron source $^{13}\text{C}(\alpha, n)^{16}\text{O}$, probably the main neutron source in AGB stars, is independent of metallicity. However, the neutron number by seed iron nucleus will be larger at low metallicities (Clayton 1988). If τ_o is proportional to $[hs/ls]$ and inversely proportional to $[Fe/H]$, $[hs/ls]$ will also be inversely proportional to $[Fe/H]$, so

it is expected that the lower the metallicity, the higher the ratio $[hs/ls]$. Figure 24 confirms a correlation between τ_o and $[hs/ls]$ for barium and post-AGB stars. However, the anticorrelation between $[hs/ls]$ and $[Fe/H]$ is weak for barium and post AGBs stars, as shown in Fig. 22. In the same way, the anticorrelation between τ_o and $[Fe/H]$ is not confirmed in Fig. 24. The yield of all s -elements to decrease with decreasing metallicities is compatible with the secondary characteristic of the s -process, which requires pre-existing seed nuclei. At intermediate metallicities (≈ -0.8), the Ba peak is dominant among s -process products in AGB models (Busso et al. 1999). For higher metallicities the Zr peak dominates. If giant, as well as dwarf, barium stars have the same physical origin for the accretion of enriched material from a more evolved companion, it is reasonable to expect that if the neutron exposure is higher for dwarf and more metal-deficient stars, the same occurs for giants.

In Fig. 24, τ_o derived from the σN curve are mainly within $1.8 < \tau_o < 0.6$, with less spread as compared to those derived from theoretical predictions by Malaney (1987a,b), although both show the same trend. For giant stars, $\tau_o \approx 1$ was found from theoretical predictions, but not from the σN curves.

Solid and dashed lines in Fig. 24 are least-square fittings, with parameters:

$$[hs/ls] = (0.423 \pm 0.095)\tau_o + (0.011 \pm 0.043) \quad (23)$$

$$[hs/ls] = (0.899 \pm 0.173)\tau_o + (-0.160 \pm 0.068) \quad (24)$$

where Eq. (23) uses τ_o values from theoretical predictions by Malaney (1987a,b), with $\chi^2_{\text{red}} = 1.710$ and Eq. (24) uses τ_o values derived from σN curves, with $\chi^2_{\text{red}} = 1.464$. Regarding χ^2_{red} , in both cases the linear and increasing correlation toward higher values of τ_o have good quality.

Figure 10 from van Winckel & Reyniers (2000) shows $[hs/ls]$ vs. $[Fe/H]$, including data from several previous work. Despite the dispersion, $[hs/ls]$ increases toward higher $[Fe/H]$. The dependence of neutron exposure on $[Fe/H]$ could indicate that other important parameters affect dredge-up events and nucleosynthetic processes along the red giant branch evolution.

For the present sample of barium stars, $[s]$, $[ls]$, $[hs/fe]$ and $[hs/ls]$ decrease slightly toward higher metallicities in the range $0.45 \leq [s/fe] \leq 1.6$, $0.4 \leq [ls/fe] \leq 1.6$, $0.7 \leq [hs/fe] \leq 1.75$, and

Table 9. *s*-process indices: *s*, *ls*, and *hs* for the present sample of barium stars.

star	[s/Fe]	[ls/Fe]	[hs/Fe]	[hs/ls]
HD 749	1.12 ± 0.21	1.09 ± 0.23	1.31 ± 0.22	0.22 ± 0.32
HR 107	0.71 ± 0.08	0.69 ± 0.09	0.82 ± 0.07	0.13 ± 0.11
HD 5424	1.15 ± 0.21	0.98 ± 0.23	1.64 ± 0.22	0.66 ± 0.32
HD 8270	0.95 ± 0.08	0.93 ± 0.09	1.03 ± 0.07	0.10 ± 0.11
HD 12392	1.17 ± 0.21	1.07 ± 0.23	1.57 ± 0.22	0.50 ± 0.32
HD 13551	1.02 ± 0.08	1.02 ± 0.09	1.08 ± 0.07	0.07 ± 0.11
HD 22589	0.92 ± 0.08	0.93 ± 0.09	0.77 ± 0.07	-0.16 ± 0.11
HD 27271	0.81 ± 0.21	0.81 ± 0.23	0.81 ± 0.22	0.00 ± 0.32
HD 48565	1.14 ± 0.08	1.08 ± 0.09	1.40 ± 0.07	0.32 ± 0.11
HD 76225	1.25 ± 0.08	1.25 ± 0.09	1.26 ± 0.07	0.01 ± 0.11
HD 87080	1.23 ± 0.08	1.13 ± 0.09	1.59 ± 0.07	0.46 ± 0.11
HD 89948	1.04 ± 0.08	1.06 ± 0.09	0.92 ± 0.07	-0.14 ± 0.11
HD 92545	0.76 ± 0.08	0.73 ± 0.09	0.92 ± 0.07	0.19 ± 0.11
HD 106191	0.83 ± 0.08	0.83 ± 0.09	0.80 ± 0.07	-0.04 ± 0.11
HD 107574	1.16 ± 0.08	1.05 ± 0.09	1.55 ± 0.07	0.50 ± 0.11
HD 116869	0.57 ± 0.21	0.45 ± 0.23	0.99 ± 0.22	0.54 ± 0.32
HD 123396	0.95 ± 0.21	0.79 ± 0.23	1.44 ± 0.22	0.64 ± 0.32
HD 123585	1.37 ± 0.08	1.27 ± 0.09	1.74 ± 0.07	0.47 ± 0.11
HD 147609	1.58 ± 0.08	1.58 ± 0.09	1.58 ± 0.07	0.00 ± 0.11
HD 150862	0.90 ± 0.08	0.90 ± 0.09	0.91 ± 0.07	0.00 ± 0.11
HD 188985	1.07 ± 0.08	1.05 ± 0.09	1.20 ± 0.07	0.16 ± 0.11
HD 210709	0.49 ± 0.21	0.44 ± 0.23	0.73 ± 0.22	0.29 ± 0.32
HD 210910	0.76 ± 0.21	0.74 ± 0.23	0.89 ± 0.22	0.15 ± 0.32
HD 222349	1.15 ± 0.08	1.10 ± 0.09	1.38 ± 0.07	0.28 ± 0.11
BD+18 5215	1.19 ± 0.08	1.17 ± 0.09	1.35 ± 0.07	0.19 ± 0.11
HD 223938	0.86 ± 0.21	0.79 ± 0.23	1.17 ± 0.22	0.38 ± 0.32

Table 10. *s*-process indices *s*, *ls*, and *hs* for barium stars collected in the literature. References: N94 – North et al. (1994); LB91 – Luck & Bond (1991).

star	[Fe/H]	[ls/Fe]	[hs/Fe]	[hs/ls]	ref
48565	-0.90	0.70	1.07	0.37	N94
76225	-0.50	1.13	1.11	-0.02	N94
89948	-0.13	1.20	0.70	-0.50	LB91
92545	-0.33	0.49	0.68	0.19	N94
106191	-0.40	0.86	0.59	-0.27	N94
107574	-0.80	0.85	1.22	0.37	N94
123585	-0.50	1.28	1.50	0.22	N94
123585	-0.50	1.10	1.10	0.00	LB91
147609	-0.50	0.88	0.98	0.10	N94
150862	-0.30	1.05	0.61	-0.44	N94
150862	-0.20	0.60	0.40	-0.20	LB91
188985	-0.30	1.02	1.10	0.08	N94

$-0.2 \leq [\text{hs}/\text{ls}] \leq 0.7$. According to Wheeler et al. (1989), $[\text{s}/\text{Fe}] = 0$ for less evolved stars in this same range of metallicities; therefore, the results found for the present sample show the overabundance of *s*-elements in barium stars.

