Investigation of the single neutron exposure model for the s-process: the primary nature of the neutron source

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ABSTRACT
The primary nature of the $^{12}$C neutron source is very significant for the studies of the s-process nucleosynthesis. In this paper we present an attempt to fit the element abundances observed in 16 s-rich stars using parametric model of the single neutron exposure. The calculated results indicate that almost all s-elements were made in a single neutron exposure for 9 sample stars. Although a large spread of neutron exposure is obtained, the maximum value of the neutron exposure will reach about 7.0 mbarn, which is close to the theoretical predictions by the AGB model. The calculated result is a significant evidence for the primary nature of the neutron source. Combining the result obtained in this work and the neutron exposure-initial mass relations, a large spread of neutron exposure can be explained by the different initial stellar mass and their time evolution. The possibility that the rotationally induced mixing process can lead to a spread of the neutron exposure in AGB stars is also existent.

Key words: nucleosynthesis; abundances-stars; AGB-stars.

1 INTRODUCTION
The two neutron-capture processes, the slow (s-process) and the rapid (r-process), occur under different physical conditions, and therefore are likely to arise in different astrophysical sites (Burbidge et al. 1957). The most likely site for the s-process is the inter-shell region of a thermally pulsing AGB star, provided a suitable neutron source is active. Our present understanding of the behavior of s-process nucleosynthesis has been reviewed by Busso, Gallino & Wasserburg (1999). There is a general consensus that the neutron source is the reaction $^{13}$C($\alpha$,n)$^{16}$O. In order to activate it, a partial mixing of protons (PMP) from the envelope down into the C-rich layers is required. PMP activates the chain of reactions $^{12}$C(p, $\gamma$)$^{13}$N($\beta$)$^{13}$C($\alpha$,n)$^{16}$O. The physical cause of PMP could be diffusive convective overshooting (Herwig et al. 1997; Goriely & Mowlavi 2000), rotationally induced mixing (Langer et al. 1999; Herwig, Lugaro & Langer 2003) and gravity waves (Denissenkov & Tout 2003). The s-elements produced in the deep interior by successive neutron captures are subsequently brought to the surface by the third dredge-up (Gallino et al. 1998). Using the primary-like neutron source ($^{13}$C($\alpha$,n)$^{16}$O) and starting with a very low initial metallicity, most iron seeds are converted into $^{208}$Pb. So, when third dredge up episodes mix the neutron capture products into the envelope, the star appears s-enhanced and lead-rich. Therefore, if the standard PMP scenario holds, all s-process-enriched AGB stars with metallicities [Fe/H]≤-1.3 are thus predicted to be Pb stars ([Pb/hs]≥1, where “hs” denotes the ‘heavy’ s-process elements such as Ba, La, Ce), independent of their mass and metallicity (Goriely & Mowlavi 2000).

The first three such lead stars (HD187861, HD224959, HD196944) have been reported by Van Eck et al. (2001). At the same time, Aoki et al. (2001) found that the slightly more metal-deficient stars LP 625-44 and LP 706-7 are enriched in s-elements, but cannot be considered as lead stars, in disagreement with the standard PMP predictions.

The large observation data spreads of [Pb/hs] are strong indication to suspect a large intrinsic spread of integrated neutron irradiations. A large spread of $^{13}$C pocket efficiencies is proposed by Straniero et al. (2005) in order to explain the spreads of [Pb/hs]. It should be stressed here that the primary nature of the $^{13}$C neutron source are rather robust (Goriely & Mowlavi 2000). In the framework of the PMP scenario, there is no obvious degree of freedom that could be used to reduce the $^{13}$C pocket efficiencies in low-metallicity AGB stars (Van Eck et al. 2003). The possibility that the rotationally induced mixing process may lead to a spread of the neutron exposure in AGB stars is proposed by Herwig, Lugaro & Langer (2003), Siess, Goriely & Langer (2004) explored the effects of rotationally induced mixing on the nucleosynthesis of s-elements during the TP-AGB phase. The results show that rotation of the AGB star quenches the s-process efficiency because of the contamination of the $^{13}$C layer by $^{14}$N. They find that although rotational mixing is an efficient mechanism to trigger the third dredge-up, this process fails to reproduce the observed strong s-process overabundances. The dependence of the...
induced mixing on the initial value of the rotational velocity is also largely unknown. So the fundamental problems, such as the formation and the consistency of the $^{13}$C pocket, the development of the third dredge-up and the neutron exposure signature in the interpulse, currently exist in the models of AGB stars. In contrast to other studies, Cui and Zhang (2006) find that a large spread of the $^{13}$C efficiency is not needed to explain the observed spread of [Pb/hs], but this comes naturally from the range of different initial stellar masses and their time evolution (see also Bonacić et al. 2006). The neutron exposure per circle deduced for the s-rich stars lies between 0.45 and 0.88 mbarn$^{-1}$ (Zhang, Ma & Zhou 2006). For the metallicites of the Pb-enhanced stars, based on the primary nature of the $^{13}$C neutron source (Busso, Gallino & Wasserburg 1999), the neutron exposure per interpulse will reach about 7.0 mbarn$^{-1}$ (Cui & Zhang 2006) which are about 10 times of the results obtained by Zhang, Ma & Zhou (2006) for s-rich metal-poor stars.

