Mass Fraction of $^{13}$C-Pocket in Metal-Poor AGB Stars and the Primary Nature of Neutron Source

CUI Dong-Nuan, GENG Yuan-Yuan, CUI Wen-Yuan, ZHANG Bo

Department of Physics, Hebei Normal University, Shijiazhuang 050016
Hebei Advanced Thin Films Laboratory, Shijiazhuang 050016

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Chemical abundances of very metal-poor s-rich stars contain excellent information to set new constraints on models of neutron-capture processes at low metallicity. Using the parametric approach based on the radiative s-process nucleosynthesis model, we obtain the mass fraction $q$ of $^{13}$C-pocket, the overlap factor $r$, the neutron exposure per interpulse $\Delta \tau$, and the component coefficients of the s-process and the r-process for 25 s-rich stars, respectively. We find that $q$ deduced for the lead stars is comparable to the overlap factor $r$, which is larger than the standard case (hereafter ST case) of the AGB model ($q \sim 0.05$) about 10 times, and $\Delta \tau$ are about 10 times smaller than the ST case ($\Delta \tau = 7.0 \text{mbarn}^{-1}$). Although the two parameters obtained for the lead stars are very different from the ST case of the AGB stellar model, it is worth noting that the total amounts of $^{13}$C in metal-poor condition are close to the ST case. The above relation is a significant evidence for the primary nature of the neutron source and the lead stars could be polluted by low-mass AGB stars. Because interpulse period declines with increasing stellar mass, for high-mass AGB star, the neutron irradiation may be terminated due to their shorter interpulse period. Thus the neutron exposure per interpulse of the larger AGB stars should be about 10 times smaller than the ST case. In this case, the primary nature of the neutron source also exists. 

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The s-process elements have been synthesized in the intershell region between the C-O core and the convective H-rich envelope of thermally pulsing asymptotic giant branch (AGB) stars. The main neutron source is believed to be $^{13}$C nuclei, releasing neutrons via $^{13}$C$(\alpha, n)^{16}$O reaction in the thin layer of the intershell (the $^{13}$C-pocket, see e.g. Gallino et al. 1998 for details) during the interpulse phases. In order to activate it, a partial mixing of protons (PMP) from the envelope down into the C-rich layers is required. In low mass AGB stars, the main source of neutrons, the $^{13}$C$(\alpha, n)^{16}$O is primary-like, i.e. not directly affected by the metallicity of the material. Nevertheless, the iron seeds scale with the metallicity, so that the lower the metallicity is the larger the number of neutrons available per seed. If the standard PMP scenario holds, all s-process-enriched AGB stars with metallicities $[\text{Fe}/\text{H}] \leq -1.3$ are predicted to be lead stars ($[\text{Pb}/\text{hs}] \gtrsim 1$, where hs denotes the ‘heavy’ s-process elements such as Ba, La, Ce), independent of their mass and metallicity.

The first three such lead stars (HD 187861, HD 224959, HD 196944) have been reported by Van Eck et al. At the same time, Aoki et al. 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. Recently, more s-rich and lead-rich stars have been reported. A large spread of $^{13}$C-pocket efficiencies is proposed by Straniero et al. to explain the spreads of $[\text{Pb}/\text{hs}]$. In fact, 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. In order to derive constraints on the free parameters describing the properties of the neutron source, the spreads of $[\text{Pb}/\text{hs}]$ are also used by Bonačić Marinović et al. They found that the abundance ratios of [hs/ls] for the s-rich stars could not be reproduced simultaneously in their calculations, where ls denotes the ‘light’ s-process elements such as Sr, Y, Zr. At present, the physical explanation for the different $^{13}$C-pocket strengths, which perhaps should not be consistent with the primary nature of the neutron source, is not found yet. Thus the fundamental problems, such as the formation and the consistency of the $^{13}$C-pocket, the neutron exposure signature in the interpulse period, currently exist in the models of AGB stars.