One has to be careful in comparing the indices of the present work to those of post-AGBs in Figs. 11, 22, and 23, given that Reyniers et al. (2004) and van Winckel & Reyniers (2000) included Sm and not Ce in *s* and *hs*, and only Y and Zr in *ls*. Figure 23 shows that $[\text{hs}/\text{ls}]$ vs. $[\text{s}/\text{Fe}]$ has a large dispersion for barium stars, whereas there is a linear correlation for post-AGBs. Figure 8 from Reyniers et al. shows the same correlation but using different combinations of the elements included in the indices. One of them uses Ce, but the linear correlation is still present comparing with using Ba, La, Nd, and Sm in *hs*. Other configurations show larger dispersion, hence the presence of Ce in *hs* and *s* is not the origin of the dispersion for barium stars.

Fig. 23. $[\text{hs}/\text{ls}]$ vs. $[\text{s}/\text{Fe}]$. Symbols are the same as in Fig. 7. Error bars in the bottom right corner show the largest uncertainties. **Fig. 24.** $[\text{hs}/\text{ls}]$ vs. τ_0 (upper panel), and τ_0 vs. $[\text{Fe}/\text{H}]$ (lower panel). Crosses are post-AGBs from Reyniers et al. (2004) and van Winckel & Reyniers (2000). Circles, triangles, and squares represent the sample of barium stars according to $\log g$, as in Fig. 7. Open symbols correspond to τ_0 values derived from theoretical predictions by Malaney (1987a,b) and filled symbols are those from σN curves. The solid line is the least-square fitting with τ_0 from σN curves and dotted, with τ_0 from theoretical predictions.

According to Table 7 and Fig. 11, there is no difference as a function of $\log g$, confirming that the overabundances characteristic of a barium star do not depend on luminosity classes.

6. Conclusions

In this work, *s*-, *r*-, and *p*-processes in barium stars were studied relative to normal stars.

Abundances of elements with a lower contribution from the *s*-process main component are closer to the normal stars, whereas elements with a higher *s*-contribution are more overabundant. However, *r*-elements such as Sm, Eu, Gd, and Dy are also enriched in barium stars, sometimes at similar magnitudes to *s*-elements, and this occurs because the *s*-process main component chain includes the *r*-elements with $A < 209$.

The ratios involving light *s*-elements (Sr, Y, and Zr) and Ba, a heavy *s*-element, are approximately constant in the range of metallicities of the present sample, with a dispersion similar to normal stars and post-AGBs.

Considering that the abundance fraction due to all processes, except the *s*-process main component, was present in the proto-barium star, it was possible to isolate the fraction corresponding to the *s*-process main component for barium stars. The solar isotopic distribution of this abundance fraction was used to build the observed σN curves. Their fittings to theoretical curves indicate that it is possible to use a solar isotopic mix to estimate the contribution of the *s*-process main component for each isotope of an element.

The derivation of τ_0 was obtained by fitting observed data to theoretical predictions and σN curves. Theoretical predictions for abundances starting with Sr fit the observed data very well for the present sample, thereby providing an estimation for neutron exposure that occurred in AGB supplying the *s*-process. The [hs/l_s] vs. τ_0 considering these theoretical predictions increases linearly, whereas no conclusion was reached for τ_0 vs. [Fe/H]. The τ_0 values from σN fittings also provide linear and increasing τ_0 vs. [hs/l_s], but data in this case are in the range $0.2 \leq \tau_0 \leq 0.8$, showing lower dispersion than those for theoretical predictions.

Abundances obtained for barium stars are close to those for AGBs stars, but they are usually lower. This is reasonable considering that only part of the surface material of AGBs is transferred to the companion, which becomes a barium star.

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Fig. 18. The σN curves for the sample of barium stars. Open squares represent the solar distribution of abundances (Col. 18 of Table 6) and filled squares represent the distribution taking the overabundance of barium stars into account (Col. 16 of Table 6). Error bars in the HD 749 panel at $A = 190$ and $A = 195$ indicate the typical errors in each region of the logarithmic scale.

Fig. 19. Same as Fig. 18 for 6 other sample stars.

Fig. 20. Same as Fig. 18 for 6 other sample stars.

Fig. 21. Same as Fig. 18 for 8 other sample stars.

Table 4. Cross-sections in mb^{-1} for 30, 23, and 8 keV and abundance fractions for s -, r -, and p -processes relative to total abundance and to total abundance of each process.