Another possibility is that the s-process material has experienced only a few neutron exposures in the convective He-burning shell. This is consistent with a proposed mechanism for the s-process in metal-poor AGB stars with [Fe/H] $<$−2.5 (Fujimoto, Ikeda & Iben 2000). These authors proposed a scenario in which the convective shell triggered by the thermal runaway develops inside the helium layer. Once this occurs, $^{13}$C captures proton to synthesize $^{13}$N and other neutron-source nuclei. The thermal runaway continues to heat material in the thermal pulse so that neutrons produced by the $^{22}$Ne($\alpha$, n)$^{25}$Mg reaction as well as the $^{13}$C($\alpha$, n)$^{16}$O reaction may contribute. It is possible that only one episode of $\alpha$-process mixing into He interpulse layer occurs in metal-poor stars (Fujimoto, Ikeda & Iben 2000, Aoki et al. 2001, Iwamoto et al. 2002). After the first two pulses no more proton mixing occurs although the third dredge-up events continue to repeat, so the abundances of the s-rich metal-poor stars can be characterized by only one neutron exposure. Detailed stellar evolution calculations are therefore highly desired, in order to clarify which site is the most likely to dominate the s-process in metal-poor AGB stars [interpulse (Gallino et al. 1998), or thermal pulse (Fujimoto, Ikeda & Iben 2000)].

Obviously, the detailed study of s-rich stars are needed in order to make progress in our understanding of the s-rich phenomenon, investigate what its physical reasons might be and for constraining what the possible physical conditions are. These reasons motivated us to start a systematic study for s-rich stars. In this paper we use the parametric approach of only one neutron exposure to investigate the characteristics of the nucleosynthesis pathway that produces the abundance ratios of s-rich objects.

## 2 PARAMETRIC MODEL OF THE SINGLE NEUTRON EXPOSURE

In order to investigate the efficiency of the s-process, the elemental abundances of s-rich stars are particularly useful. There have been many theoretical studies of s-process nucleosynthesis in low-mass AGB stars. Unfortunately, however, the precise mechanism for chemical mixing of protons from the hydrogen-rich envelop into the $^{12}$C-rich layer to form $^{13}$C-pocket ($^{12}$C(p,$\gamma$)$^{13}$N(e$^{-}$,$\nu$)$^{13}$C) is still unknown. In this paper we analyze the direct observational constraints provided by the photospheric composition of s-rich stars. Preliminary attempts to fit their abundances either using parameterized s-process distributions (e.g. Aoki et al. 2001) give encouraging results. For this reason, we use the parametric approach of only one neutron exposure, with many of neutron-capture rates updated (Bao et al. 2000), to investigate what physical conditions are possible to reproduce the observed abundance patterns found in the s-rich stars (Aoki et al. 2001, 2002, Cohen et al. 2003, Johnson & Bolte 2004, Lucatello et al. 2004, Barbuy et al. 2005, Ivans et al. 2005, Jonsell et al. 2006).

