SiCの重元素同位体分析　～AGB星で起こった中性子捕獲反応の考察～

○ 寺田健太郎（広島大理）、吉田敬（国立天文台）、
岩本信之（日本原子力研究開発機構）、青木和光(国立天文台)、
I. S. Williams(オーストラリア国立大学)

Introduction:

It is generally agreed that Asymptotic Giant Branch stars (AGB stars) are the main contributors of the slow neutron capture process (s-process) elements. According to the recent stellar evolution models of thermally pulsing AGB stars [1-4], the best candidate reactions for the neutron source are $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ and/or $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$. The former reaction operates at temperatures from about 8 keV up to 10keV in the ^{13}C-pocket at the top of the He inter-shell during the inter-pulse phase, where the neutron density is low (up to 10^7 cm^{-3} in solar-metallicity stars). This phase is followed by He-shell flash episodes which are characterized by higher temperatures of 25–30 keV. In this flash phase, the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ reaction is activated and gives rise to a higher neutron density (10^8–10^{11} cm^{-3} in the case of solar-metallicity stars).

Several approaches based on the chemical and isotopic composition of the bulk of Solar system materials have been used to try and understand the "origin of the s-process element in the Solar system" [e.g. 5-8]. For example, based on the σN curve of isotopes produced only by the s-process, Howard et al. [5] calculated average neutron densities of $N_n = 1.1\ (+0.6, -0.3) \times 10^8$ cm^{-3} at an optimum temperature of $T = (2.7 \pm 0.3) \times 10^8$ K and a mean neutron exposure of $\tau_0 = 0.26 \pm 0.01$ mbarn^{-1}. Wisshak et al. [6] and Toukan et al. [7] suggested that neutron densities were possibly $N_n = (4.1 \pm 0.6) \times 10^8$ cm^{-3} and $N_n = (3.8 \pm 0.6) \times 10^8$ cm^{-3}, respectively, based on the $^{148}\mathrm{Sm}/^{150}\mathrm{Sm}$ isotopic ratio of bulk solar materials. Moreover, Wisshak et al. [8] suggested a temperature of 28–33 keV based on the $^{152}\mathrm{Gd}/^{154}\mathrm{Gd}$ ratio of solar materials. They suggested that this higher temperature and neutron density might result from the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ reaction being the neutron source.

In contrast, a series of studies of relict presolar grains in primitive meteorites has provided a different point of view of nucleosynthesis in AGB stars (for a general review, see [9]). For example, the enhancements of ^{25}Mg expected as a result of the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ reaction are uncommon, even in the presolar grains rich in s-process elements [10], indicating that the $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ reaction is a more likely neutron source. Nicolussi et al. [11] suggested, based on Mo and Zr measurements, that most of the SiC grains condensed around low-mass AGB stars where the $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ reaction is the principal neutron source. Moreover, Nicolussi et al. [12] suggested that neutron densities in most parent stars were lower than 10^7 cm^{-3}, based on the observation that the measured $^{88}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratios in most SiC grains indicated the dominant β decay of short-lived ^{85}Kr. To better understand the physical parameters of nucleosynthesis in parent stars prior to formation of the Solar system, we focus here on the *s*-process parameters reflected in Eu isotopic compositions.

Analytical methods and results:

Presolar SiC grains were recovered from the Murchison meteorite using the procedure of Amari and others [13]. The grains remaining after acid digestion and density separation, corresponding to the KJ fraction [13], were mounted by pressing them onto a copper plate. They were analyzed for major elements and identified by the Electron Probe Micro Analyzer at Hiroshima University, then the three largest SiC grains (>5 µm) were selected for isotopic study.

First the Si and C isotopic compositions of individual grains were measured on the SHRIMP II at the Australian National University, using a Cs$^+$ primary ion beam. The Eu isotopic compositions of same grains were then measured on the SHRIMP II at Hiroshima University, using an O_2^- primary beam. Details of the experimental procedures and calibrations are given in [14].

Among three grains, grain SiC35 and SiC67 have slightly lower $^{12}\mathrm{C}/^{13}\mathrm{C}$ than the terrestrial reference value of 89. They are also slightly enriched in ^{29}Si and ^{30}Si relative to ^{28}Si. These are the characteristics of Mainstream grains [15], considered to originate from low-mass AGB stars with a solar metallicity. On the other hand, grain SiC39 is depleted in ^{12}C and has a large excess in ^{30}Si relative to ^{28}Si and ^{29}Si ($^{12}\mathrm{C}/^{13}\mathrm{C} = 55$, $\delta(^{30}\mathrm{Si}/^{28}\mathrm{Si}) = 278$ and $\delta(^{29}\mathrm{Si}/^{28}\mathrm{Si}) = 12$), indicating that it is a Z-grain [9]. It is proposed that such grains come from low-mass stars of much lower metallicity (approximately less than one-third solar) [15, 16].