A	el	g_s	g_{sw}	g_{st}	g_r	g_p	f_s	f_{sw}	f_{st}	f_r	f_p	$\sigma_c(30 \text{ keV})$	$\sigma_c(23 \text{ keV})$	$\sigma_c(8 \text{ keV})$	Ref.
84	Sr	...	...	...	...	5.650e-03	...	...	...	...	1.000e00	368 ± 126	...	...	1
86	Sr	4.666e-02	5.265e-02	...	...	...	5.519e-02	3.534e-01	...	...	...	64 ± 3	66.80	80.10	1
87	Sr	3.253e-02	3.210e-02	...	...	...	3.848e-02	2.155e-01	...	...	...	92 ± 4	101.60	126.00	1
88	Sr	7.662e-01	6.421e-02	...	...	...	9.063e-01	4.310e-01	...	...	...	6.2 ± 0.3	6.60	6.00	1
		84.54%	14.90%	...	...	0.56%	...	...	...	...	...	...	...	...	...
89	Y	9.203e-01	...	...	8.000e-02	...	1.000e00	...	...	1.000e00	...	19.0 ± 0.6	19.60	24.50	1
		92.03%	...	...	8.00%	...	...	...	...	...	...	...	...	...	...
90	Zr	3.716e-01	...	...	1.429e-01	...	4.477e-01	...	...	8.993e-01	...	21 ± 2	20.80	18.90	1
91	Zr	1.078e-01	...	...	4.785e-03	...	1.299e-01	...	...	3.012e-02	...	60 ± 8	64.70	90.50	1
92	Zr	1.604e-01	...	...	1.122e-02	...	1.932e-01	...	...	7.062e-02	...	33 ± 4	34.60	47.20	1
94	Zr	1.748e-01	...	...	...	...	2.106e-01	...	...	...	...	26 ± 1	26.60	30.10	1
96	Zr	1.542e-02	1.100e-02	...	...	...	1.859e-02	1.000e00	...	...	...	10.7 ± 0.5	11.10	18.10	1
		83.00%	1.10%	...	15.89%	...	...	...	...	...	...	...	...	...	...
92	Mo	...	...	...	...	1.509e-01	...	...	...	...	6.156e-01	70 ± 10	...	...	1
94	Mo	5.995e-04	...	...	...	9.165e-02	1.205e-03	...	...	...	3.844e-01	102 ± 20	103.70	120.30	1
95	Mo	8.816e-02	...	...	7.093e-02	...	1.772e-01	...	...	2.710e-01	...	292 ± 12	301.40	322.00	1
96	Mo	1.665e-01	...	...	...	...	3.347e-01	...	...	...	...	112 ± 8	118.00	150.40	1
97	Mo	5.604e-02	...	...	3.958e-02	...	1.126e-01	...	...	1.512e-01	...	339 ± 14	352.90	387.80	1
98	Mo	1.826e-01	...	...	5.839e-02	...	3.669e-01	...	...	2.231e-01	...	99 ± 7	100.10	111.80	1
100	Mo	3.691e-03	...	...	9.237e-02	...	7.418e-03	...	...	3.548e-01	...	108 ± 14	106.90	110.90	1
		49.76%	...	...	26.18%	24.06%	...	...	...	...	...	...	...	...	...
130	Ba	...	...	...	...	1.060e-03	...	...	...	...	5.124e-01	760 ± 110	...	...	1
132	Ba	...	...	...	...	1.009e-03	...	...	...	...	4.876e-01	379 ± 137	...	...	1
134	Ba	2.427e-02	...	...	...	...	3.003e-02	...	...	...	...	176.0 ± 5.6	172.10	157.90	1
135	Ba	1.726e-02	...	...	4.877e-02	...	2.135e-02	...	...	2.570e-01	...	455 ± 15	463.50	498.40	1
136	Ba	7.860e-02	...	...	...	...	9.726e-02	...	...	...	...	61.2 ± 2.0	62.20	68.60	1
137	Ba	7.348e-02	...	...	3.875e-02	...	9.092e-02	...	...	2.042e-01	...	76.3 ± 2.4	77.40	81.90	1
138	Ba	6.146e-01	...	...	1.022e-01	...	7.604e-01	...	...	5.387e-01	...	4.0 ± 0.2	4.00	4.80	1
		80.82%	...	...	18.97%	0.21%	...	...	...	...	...	...	...	...	...
138	La	...	...	...	...	8.893e-04	...	...	...	...	1.000e00	...	...	...	1
139	La	6.205e-01	...	...	3.786e-01	...	1.000e00	...	...	1.000e00	...	31.6 ± 0.8	37.50	70.10	2
		62.05%	...	...	37.86%	0.09%	...	...	...	...	...	...	...	...	...
136	Ce	...	...	...	...	1.901e-03	...	...	...	...	4.320e-01	328 ± 21	...	...	1
138	Ce	...	...	...	...	2.500e-03	...	...	...	...	5.680e-01	179 ± 5	...	...	1
140	Ce	7.359e-01	...	...	1.488e-01	...	9.677e-01	...	...	6.327e-01	...	10.6 ± 0.5	...	...	3
142	Ce	2.456e-02	...	...	8.636e-02	...	3.230e-02	...	...	3.673e-01	...	28.3 ± 1.0	...	...	3
		76.05%	...	...	23.52%	0.44%	...	...	...	...	...	...	...	...	...
141	Pr	4.868e-01	...	...	5.132e-01	...	1.000e00	...	...	1.000e00	...	111.4 ± 1.4	...	...	3
		48.68%	...	...	51.32%	...	...	...	...	...	...	...	...	...	...
142	Nd	2.515e-01	...	...	...	2.056e-02	4.535e-01	...	...	...	2.669e-01	35.0 ± 0.7	...	...	1
143	Nd	3.821e-02	...	...	8.271e-02	...	6.890e-02	...	...	2.246e-01	...	245 ± 3	...	...	1
144	Nd	1.209e-01	...	...	1.171e-01	...	2.180e-01	...	...	3.178e-01	...	81.3 ± 1.5	...	...	1
145	Nd	2.285e-02	...	...	6.022e-02	...	4.121e-02	...	...	1.635e-01	...	425 ± 5	...	...	1
146	Nd	1.102e-01	...	...	6.155e-02	...	1.986e-01	...	...	1.671e-01	...	91.2 ± 1.0	...	...	1
148	Nd	1.094e-02	...	...	4.680e-02	...	1.973e-02	...	...	1.270e-01	...	147 ± 2	...	...	1
150	Nd	...	...	...	...	5.647e-02	...	...	...	...	7.331e-01	159 ± 10	...	...	1
		55.46%	...	...	36.84%	7.70%	...	...	...	...	...	...	...	...	...
144	Sm	...	...	...	...	3.096e-02	...	...	...	...	1.000e00	92 ± 6	...	...	1
147	Sm	3.193e-02	...	...	1.227e-01	...	1.082e-01	...	...	1.821e-01	...	973 ± 1	...	...	1
148	Sm	1.091e-01	...	...	...	...	3.697e-01	...	...	...	...	241 ± 2	...	...	1
149	Sm	1.722e-02	...	...	1.208e-01	...	5.835e-02	...	...	1.792e-01	...	1820 ± 17	...	...	1
150	Sm	7.392e-02	...	...	...	...	2.504e-01	...	...	...	...	422 ± 4	...	...	1
152	Sm	6.115e-02	...	...	2.055e-01	...	2.072e-01	...	...	3.050e-01	...	473 ± 4	...	...	1
154	Sm	1.815e-03	...	...	2.249e-01	...	6.149e-03	...	...	3.337e-01	...	206 ± 12	...	...	1
		29.51%	...	...	67.39%	3.1%	...	...	...	...	...	...	...	...	...
151	Eu	3.124e-02	...	...	4.471e-01	...	5.409e-01	...	...	4.744e-01	...	3775 ± 150	...	...	1
153	Eu	2.652e-02	...	...	4.954e-01	...	4.591e-01	...	...	5.256e-01	...	2780 ± 100	...	...	1
		5.78%	...	...	94.25%	...	...	...	...	...	...	...	...	...	...
152	Gd	1.767e-03	...	...	...	2.334e-04	1.151e-02	...	...	...	1.846e-01	1049 ± 17	...	...	1
154	Gd	2.076e-02	...	...	...	1.031e-03	1.352e-01	...	...	...	8.153e-01	1028 ± 12	...	...	1
155	Gd	8.730e-03	...	...	1.391e-01	...	5.684e-02	...	...	1.646e-01	...	2648 ± 30	...	...	1
156	Gd	3.486e-02	...	...	1.700e-01	...	2.270e-01	...	...	2.011e-01	...	615 ± 5	...	...	1
157	Gd	1.676e-02	...	...	1.397e-01	...	1.091e-01	...	...	1.653e-01	...	1369 ± 15	...	...	1
158	Gd	6.820e-02	...	...	1.804e-01	...	4.440e-01	...	...	2.133e-01	...	324 ± 3	...	...	1
160	Gd	2.507e-03	...	...	2.161e-01	...	1.632e-02	...	...	2.556e-01	...	154 ± 28	...	...	1
		15.36%	...	...	84.53%	0.13%	...	...	...	...	...	...	...	...	...
156	Dy	...	...	...	...	5.601e-04	...	...	...	...	1.256e-01	1567 ± 145	...	...	1
158	Dy	...	...	...	...	9.580e-04	...	...	...	...	2.149e-01	1060 ± 400	...	...	1
160	Dy	2.043e-02	...	...	...	2.940e-03	1.385e-01	...	...	...	6.595e-01	890 ± 12	...	...	1
161	Dy	1.044e-02	...	...	1.784e-01	...	7.079e-02	...	...	2.104e-01	...	1964 ± 19	...	...	1
162	Dy	4.156e-02	...	...	2.144e-01	...	2.818e-01	...	...	2.528e-01	...	446 ± 4	...	...	1
163	Dy	8.921e-03	...	...	2.400e-01	...	6.048e-02	...	...	2.830e-01	...	1112 ± 11	...	...	1
164	Dy	6.615e-02	...	...	2.152e-01	...	4.485e-01	...	...	2.537e-01	...	212.0 ± 3.0	...	...	1
		14.75%	...	...	84.80%	0.45%	...	...	...	...	...	...	...	...	...
204	Pb	1.841e-02	...	1.119e-03	...	...	3.997e-02	...	2.074e-03	...	...	89.0 ± 5.5	...	...	1
206	Pb	1.096e-01	...	7.992e-02	...	...	2.380e-01	...	1.481e-01	...	...	15.8 ± 0.8	...	...	1
207	Pb	1.311e-01	...	7.481e-02	...	...	2.845e-01	...	1.387e-01	...	...	9.7 ± 1.3	...	...	1
208	Pb	2.014e-01	...	3.836e-01	...	...	4.372e-01	...	7.111e-01	...	...	0.36 ± 0.03	...	...	1
		46.05%	...	53.94%	...	...	...	...	...	...	...	...	...	...	...