We explored the origin of the neutron-capture elements in s-rich stars by comparing the observed abundances with predicted s- and r-process contributions. The i-th element abundance in the envelope of the star can be calculated as follows (Zhang, Ma & Zhou 2006):

$$N_i(Z) = C_s N_{i,s} + C_r N_{i,r} 10^{\nu_i(Z)/\nu_{Fe/H}},$$

(1)

where Z is the metallicity of the star, $N_{i,s}$ is the abundance of the i-th element produced by the s-process in AGB star and $N_{i,r}$ the abundance of the i-th element produced by the r-process (per Si$=10^6$ at Z$=Z_\odot$), $C_s$ and $C_r$ are the component coefficients that correspond to relative contribution from the s-process and r-process. It should be noted that the s-process abundance in the envelope of the stars could be expected to be lower than the abundance produced by the s-process in AGB star because the material is mixed with the envelopes of the primary (former AGB star) and secondary stars.

For the single neutron exposure model, the overlap factor $\tau$, which is the fraction of material that remains to experience subsequent neutron exposures, is not a parameter because there is no material that experience subsequent neutron exposures. So there are only three parameters in the parametric model. They are the neutron exposure $\Delta\tau$, the component coefficient of the s-process $C_s$ and the component coefficient of the r-process $C_r$.

We can carry out s-process nucleosynthesis calculation of single neutron exposure to fit the abundance profile observed in the s-rich stars, in order to look for the minimum $\chi^2$ in the three-parameter space formed by $\Delta\tau$, $C_s$ and $C_r$. Using the method presented by Aoki et al. 2001), we chose Sr as the representative for the first peak elements, Ba as the representative for the second peak elements and Pb as the representative for the third peak elements, so the uncertainties of the parameters are determined by the error limits of the representative elements. The adopted initial abundances of seed nuclei lighter than the iron peak elements were taken to be the solar-system abundances, scaled to the value of [Fe/H] of the star. Because the neutron-capture-element component of the interstellar gas that formed very metal-deficient stars is expected to consist of mostly pure r-process elements, for the other heavier nuclei we use the r-process abundances of the solar system (Arlandini et al. 1999), normalized to the value of [Fe/H]. The adopted abundances of r-process nuclei in equation (1) are taken to be the solar-system r-process abundances (Arlandini et al. 1999) for the elements heavier than Ba, for the lighter nuclei we use solar-system r-process abundances multiplied by a factor of 0.4266 (Zhang, Ma & Zhou 2006).

## 3 RESULTS AND DISCUSSION

With the observed data in 16 sample stars, the model parameters can be obtained from the parametric approach. The results of the neutron exposures $\Delta\tau$, $C_s$, $C_r$ and s-process fractional contributions for Ba and Eu, $f_{Ba,s}$ and $f_{Eu,s}$ are listed in the table 1. For 9 sample stars (the first 9 stars listed in table 1), a single neutron exposure fits well the observed data within the error limits of the representative elements, whereas for others, although we can find...
the minimum $\chi^2$ in the three-parameter space, a single neutron exposure does not provide the parameters within the error limits for the entire representative elements.

Figure 1 shows our calculated best-fit results for the 9 sample stars. In order to facilitate the comparisons of the theoretical abundances with observations, the observed abundances of heavy elements are marked by filled circles in these figures. We note from the figure that, for most stars, the curves produced by the model are consistent with the observed abundances within the error limits. The agreement of the model results with the observations provides a strong support to the validity of the parametric model adopted in this work.

The neutron exposure deduced for s-rich stars lies between 0.7 and 7.12 mbarn$^{-1}$. Aoki et al. (2001) have reported a neutron exposure, $\Delta \tau \sim 0.71$ mbarn$^{-1}$ for metal-poor star LP 625-44 and $\Delta \tau \sim 0.8$ mbarn$^{-1}$ for LP 706-7, our calculated results are close to their values. Gallino et al. (1998) pointed out that the neutron density is relatively low, reaching $10^7$ cm$^{-3}$ at solar metallicity, corresponding to $\Delta \tau \sim 0.2$ mbarn$^{-1}$. Since the $^{13}$C neutron source is of primary nature, the typical neutron density in the nucleosynthesis zone scales roughly as $1/Z^{0.6}$, from $Z_\odot$ down to 1/50 $Z_\odot$. At lower metallicities, the effect of the primary poisons prevails (Busso, Gallino & Wasserburg 1999). For the metallicities of the sample stars [Fe/H]<-2.0, based on the primary nature of the $^{13}$C neutron source, the mean value of neutron density in the $^{13}$C-pocket is about 35 times of the value for solar metallicity (Gallino et al. 1999), which indicates that the neutron exposure per interpulse will reach about 7.0 mbarn$^{-1}$. It is interesting to note that, although a large spread of neutron exposure is shown in table 1, the maximum neutron exposure is close to this value.