In contrast to the other studies, Cui and Zhang find that a large spread of the $^{13}$C efficiency is not needed to explain the observed spread of $[\text{Pb}/\text{hs}]$, but this comes naturally from the range of different initial stellar masses and their time evolution (see also Bonačić Marinović). Zhang and Ma investigated the characteristics of the nucleosynthesis path-
way that produces the abundance ratios of the s-rich stars using the parametric model of the s-process without adopting any specific stellar model. The neutron exposure per circle deduced for the s-rich stars lies between 0.45 and 0.88 mbarn$^{-1}$. For the lead-enhanced stars, based on the primary nature of the $^{13}$C neutron source,[13] the neutron exposure per interpulse will reach about 7.0 mbarn$^{-1}$,[15] which are about 10 times of the results obtained by Zhang and Ma (2006)[16] for s-rich metal-poor stars. Ma et al.[17] investigated the neutron exposure using parametric model of the single neutron exposure. The calculated result is a significant evidence for the primary nature of the $^{13}$C neutron source. However, they did not consider that the s-process does happen in the $q$ zone (i.e. $^{13}$C-pocket) of He intershell.

There have been many theoretical studies of s-process nucleosynthesis in low-mass AGB stars. The most likely site for the s-process is the intershell region (i.e. $^{13}$C-pocket) of a thermally pulsing AGB star, provided that a suitable neutron source is active. Unfortunately, the precise mechanism for chemical mixing of protons from the hydrogen-rich envelope into the $^{13}$C-rich layer to form $^{13}$C-pocket ($^{12}$C($p,\gamma$)$^{13}$N($\beta$)$^{13}$C) is still unknown. Thus, there are still large uncertainties associated with the formation of the $^{13}$C neutron source. This makes it even harder to understand the particular abundance pattern of the s-process elements found in metal-poor stars. Obviously, detailed studies of s-rich stars are needed to make progress in our understanding of the s-rich phenomenon. We should investigate what its physical reasons might be and constrain what the possible physical conditions are. In this Letter we use the parametric approach considering that the s-process does happen in the $q$ zone of He intershell to investigate the characteristics of the nucleosynthesis pathway that produces the abundance ratios of s-rich objects.

We use the parametric approach based on the model of low-mass AGB star computed by Gallino et al.[2] with the updated neutron-capture rates (Bao et al.[18]) to investigate what physical conditions are possible to reproduce the observed abundance pattern found in the s-rich stars. The final s-process abundance distributions depend only upon the neutron exposure $\Delta\tau$, the mass fraction of $^{13}$C-pocket in the He intershell $q$ and the overlap factor $r$. The ith element abundance in the envelope of a star can be calculated as follows:[16]

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

(1)

where $Z$ is the metallicity of the star, $N_{i,s}$ is the abundance of the ith element produced by the s-process in AGB star and $N_{i,r}$ is the abundance of the ith 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 the r-process. Based on Eq. (1), we can carry out s-process nucleosynthesis calculation combined with the contribution of r-process to fit the abundance profile observed in the s-rich stars, in order to look for the minimum $\chi^2$ in the five-parameter space formed by $r$, $\Delta\tau$, $q$, $C_s$ and $C_r$. Using the method presented by Aoki et al.[5] and Cui et al.[19] we choose Sr, Ba and Pb as the representative for the first, second and third peak elements, respectively, 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 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.[20]) normalized to the value of [Fe/H].

Using the observed data of 25 sample stars,[5–11,21–26] the model parameters can be obtained from the parametric approach. The results of the neutron exposures $\Delta\tau$, overlap factors $r$, the mass fraction of $^{13}$C-pocket $q$ and the component coefficients are listed in Table 1.

The neutron exposure per pulse $\Delta\tau$ deduced for the s-rich stars lies between 0.44 and 0.90 mbarn$^{-1}$. Gallino et al.[2] have pointed out that the neutron number density is relatively low, reaching $10^7$ cm$^{-3}$ at solar metallicity, corresponding to $\Delta\tau = 0.2$ mbarn$^{-1}$. For the metallicities of the s-rich stars, based on the primary nature of the neutron source, the neutron exposure per interpulse will reach about 7.0 mbarn$^{-1}$, which are about 10 times larger than the results obtained in this work for the s-rich stars.