Cross-section references: 1 – Bao et al. (2000), 2 – O'Brien et al. (2003), 3 – Arlandini et al. (1999).

Table 5. Abundance fractions corresponding to the *s*-process main component for barium stars calculated with Eq. (8) (upper table) and percentage of abundance (lower table) relative to the *s*-process main component of a barium star compared to normal stars of a same metallicity ($\epsilon_s(X)/\epsilon_s(X)_{\text{nor}} \times 100$).

Star	$\epsilon_s(\text{Sr})$	$\epsilon_s(\text{Y})$	$\epsilon_s(\text{Zr})$	$\epsilon_s(\text{Mo})$	$\epsilon_s(\text{Ba})$	$\epsilon_s(\text{La})$	$\epsilon_s(\text{Ce})$	$\epsilon_s(\text{Pr})$	$\epsilon_s(\text{Nd})$	$\epsilon_s(\text{Sm})$	$\epsilon_s(\text{Eu})$	$\epsilon_s(\text{Gd})$	$\epsilon_s(\text{Dy})$	$\epsilon_s(\text{Pb})$
HD 749	3781 ± 2150	2260 ± 994	9600 ± 4450	63 ± 64	1771 ± 784	207 ± 94	1364 ± 600	28 ± 18	512 ± 241	70 ± 35	3 ± 3	14 ± 21	106 ± 74	144 ± 126
HR 107	2237 ± 791	294 ± 28	614 ± 74	127 ± 45	512 ± 60	24 ± 4	53 ± 7	5 ± 1	20 ± 4	6 ± 2	...	16 ± 5	...	288 ± 135
HD 5424	1012 ± 579	522 ± 230	2517 ± 1169	26 ± 23	1132 ± 498	131 ± 58	1027 ± 450	30 ± 18	410 ± 190	52 ± 25	1.4 ± 1.4	7 ± 9	197 ± 129	303 ± 211
HD 8270	2790 ± 980	580 ± 54	1475 ± 173	110 ± 39	652 ± 76	48 ± 7	127 ± 15	4 ± 1	52 ± 8	6 ± 2	0.92 ± 0.61	5 ± 2	2 ± 1	89 ± 47
HD 12392	4179 ± 2362	2147 ± 944	6854 ± 3182	169 ± 118	3331 ± 1465	406 ± 181	1792 ± 786	83 ± 49	647 ± 302	226 ± 106	5 ± 4	28 ± 32	60 ± 44	918 ± 638
HD 13551	3366 ± 1178	758 ± 70	1481 ± 174	176 ± 58	704 ± 82	45 ± 7	144 ± 17	5 ± 1	50 ± 8	8 ± 2	0.33 ± 0.47	13 ± 4	3 ± 1	85 ± 45
HD 22589	3748 ± 1318	619 ± 58	2463 ± 288	49 ± 26	543 ± 64	32 ± 5	71 ± 9	3 ± 1	24 ± 4	3 ± 1	0.70 ± 0.69	2 ± 2	3 ± 1	...
HD 27271	3177 ± 1812	1075 ± 475	3459 ± 1620	...	816 ± 365	51 ± 26	182 ± 82	9 ± 7	67 ± 36	16 ± 10	2.4 ± 2.8	10 ± 17	12 ± 14	109 ± 100
HD 48565	2451 ± 857	421 ± 39	1462 ± 170	53 ± 20	620 ± 72	77 ± 11	474 ± 55	13 ± 2	136 ± 19	20 ± 4	0.59 ± 0.42	13 ± 4	16 ± 3	467 ± 209
HD 76225	8244 ± 2868	1259 ± 117	3524 ± 410	142 ± 50	1457 ± 169	105 ± 15	281 ± 33	11 ± 2	74 ± 11	13 ± 3	0.85 ± 0.69	12 ± 4	10 ± 2	285 ± 135
HD 87080	3366 ± 1178	812 ± 75	3196 ± 371	61 ± 24	1476 ± 171	265 ± 37	977 ± 113	27 ± 4	365 ± 51	46 ± 9	3.8 ± 1.3	34 ± 9	75 ± 11	346 ± 159
HD 89948	5506 ± 1923	915 ± 85	2078 ± 244	112 ± 42	651 ± 76	54 ± 8	125 ± 15	7 ± 1	56 ± 9	10 ± 3	0.33 ± 0.58	6 ± 3	...	76 ± 44
HD 92545	3670 ± 1300	563 ± 53	1624 ± 193	128 ± 52	1113 ± 130	47 ± 7	147 ± 18	7 ± 1	46 ± 8	8 ± 3	2.4 ± 1.2	5 ± 3	7 ± 2	302 ± 148
HD 106191	2088 ± 743	723 ± 67	2352 ± 275	114 ± 43	515 ± 61	28 ± 4	102 ± 12	14 ± 2	36 ± 6	11 ± 3	0.55 ± 0.64	11 ± 4	10 ± 2	179 ± 90
HD 107574	3277 ± 1144	442 ± 41	978 ± 115	175 ± 56	1923 ± 222	53 ± 8	145 ± 17	5 ± 1	54 ± 8	10 ± 2	1.45 ± 0.65	5 ± 2	6 ± 1	268 ± 123
HD 116869	735 ± 440	314 ± 140	869 ± 417	...	660 ± 294	55 ± 26	187 ± 84	8 ± 6	92 ± 45	14 ± 8	0.3 ± 1.3	5 ± 10	21 ± 18	279 ± 202
HD 123396	144 ± 84	56 ± 25	394 ± 184	...	170 ± 75	16 ± 7	134 ± 59	4 ± 3	64 ± 30	9 ± 5	0.26 ± 0.36	5 ± 5	15 ± 10	88 ± 61
HD 123585	4987 ± 1737	1248 ± 115	2980 ± 346	262 ± 83	2716 ± 314	199 ± 28	804 ± 93	30 ± 4	236 ± 33	51 ± 10	5.9 ± 1.7	12 ± 4	19 ± 3	1031 ± 458