We discuss the uncertainty of the parameters using the method presented by Aoki et al. (2001). Figure 2 shows the calculated abundances $\log\varepsilon$(Pb), $\log\varepsilon$(Ba) and $\log\varepsilon$(Sr) as a function of the neutron exposure $\Delta \tau$ in a model with $C_\ast=10.7$ and $C_e=0.0014$. These are compared with the observed abundances of HE 0024-2523. There is only one region in Figure 2, $\Delta \tau=7.12\pm0.32$ mbarn$^{-1}$, in which all the observed ratios of four representative elements can be accounted for within the error limits. The bottom panel in Figure 2 displays the reduced $\chi^2$ value calculated in our model with all detected elemental abundances being taken into account and there is a minimum, with $\chi^2=4.27$, at $\Delta \tau = 7.12$ mbarn$^{-1}$. For most sample stars shown in Figure 1, the uncertainties of the neutron exposure are smaller than that of HE 0024-2523.

It is worth commenting on the behavior of $\log\varepsilon$(Sr), $\log\varepsilon$(Ba) and $\log\varepsilon$(Pb) as a function of the neutron exposure $\Delta \tau$ seen in Figure 2. The nonlinear trends displayed in the plot reveal the complex dependence on the neutron exposure. The trends can be illustrated as follows. Starting at low neutron exposure and moving toward higher neutron exposure values, they show how the Sr peak elements are preferentially produced at nearly $\Delta \tau \sim 0$ mbarn$^{-1}$. At larger neutron exposure (e.g., $\Delta \tau \sim 0.7$ mbarn$^{-1}$), the Ba-peak elements become dominant. Then a higher value of $\log\varepsilon$(Pb) $\sim 2$ follows at $\Delta \tau = 1.5$ mbarn$^{-1}$. In this case, the s-process flow extends beyond the Sr-peak and Ba-peak nuclei to cause an accumulation at 208Pb. At very high neutron exposure values ($\Delta \tau > 2$ mbarn$^{-1}$), the role of Fe nuclei as seeds of the s-process is replaced partly by lighter (intermediate atomic mass) nuclei. Neutron capture on them can cross the iron peak, thus allowing the s-processing on heavy isotopes to continue. It is clear from Figure 2 that there is another maximum, with $\log\varepsilon$(Ba) $\sim 1.0$ at $\Delta \tau = 5.5$ mbarn$^{-1}$. In this case, the Ba-peak elements become dominant again. For extremely high neutron exposure values ($\Delta \tau > 6$ mbarn$^{-1}$), the lighter seeds are also converted into 208Pb. Clearly, $\log\varepsilon$(Pb) is very sensitive to the neutron exposure.

Our model is based on the observed abundances of the s-rich stars and the nucleosynthesis calculations, so the uncertainties of those observations and measurement of the neutron-capture cross sections will be involved in the model calculations. For HE 0024-2523, abundances of four neutron capture elements (Sr, Ba, La and Pb) and upper limits for an additional three elements (Y, Zr and Eu) have been taken into account in our model. The three upper limits will enlarge the uncertainties of the parameters. We note from Table 1 that for four stars (CS 31062-50, HE 2148-1247, LP 625-44, HE 0024-2523), the reduced $\chi^2$ are larger than 2. The probability that $\chi^2$ could be this large as a result of random errors in the measurement of the neutron-capture cross sections and abundances of the neutron-capture elements is less than 2%. We find that all these uncertainties cannot explain the larger errors of neutron-capture elements, such as Zr in HE 2148-1247 and Y in LP 625-44. This implies that our understanding of the true nature of s-process or r-process is incomplete for at least some of these elements (Travaglio et al. 2004).