The overlap factor deduced for the s-rich stars lies between 0.1 and 0.88, which is similar to the result obtained by Zhang et al.[16] In an evolution model of AGB stars, a small $r$ may be realized if the third dredge-up is deep enough for s-processed material to be diluted by extensive admixture of unprocessed material. Karakas[27] and Herwig[28] have found that the third dredge-up is more efficient for the AGB star with high core mass. The overlap factor $r$ deduced for the lead stars ([Pb/hs] $\gtrsim 1$) is larger than 0.50, which implies that the formation of lead stars could be explained by the matter transfer from the lower mass AGB star. Taking into account the dependence of the initial-final mass relations on metallicity, the large range $r$-value for the s-rich stars could possibly be explained by large range core-mass value of AGB stars at low metallicity.
The mass fraction of $^{13}$C-pocket, $q$, is an important parameter in the radiative s-process nucleosynthesis models. Busso et al.[29] have suggested that keeping the total amount of $^{13}$C and total mass of the $^{13}$C-pocket (i.e., $q = 0.05$) as in the ST case for all metallicities, the s-process-enriched AGB stars with metallicities are predicted to be lead stars. The standard case (ST) corresponds to the choice of the mass of the $^{13}$C-pocket to $3.1E^{-6}M_{\odot}$ of $^{13}$C,[2] which can reproduce the abundance distribution of the solar main component at metallicity $Z = Z_{\odot}/2$ (see also Arlandini et al.[29]). The mass fraction of $^{13}$C-pocket deduced for the lead stars lies between 0.32 and 0.87, which are larger than the value of the ST case about from 7 to 17 times, this seems not to support the hypothesis that the total mass of the $^{13}$C-pocket is similar for all metallicities. The results also imply that the larger value of $q$ and the smaller value of neutron exposure $\Delta\tau$ than the ST case can also explain the abundance distribution of the lead stars. Since the s-process nucleosynthesis occurs in the $q$ layer, an increase in $q$ can effectively increase the fraction of Fe seeds with higher neutron exposure, which favours the production of heavier neutron-capture elements.[5,30]

We compare the parameters obtained for the lead stars with the ST case presented by Gallino et al.[2] It is interesting to note that for the lead stars there is a fair relation between $q$ and $\Delta\tau$. The results obtained for the lead stars can be understood as that, for the low mass AGB stars with low metallicity, the mass of the $^{13}$C-pocket are larger than that with the solar metallicity about 10 times, since the total amount of $^{13}$C keep in the ST case for all metallicities, a reduction of the neutron exposure per interpulse, $\Delta\tau$, by factor about 10 is required. Although the two parameters obtained for the lead stars are very different from the ST case of the AGB stellar model, it is worth noting that the total amounts of $^{13}$C in lead stars are close to the ST case. The relation obtained from this work is a significant evidence for the primary nature of the neutron source. In fact, the other s-rich stars with $q \gtrsim 0.30$ could also be explained by this scenario.

In the s-process scenario that invokes radiative-burning, the nucleosynthesis mostly occurs during the relatively long interpulse period, in the radiative layer at the top of the He intershell. Because interpulse period declines with increasing stellar mass, for the high-mass AGB star, the neutron irradiation...
terminated due to their shorter interpulse period (Cui and Zhang[15]). The results obtained for four sample stars with $q < 0.1$ (the last four stars listed in Table 1) could be explained as that both the total amount of $^{13}\text{C}$ and the mass of the $^{13}\text{C}$-pocket are similar to that of the ST case, but the neutron irradiation time is shorter for the high-mass AGB stars, so the neutron exposure per interpulse of these stars should be about 10 times smaller than the ST case. In this case, the primary nature of the neutron source also exists. As an example, it is interesting to investigate a possible explanation of the parameters obtained for HE 2148-1247 which are $r = 0.1$ and $\Delta r = 0.88$ nbarn$^{-1}$. Adopting the analytical formula for the overlap factor and core mass of AGB stars given by Iben[31] and the initial-final mass relations,[32] we can know that the initial mass of the former AGB star is about $3-4M_\odot$, which lies in the range of $M \sim 3-12M_\odot$ reported by Cohen et al.[7]

The mass fraction of $^{13}\text{C}$-pocket deduced for the s-rich stars is close to the value of the overlap factors (see Fig. 1). Aoki et al.[9] and Suda et al.[33] discussed another possibility that the s-process should take place during thermal pulses in the AGB stars. In this case, the mixed $^{13}\text{C}$ is diluted over the entire helium convective zone and will not give such large numbers of neutrons allotted per seed nuclei as predicted from the radiative $^{13}\text{C}$ burning model. The results obtained in this work may also be interpreted as an evidence that there exists a critical metallicity near [Fe/H] = $-2.0$ below which the radiative $^{13}\text{C}$ burning is ineffective during the third dredge-up. Further studies to identify the physical mechanism that produces neutron-capture elements of s-rich stars are clearly desired.

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**References**