HD 147609	112924 ± 4479	2291 ± 211	5047 ± 584	144 ± 48	1755 ± 203	203 ± 28	768 ± 89	25 ± 4	204 ± 29	42 ± 8	4.8 ± 1.5	25 ± 7	24 ± 4	173 ± 83
HD 150862	3616 ± 1283	1647 ± 153	4128 ± 482	177 ± 67	1116 ± 131	60 ± 9	134 ± 16	8 ± 1	38 ± 7	8 ± 3	1.15 ± 0.98	9 ± 4	9 ± 3	317 ± 155
HD 188985	4358 ± 1527	900 ± 83	2957 ± 345	112 ± 42	1070 ± 125	95 ± 14	425 ± 49	14 ± 2	149 ± 21	23 ± 5	1.14 ± 0.76	17 ± 5	7 ± 2	374 ± 174
HD 210709	944 ± 587	526 ± 235	2158 ± 1024	...	639 ± 289	50 ± 26	242 ± 109	8 ± 6	97 ± 50	13 ± 9	0.3 ± 2.1	...	11 ± 14	185 ± 154
HD 210910	2807 ± 1580	254 ± 114	357 ± 180	...	547 ± 244	29 ± 14	93 ± 42	13 ± 8	37 ± 20	8 ± 5	3.1 ± 2.4	16 ± 18	8 ± 9	...
HD 222349	2442 ± 945	439 ± 185	1536 ± 948	52 ± 22	758 ± 434	69 ± 29	297 ± 108	7 ± 4	118 ± 70	16 ± 12	0.20 ± 0.32	9 ± 12	12 ± 15	578 ± 248
BD+18 5215	3880 ± 1353	515 ± 48	2072 ± 241	111 ± 37	1151 ± 133	59 ± 8	189 ± 22	9 ± 1	52 ± 8	13 ± 3	0.3 ± 0.4	52 ± 13	13 ± 2	60 ± 33
HD 223938	1654 ± 853	418 ± 41	2024 ± 179	...	982 ± 88	63 ± 10	242 ± 34	6 ± 1	145 ± 17	22 ± 3	1.5 ± 1.8	9 ± 3	18 ± 2	350 ± 258
Star	Sr(%)	Y(%)	Zr(%)	Mo(%)	Ba(%)	La(%)	Ce(%)	Pr(%)	Nd(%)	Sm(%)	Eu(%)	Gd(%)	Dy(%)	Pb(%)
HD 749	636	1652	3123	185	2020	1654	6526	1166	3650	2987	1508	795	6715	404
HR 107	758	464	382	728	1159	440	514	392	274	421	...	1755	...	1609
HD 5424	534	1337	2362	224	3955	4015	15334	3274	8525	5487	1657	1293	32236	2619
HD 8270	1087	1066	1045	724	1691	1029	1398	341	813	514	888	609	268	570
HD 12392	809	1830	2539	568	4357	3820	9851	3890	5253	10711	2604	1844	4262	2953
HD 13551	1374	1466	1096	1206	1912	1019	1664	439	821	671	334	1755	358	570
HD 22589	1029	775	1261	231	1000	452	553	183	276	176	513	142	317	...
HD 27271	573	849	1201	...	996	439	934	396	506	732	1280	595	804	326
HD 48565	1522	1290	1596	545	2542	2862	8336	1591	3306	2377	824	2621	2914	4749
HD 76225	2485	1746	1968	731	2942	1666	2404	756	915	910	673	1251	981	1422
HD 87080	1374	1570	2365	419	4011	5984	11296	2417	5971	3973	3848	4627	9942	2322
HD 89948	1621	1236	1136	560	1285	828	1042	497	671	676	259	606	...	369
HD 92545	710	480	601	430	1456	444	810	343	374	402	1336	342	483	972
HD 106191	601	953	1258	560	993	418	831	946	429	746	417	1093	1002	854
HD 107574	1729	1134	918	1532	6716	1604	2164	605	1118	1083	1773	943	1023	2322
HD 116869	227	447	496	...	1364	896	1641	559	1156	977	241	539	2257	1422
HD 123396	337	737	1474	...	2565	2817	8848	1743	5382	3318	1004	2514	8375	3328
HD 123585	2235	2673	2404	1964	8085	5023	10199	2859	4219	4747	6372	1755	2702	495
HD 147609	5400	4546	3815	1010	4879	4725	9087	2297	3414	3666	4903	3533	3192	1193
HD 150862	668	1334	1464	569	1395	534	702	356	298	388	623	542	613	972
HD 188985	1283	1216	1616	560	2112	1461	3552	903	1791	1547	881	1691	672	1820
HD 210709	152	365	672	...	696	381	1106	299	660	517	137	...	673	81
HD 210910	973	411	227	...	1267	533	914	986	512	606	2718	1808	982	...
HD 222349	1553	1380	1714	545	3176	2643	5333	958	2931	2008	282	1869	2203	6009
BD+18 5215	1954	1255	1862	930	3840	1717	2692	980	1041	1307	353	8625	1978	7596
HD 223938	547	642	1233	...	2173	1107	2274	454	1950	1629	1288	979	1988	495

Table 7. [X/Eu] (*upper table*) and [X/Ba] (*lower table*) for the barium stars.