It was possible to isolate the contributions corresponding to the s- and r-process by our parametric model. In the Sun, the elemental abundances of Ba and Eu consist of significantly different combinations of s- and r-process isotope contributions, with s/r ratios for Ba and Eu of 81:19 and 6:94, respectively (Arlandini et al. 1999). The Ba and Eu abundances are most useful for unraveling the sites and nuclear parameters associated with the s- and r-process correspond to those in extremely metal-poor stars, polluted by material with a few times of nucleosynthesis processing. We explored the contributions of s- and r-process for these two elements in the s-rich stars. In Table 1 we display the s-process fractions calculated from equation (1) for the 16 sample stars. Clearly, for the first 9 stars listed in table 1, the s/r ratios for Ba and Eu are larger than 90:10 and 15:85, which are larger than the ratios in the solar system. The abundances of r-elements, such as Eu, in s-rich stars are usually higher than those in normal stars, so s-rich stars seemed to be also enriched in r-elements, although in a lower degree than s-elements.

4 CONCLUSIONS

In this work, s- and r-process in s-rich stars were studied using the parametric approach of single neutron exposure. Theoretical predictions for abundances starting with Sr fit well the observed data for 9 sample stars (the first nine stars listed in table 1), providing an estimation for neutron exposure occurred in AGB stars. The calculated results indicated that almost all s-elements were made in the first neutron exposure for 9 sample stars. Once this happens, after only one time dredge-up, the observed abundance profile of the s-rich stars may be reproduced in a single neutron exposure. This should be consistent with a proposed mechanism for the s-process in metal-poor AGB stars with [Fe/H]<-2.5 (Fujimoto, Ikeda & Iben 2000).

For the third dredge-up and the AGB model, several important properties depend primarily on the core mass (Iben 1977; Karakas et al. 2002). The analytical formula for AGB stars given by Iben (1977) show that the overlap factor decreases with increasing core mass (Karakas et al. 2002) and Herwig et al. (2000, 2004) have also found that the third dredge-up is more efficient.
Table 1. Observed abundance ratios and the derived parameters for s-rich stars

| Star       | [Fe/H] | [Ba/Fe] | [Eu/Fe] | [Pb/Ba] | $\Delta \tau$ (mbarn$^{-1}$) | $C_s$ | $C_r$ | $f_{Ba,s}$ % | $f_{Eu,s}$ % | $\chi^2$ |
|------------|--------|---------|---------|---------|-----------------------------|------|------|--------------|--------------|---------|
| CS 29526-110 | -2.38  | 2.11    | 1.73    | 1.19    | 4.10                        | 0.0050 | 49.6 | 85.9         | 14.5         | 0.726588 |
| CS 22898-027 | -2.25  | 2.23    | 1.88    | 0.61    | 0.88                        | 0.0035 | 62.8 | 90.6         | 23.3         | 1.435540 |
| CS 31062-012 | -2.55  | 1.98    | 1.62    | 0.42    | 0.84                        | 0.0017 | 34.7 | 91.1         | 22.9         | 1.162933 |
| CS 31062-050 | -2.32  | 2.30    | 1.84    | 0.60    | 0.82                        | 0.0041 | 49.3 | 94.9         | 34.0         | 2.229041 |
| HE 2148-1247 | -2.30  | 2.36    | 1.98    | 0.76    | 0.90                        | 0.0049 | 64.5 | 92.3         | 28.1         | 2.130968 |
| LP 625-44    | -2.71  | 2.74    | 1.97    | -0.19   | 0.70                        | 0.0058 | 63.6 | 96.7         | 35.4         | 3.006556 |
| LP 706-7     | -2.74  | 2.10    | 1.40    | 0.27    | 0.84                        | 0.0019 | 59.1 | 96.1         | 41.3         | 0.602440 |
| HE 0024-2523 | -2.71  | 1.46    | 1.10    | 1.84    | 7.12                        | 0.0014 | 10.7 | 92.2         | 19.7         | 4.273823 |
| HE 0338-3945 | -2.42  | 2.41    | 1.94    | 0.69    | 0.90                        | 0.0055 | 55.5 | 94.0         | 33.8         | 1.435311 |
| CS 29497-34  | -2.90  | 2.03    | 1.80    | 0.92    | 3.80                        | 0.0035 | 56.9 | 82.6         | 8.5          | 2.399216 |
| HD 196944    | -2.25  | 1.10    | 0.17    | 0.80    | 3.30                        | 0.0010 | 5.0  | 99.2         | 69.0         | 2.598222 |
| CS 30301-015 | -2.64  | 1.45    | 0.2     | 0.25    | 3.76                        | 0.0007 | 0.7  | 98.6         | 58.3         | 3.644140 |
| CS 22948-34  | -2.57  | 2.32    | 1.99    | 1.33    | 4.54                        | 0.0053 | 67.3 | 85.2         | 10.3         | 2.459433 |
| CS 30322-023 | -3.41  | 0.54    | 0.15    | 0.95    | 4.12                        | 0.0002 | 0.1  | 99.3         | 72.2         | 1.576791 |
| CS 22183-015 | -3.12  | 2.09    | 1.39    | 0.7     | 1.28                        | 0.0056 | 21.5 | 85.0         | 17.0         | 1.291154 |