Star	[Sr/Eu]	[Y/Eu]	[Zr/Eu]	[Mo/Eu]	[Ba/Eu]	[La/Eu]	[Ce/Eu]	[Nd/Eu]	[Pr/Eu]	[Pb/Eu]
HD 749	0.35 ± 0.21	0.85 ± 0.12	1.12 ± 0.14	-0.20 ± 0.21	0.85 ± 0.13	0.93 ± 0.12	1.17 ± 0.13	1.00 ± 0.13	0.56 ± 0.25	0.05 ± 0.27
HR 107	0.71 ± 0.18	0.56 ± 0.10	0.53 ± 0.10	0.56 ± 0.16	0.91 ± 0.11	0.63 ± 0.10	0.37 ± 0.10	0.28 ± 0.10	0.48 ± 0.18	0.86 ± 0.22
HD 5424	0.14 ± 0.21	0.57 ± 0.12	0.89 ± 0.14	-0.26 ± 0.21	1.02 ± 0.13	1.09 ± 0.12	1.40 ± 0.13	1.26 ± 0.13	0.92 ± 0.25	0.64 ± 0.27
HD 8270	0.58 ± 0.18	0.63 ± 0.10	0.68 ± 0.10	0.28 ± 0.16	0.79 ± 0.11	0.68 ± 0.10	0.51 ± 0.10	0.41 ± 0.10	0.16 ± 0.18	0.18 ± 0.22
HD 12392	0.30 ± 0.21	0.73 ± 0.12	0.88 ± 0.14	0.02 ± 0.21	1.03 ± 0.13	1.13 ± 0.12	1.19 ± 0.13	1.01 ± 0.13	0.91 ± 0.25	0.67 ± 0.27
HD 13551	0.79 ± 0.18	0.87 ± 0.10	0.81 ± 0.10	0.59 ± 0.16	0.95 ± 0.11	0.78 ± 0.10	0.70 ± 0.10	0.52 ± 0.10	0.36 ± 0.18	0.29 ± 0.22
HD 22589	0.67 ± 0.18	0.62 ± 0.10	0.86 ± 0.10	-0.01 ± 0.16	0.67 ± 0.11	0.49 ± 0.10	0.24 ± 0.10	0.11 ± 0.10	0.06 ± 0.18	-0.36 ± 0.22
HD 27271	0.33 ± 0.21	0.58 ± 0.12	0.73 ± 0.14	-0.35 ± 0.21	0.57 ± 0.13	0.41 ± 0.12	0.35 ± 0.13	0.22 ± 0.13	0.18 ± 0.25	0.00 ± 0.27
HD 48565	0.69 ± 0.18	0.66 ± 0.10	0.84 ± 0.10	0.15 ± 0.16	0.94 ± 0.11	1.04 ± 0.10	1.25 ± 0.10	0.96 ± 0.10	0.74 ± 0.18	1.00 ± 0.22
HD 76225	1.01 ± 0.18	0.92 ± 0.10	1.01 ± 0.10	0.35 ± 0.16	1.10 ± 0.11	0.97 ± 0.10	0.81 ± 0.10	0.52 ± 0.10	0.50 ± 0.18	0.60 ± 0.22
HD 87080	0.34 ± 0.18	0.45 ± 0.10	0.69 ± 0.10	-0.26 ± 0.16	0.82 ± 0.11	1.08 ± 0.10	1.07 ± 0.10	0.90 ± 0.10	0.58 ± 0.18	0.39 ± 0.22
HD 89948	0.92 ± 0.18	0.86 ± 0.10	0.87 ± 0.10	0.34 ± 0.16	0.83 ± 0.11	0.77 ± 0.10	0.55 ± 0.10	0.49 ± 0.10	0.44 ± 0.18	0.19 ± 0.22
HD 92545	0.41 ± 0.18	0.32 ± 0.10	0.43 ± 0.10	0.08 ± 0.16	0.72 ± 0.11	0.40 ± 0.10	0.28 ± 0.10	0.10 ± 0.10	0.12 ± 0.18	0.38 ± 0.22
HD 106191	0.45 ± 0.18	0.71 ± 0.10	0.87 ± 0.10	0.30 ± 0.16	0.68 ± 0.11	0.46 ± 0.10	0.41 ± 0.10	0.28 ± 0.10	0.64 ± 0.18	0.45 ± 0.22
HD 107574	0.63 ± 0.18	0.49 ± 0.10	0.48 ± 0.10	0.43 ± 0.16	1.24 ± 0.11	0.69 ± 0.10	0.55 ± 0.10	0.39 ± 0.10	0.23 ± 0.18	0.58 ± 0.22
HD 116869	0.09 ± 0.21	0.43 ± 0.12	0.52 ± 0.14	-0.36 ± 0.21	0.86 ± 0.13	0.80 ± 0.12	0.74 ± 0.13	0.70 ± 0.13	0.48 ± 0.25	0.69 ± 0.27
HD 123396	-0.10 ± 0.21	0.20 ± 0.12	0.69 ± 0.14	-0.70 ± 0.21	0.80 ± 0.13	0.77 ± 0.12	1.12 ± 0.13	1.05 ± 0.13	0.70 ± 0.25	0.70 ± 0.27
HD 123585	0.38 ± 0.18	0.51 ± 0.10	0.53 ± 0.10	0.17 ± 0.16	0.96 ± 0.11	0.82 ± 0.10	0.86 ± 0.10	0.58 ± 0.10	0.48 ± 0.18	0.72 ± 0.22
HD 147609	0.85 ± 0.18	0.83 ± 0.10	0.82 ± 0.10	-0.01 ± 0.16	0.83 ± 0.11	0.89 ± 0.10	0.90 ± 0.10	0.58 ± 0.10	0.48 ± 0.18	0.04 ± 0.22
HD 150862	0.50 ± 0.18	0.88 ± 0.10	0.92 ± 0.10	0.30 ± 0.16	0.83 ± 0.11	0.60 ± 0.10	0.35 ± 0.10	0.14 ± 0.10	0.25 ± 0.18	0.50 ± 0.22
HD 188985	0.69 ± 0.18	0.73 ± 0.10	0.89 ± 0.10	0.21 ± 0.16	0.91 ± 0.11	0.87 ± 0.10	0.94 ± 0.10	0.75 ± 0.10	0.53 ± 0.18	0.66 ± 0.22
HD 210709	0.01 ± 0.21	0.45 ± 0.12	0.71 ± 0.14	-0.38 ± 0.21	0.65 ± 0.13	0.60 ± 0.12	0.66 ± 0.13	0.55 ± 0.13	0.31 ± 0.25	0.37 ± 0.27
HD 210910	0.32 ± 0.21	0.00 ± 0.12	-0.18 ± 0.14	-0.73 ± 0.21	0.45 ± 0.13	0.20 ± 0.12	0.11 ± 0.13	0.01 ± 0.13	0.32 ± 0.25	-0.58 ± 0.27
HD 222349	0.81 ± 0.18	0.79 ± 0.10	0.98 ± 0.10	0.26 ± 0.16	1.14 ± 0.11	1.11 ± 0.10	1.16 ± 0.10	1.02 ± 0.10	0.65 ± 0.18	1.21 ± 0.22
BD+18 5215	0.91 ± 0.18	0.77 ± 0.10	1.01 ± 0.10	0.46 ± 0.16	1.22 ± 0.11	0.95 ± 0.10	0.87 ± 0.10	0.59 ± 0.10	0.64 ± 0.18	0.21 ± 0.22
HD 223938	0.24 ± 0.21	0.37 ± 0.12	0.69 ± 0.14	-0.45 ± 0.21	0.85 ± 0.13	0.67 ± 0.12	0.67 ± 0.13	0.71 ± 0.13	0.20 ± 0.25	0.60 ± 0.27
Star	[Sr/Ba]	[Y/Ba]	[Zr/Ba]	[Mo/Ba]	[Pb/Ba]	[Pr/Ba]	[Sm/Ba]	[Gd/Ba]	[Dy/Ba]	
HD 749	-0.50 ± 0.20	0.00 ± 0.10	0.27 ± 0.13	-1.05 ± 0.20	-0.80 ± 0.26	-0.29 ± 0.24	-0.25 ± 0.13	-0.86 ± 0.35	-0.26 ± 0.23	
HR 107	-0.20 ± 0.17	-0.35 ± 0.07	-0.38 ± 0.07	-0.35 ± 0.14	-0.05 ± 0.21	-0.43 ± 0.17	-0.65 ± 0.11	-0.40 ± 0.12	...	
HD 5424	-0.88 ± 0.20	-0.45 ± 0.10	-0.13 ± 0.13	-1.28 ± 0.20	-0.38 ± 0.26	-0.10 ± 0.24	-0.21 ± 0.13	-1.03 ± 0.35	0.17 ± 0.23	
HD 8270	-0.21 ± 0.17	-0.16 ± 0.07	-0.11 ± 0.07	-0.51 ± 0.14	-0.61 ± 0.21	-0.63 ± 0.17	-0.74 ± 0.11	-0.86 ± 0.12	-1.07 ± 0.09	
HD 12392	-0.73 ± 0.20	-0.30 ± 0.10	-0.15 ± 0.13	-1.01 ± 0.20	-0.36 ± 0.26	-0.12 ± 0.24	-0.04 ± 0.13	-0.94 ± 0.35	-0.76 ± 0.23	
HD 13551	-0.16 ± 0.17	-0.08 ± 0.07	-0.14 ± 0.07	-0.36 ± 0.14	-0.66 ± 0.21	-0.59 ± 0.17	-0.71 ± 0.11	-0.61 ± 0.12	-1.07 ± 0.09	
HD 22589	0.00 ± 0.17	-0.05 ± 0.07	0.19 ± 0.07	-0.68 ± 0.14	-1.03 ± 0.21	-0.61 ± 0.17	-0.80 ± 0.11	-0.85 ± 0.12	-0.84 ± 0.09	
HD 27271	-0.24 ± 0.20	0.01 ± 0.10	0.16 ± 0.13	-0.92 ± 0.20	-0.57 ± 0.26	-0.39 ± 0.24	-0.47 ± 0.13	-0.63 ± 0.35	-0.68 ± 0.23	
HD 48565	-0.25 ± 0.17	-0.28 ± 0.07	-0.10 ± 0.07	-0.79 ± 0.14	0.06 ± 0.21	-0.20 ± 0.17	-0.34 ± 0.11	-0.60 ± 0.12	-0.60 ± 0.09	
HD 76225	-0.09 ± 0.17	-0.18 ± 0.07	-0.09 ± 0.07	-0.75 ± 0.14	-0.50 ± 0.21	-0.60 ± 0.17	-0.82 ± 0.11	-0.91 ± 0.12	-1.06 ± 0.09	
HD 87080	-0.48 ± 0.17	-0.37 ± 0.07	-0.13 ± 0.07	-1.08 ± 0.14	-0.43 ± 0.21	-0.24 ± 0.17	-0.36 ± 0.11	-0.58 ± 0.12	-0.34 ± 0.09	
HD 89948	0.09 ± 0.17	0.03 ± 0.07	0.04 ± 0.07	-0.49 ± 0.14	-0.64 ± 0.21	-0.39 ± 0.17	-0.56 ± 0.11	-0.74 ± 0.12	-1.30 ± 0.09	
HD 92545	-0.31 ± 0.17	-0.40 ± 0.07	-0.29 ± 0.07	-0.64 ± 0.14	-0.34 ± 0.21	-0.60 ± 0.17	-0.80 ± 0.11	-0.90 ± 0.12	-0.95 ± 0.09	
HD 106191	-0.23 ± 0.17	0.03 ± 0.07	0.19 ± 0.07	-0.38 ± 0.14	-0.23 ± 0.21	-0.04 ± 0.17	-0.42 ± 0.11	-0.48 ± 0.12	-0.59 ± 0.09	
HD 107574	-0.61 ± 0.17	-0.75 ± 0.07	-0.76 ± 0.07	-0.81 ± 0.14	-0.66 ± 0.21	-1.01 ± 0.17	-1.07 ± 0.11	-1.35 ± 0.12	-1.37 ± 0.09	
HD 116869	-0.77 ± 0.20	-0.43 ± 0.10	-0.34 ± 0.13	-1.22 ± 0.20	-0.17 ± 0.26	-0.38 ± 0.24	-0.46 ± 0.13	-0.80 ± 0.35	-0.47 ± 0.23	
HD 123396	-0.90 ± 0.20	-0.60 ± 0.10	-0.11 ± 0.13	-1.50 ± 0.20	-0.10 ± 0.26	-0.10 ± 0.24	-0.11 ± 0.13	-0.49 ± 0.35	-0.11 ± 0.23	
HD 123585	-0.58 ± 0.17	-0.45 ± 0.07	-0.43 ± 0.07	-0.79 ± 0.14	-0.24 ± 0.21	-0.48 ± 0.17	-0.59 ± 0.11	-1.24 ± 0.12	-1.15 ± 0.09	
HD 147609	0.02 ± 0.17	0.00 ± 0.07	-0.01 ± 0.07	-0.84 ± 0.14	-0.79 ± 0.21	-0.35 ± 0.17	-0.48 ± 0.11	-0.77 ± 0.12	-0.87 ± 0.09	
HD 150862	-0.33 ± 0.17	0.05 ± 0.07	0.09 ± 0.07	-0.53 ± 0.14	-0.33 ± 0.21	-0.58 ± 0.17	-0.80 ± 0.11	-0.80 ± 0.12	-0.89 ± 0.09	
HD 188985	-0.22 ± 0.17	-0.18 ± 0.07	-0.02 ± 0.07	-0.70 ± 0.14	-0.25 ± 0.21	-0.38 ± 0.17	-0.48 ± 0.11	-0.66 ± 0.12	-1.01 ± 0.09	
HD 210709	-0.64 ± 0.20	-0.20 ± 0.10	0.06 ± 0.13	-1.03 ± 0.20	-0.28 ± 0.26	-0.34 ± 0.24	-0.43 ± 0.13	-0.78 ± 0.35	-0.58 ± 0.23	
HD 210910	-0.13 ± 0.20	-0.45 ± 0.10	-0.63 ± 0.13	-1.18 ± 0.20	-1.03 ± 0.26	-0.13 ± 0.24	-0.58 ± 0.13	-0.43 ± 0.35	-0.69 ± 0.23	
HD 222349	-0.33 ± 0.17	-0.35 ± 0.07	-0.16 ± 0.07	-0.88 ± 0.14	0.07 ± 0.21	-0.49 ± 0.17	-0.50 ± 0.11	-0.81 ± 0.12	-0.79 ± 0.09	
BD+18 5215	-0.31 ± 0.17	-0.45 ± 0.07	-0.21 ± 0.07	-0.76 ± 0.14	-1.01 ± 0.21	-0.58 ± 0.17	-0.76 ± 0.11	-0.31 ± 0.12	-0.92 ± 0.09	
HD 223938	-0.61 ± 0.20	-0.48 ± 0.10	-0.16 ± 0.13	-1.30 ± 0.20	-0.25 ± 0.26	-0.65 ± 0.24	-0.47 ± 0.13	-0.85 ± 0.35	-0.71 ± 0.23	