Figure 1. The Best fit to observational results of metal-deficient stars. The black circles with appropriate error bars denote the observed element abundances, the solid lines represent predictions from s-process calculations considering r-process contribution.

for the AGB stars with larger core masses. Since the core mass of AGB star at low metallicity is larger than high metallicity obviously (Zijlstra 2004), the overlap factor should be significantly smaller at low metallicity. This is consist with the small overlap factor, r=0.1, deduced by Aoki et al. (2001) for metal-poor stars LP 625-44 and LP 706-7. In an evolution model of AGB stars, a small r may be also realized if the third dredge-up is deep enough for s-processed material to be diluted by extensive admixture of unprocessed material. Clearly, the behavior of very deep dredge-up (r=0) is also single neutron exposure. Once this happens, no matter how many pulses
may follow, the observed abundance profile of the s-rich stars may be reproduced in several similar single neutron exposures.

For the sample stars, the maximum value of the neutron exposure obtained in this work reach about 7.0 mbar−1, which is close to the theoretical predictions by the AGB model (Busso, Gallino & Wasserburg 1999) and the maximum value of the case of radiative 13C-burning in the low mass AGB stars (Cui & Zhang 2006). So the calculated result should be a significant evidence for the primary nature of the neutron source.

The large spread of neutron exposure given in table 1 could be explained when varying the initial mass that affect dredge-up events and nucleosynthetic processes along the AGB evolution (Cui & Zhang 2006; Bonačić et al. 2006). Certainly, the possibility that the rotationally induced mixing process may lead to a spread of the neutron exposure in AGB stars is also existent. For intermediate mass stars, the rapid rotation and significant amount of shear at the bottom of the convective envelope in AGB stars are hard to avoid. The rotations of the AGB star will quench the s-process efficiency and reduce the neutron exposure. Through a distribution of initial rotation rates, it may be lead to a natural spread of neutron exposure in AGB stars. In table 1, one interesting result is that, based on the values of the neutron exposure, the sample stars should be divided into two groups: one group (include 8 sample stars) concentrate on the value of about 0.8 mbar−1 which correspond to the value of 2.5M⊙ AGB star calculated by Cui & Zhang (2006), and the others (include 8 also sample stars) are in the range of 1.3–7.12 mbar−1 which correspond to the range of 1.5–2.0 M⊙. Should the observed abundance pattern of the group one belongs to be polluted by the rapid rotators or the AGB stars with initial mass of about 2.5–3.0 M⊙? Obviously, large uncertainties still remain in this topic. More in-depth theoretical and observational studies of s-rich stars will reveal the characteristics of the s-process at low metallicity, such as their initial rotation rate and initial mass dependence, and the history of enrichment of s- and r-elements in the early Galaxy.

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REFERENCES

Aoki W. et al., 2001, ApJ, 561, 346
Aoki W., Reyan S.G., Norris J.E., Beers T.C., Ando H., Tsangarides S., 2002, ApJ 580, 1149
Arlandini C., Käppeler F., Wisshak K., Gallino R., Lugaro M., Busso M., Straniero O., 1999, ApJ, 525, 886

Figure 2. Calculated abundances logε(Pb), logε(Ba), logε(Sr) and reduced χ2, as a function of the neutron exposure per pulse, Δτ, in a model with C_r=10.7 and C_s=0.0014. Solid curves refer to the theoretical results, and dashed horizontal lines refer to the observational results with errors expressed by dotted lines for HE 0024-2523. The shaded area illustrates the allowed region for the theoretical model.