Table 8. Results of neutron exposures. Columns 2 and 3 correspond to results of the fittings to the theoretical predictions of Malaney (1987a) and Cols. 4 to 7 to those of Malaney (1987b). $S^2(u)$, $S^2(e8)$, $S^2(e12)$ are the fit quality, respectively, for single exposure, exponential exposure under neutron density 10^8 cm^{-3} , and exponential exposure under neutron density 10^{12} cm^{-3} . τ_o^a , τ_o^b , and τ_o^c are the mean distributions of neutron exposure corresponding to $S^2(u)$, $S^2(e8)$, and $S^2(e12)$, respectively. $\tau_o(f)$ and n_n are results corresponding to smaller S^2 . Column 10 shows if the best fit corresponds to exponential (exp) or single (sing) exposure. Columns 11 to 13 correspond to the results of the fit of σN curves, with χ_{red} as the quality of the fit. Numbers in parenthesis are errors in last decimals and were estimated directly from the fittings. The uncertainties on τ_o^a , τ_o^b , and τ_o^c were estimated in 0.1 mb^{-1} . For all cases, τ_o is given in mb^{-1} .

Star	$S^2(u)$	τ_o^a	$S^2(e8)$	τ_o^b	$S^2(e12)$	τ_o^c	$\tau_o(f)$	n_n	exp	$\tau_o(\sigma N)$	$G(\%)$	χ_{red}
HD 749	0.69	1.00	0.52	0.80	0.77	0.80	0.8	10^8	exp	0.406(5)	0.568(19)	0.73
HR 107	0.98	0.10	1.47	0.20	1.30	0.30	0.1	10^8	sing	0.43(6)	0.083(20)	0.56
HD 5424	0.85	1.10	1.15	0.80	1.71	0.80	1.1	10^8	sing	1.05(1)	0.086(1)	0.94
HD 8270	1.33	0.90	1.21	0.20	1.46	0.30	0.2	10^8	exp	0.27(1)	0.35(3)	0.41
HD 12392	0.46	1.10	0.38	0.80	0.79	0.80	0.8	10^8	exp	0.40(2)	0.73(3)	0.59
HD 13551	1.57	0.90	1.25	0.20	1.44	0.30	0.2	10^8	exp	0.22(1)	1.06(56)	0.50
HD 22589	1.10	0.80	0.89	0.20	1.27	0.20	0.2	10^8	exp	0.187(23)	1.25(54)	0.52
HD 27271	0.26	0.90	0.24	0.40	0.16	0.05	0.05	10^{12}	exp	0.272(14)	0.568(19)	0.35
HD 48565	3.14	1.00	1.34	0.40	2.66	0.05	0.4	10^8	exp	0.659(10)	0.0631(23)	0.32
HD 76225	0.80	0.10	0.71	0.20	1.83	0.30	0.2	10^8	exp	0.25(1)	0.83(12)	0.38
HD 87080	2.22	1.00	1.17	0.60	2.49	0.80	0.6	10^8	exp	0.71(1)	0.145(5)	0.48
HD 89948	0.67	0.10	0.45	0.20	1.65	0.30	0.2	10^8	exp	0.24(2)	0.77(36)	0.30
HD 92545	1.42	0.90	1.22	0.20	0.85	0.30	0.3	10^{12}	exp	0.291(3)	0.261(14)	0.40
HD 106191	1.36	0.90	1.16	0.40	0.72	0.05	0.05	10^{12}	exp	0.383(1)	0.130(1)	0.38
HD 107574	1.91	0.90	2.28	0.20	2.05	0.30	0.9	10^8	sing	0.298(2)	0.245(5)	0.42
HD 116869	0.14	1.10	0.18	0.80	0.33	0.80	1.1	10^8	sing	0.55(2)	0.0646(22)	0.55
HD 123396	0.46	1.10	0.84	0.80	1.24	0.80	1.1	10^8	sing	0.54(2)	0.0315(22)	0.54
HD 123585	2.17	1.00	0.98	0.40	2.14	0.50	0.4	10^8	exp	0.46(1)	0.275(15)	0.46
HD 147609	2.33	0.10	1.90	0.20	2.42	0.30	0.2	10^8	exp	0.288(7)	1.07(11)	0.41
HD 150862	0.66	0.90	1.57	0.20	1.11	0.30	0.9	10^8	sing	0.271(3)	0.489(26)	0.47
HD 188985	1.83	0.90	1.77	0.40	1.94	0.40	0.4	10^8	exp	0.401(4)	0.225(5)	0.39
HD 210709	0.11	1.10	0.19	0.80	0.26	0.80	1.1	10^8	sing	0.314(3)	0.303(9)	0.38
HD 210910	0.55	0.10	0.63	0.20	0.38	0.30	0.3	10^{12}	exp	0.44(4)	0.075(13)	0.52
HD 222349	3.02	0.90	1.28	0.40	2.00	0.05	0.4	10^8	exp	0.379(8)	0.170(12)	0.46
BD+18 5215	2.41	0.90	2.74	0.40	1.50	0.05	0.05	10^{12}	exp	0.274(1)	0.503(2)	0.63
HD 223938	0.26	1.00	0.20	0.50	0.29	0.70	0.5	10^8	exp	0.384(5)	0.229(9)	0.34