The measured $^{153}\mathrm{Eu}/^{151}\mathrm{Eu}$ ratios in Mainstream grains SiC35 and SiC67 are 1.29 ± 0.24 and 1.33 ± 0.24, within error of the solar value of 1.09 [17], but significantly higher than the ratios of 0.85 and 0.71 predicted for products of the *s*-process by the stellar and classical models respectively [18]. In contrast, the Eu content of Z-grain SiC39 was so low that a precise isotopic analysis could not be obtained (0.97 ± 0.52). This might be concerned with the parent

AGB star for this type of grain being a low-metallicity star. The discussion below is based on an average ^{153}Eu/^{151}Eu ratio of 1.3 ± 0.2 in the two Mainstream grains, which were considered to originate from low-mass AGB stars with a solar metallicity.

Discussion:

To further investigate the s-process by using Eu isotopes, we have calculated expected Eu isotopic ratios as a function of nucleosynthetic conditions, in accordance with [19]. Here, in order to simply understand complicated nuclear flows (which are realized in the s-process of an AGB model) in wide ranges of temperature and neutron density, we adopted simple assumptions (constant temperature and neutron density conditions, in which recurrent neutron exposures are followed) for the usual s-process with the two major neutron sources. To follow the nuclear flow around the Nd-Pm-Sm-Eu-Gd region, we have used a nuclear network code in which the temporal variation of nuclides is solved with updated neutron capture rates [20], beta-decay rates and electron capture rates [21] under with various temperature and neutron density conditions. We used the recently reported neutron capture cross section for the unstable nucleus ^{151}Sm ([22], [23]). The new ^{151}Sm(n,γ) rate is a factor of 2 larger than previous theoretical predictions (e.g., [24]).

Figure 1 illustrates the changes in ^{153}Eu/^{151}Eu as a function of temperature and neutron density for different neutron exposures ($\tau_0 = 0.3$ mbarn^{-1} and $\tau_0 = 0.03$ mbarn^{-1}, respectively). As shown in Figure 1, the predicted ^{153}Eu/^{151}Eu ratios are sensitive to temperature (T) and neutron density (N_n), so the observed ^{153}Eu/^{151}Eu ratio could be a good probe for the values of these s-process parameters in the He-layer. On the other hand, the differences between ^{153}Eu/^{151}Eu ratios at $\tau_0 = 0.3$ and 0.03 mbarn^{-1} are less than 2%, indicating that the Eu isotopic ratio is not sensitive to the neutron exposure.

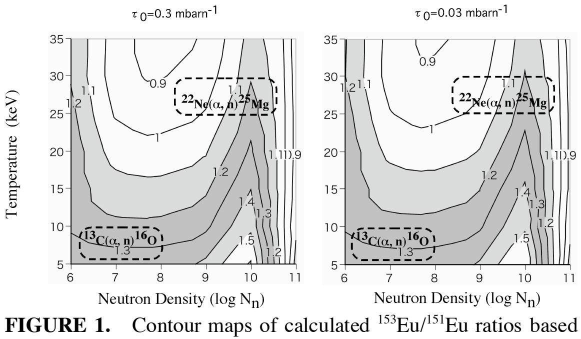

FIGURE 1. Contour maps of calculated ^{153}Eu/^{151}Eu ratios based on the thermally pulsed s-process model using the new ^{151}Sm(n,γ) reaction rate.

The observed ^{153}Eu/^{151}Eu ratio of the Mainstream grains (average 1.3 ± 0.2) constrains the possible *s*-process temperature and neutron density conditions to the gray area in Figure 1; that is, (i) T < 15 keV for 10^7–10^9 cm^{-3}, and/or (ii) T > 10 keV for 10^{10} cm^{-3}. The plausible regions of $^{13}C(\alpha, n)^{16}O$ and/or $^{22}Ne(\alpha, n)^{25}Mg$ based on the recent stellar evolution models of thermally pulsing AGB stars [1-4], are also shown as dashed enclosures. It should be noted that ^{153}Eu/^{151}Eu values previously predicted by the stellar model (0.85) and the classical model (0.71) assuming that $N_n = 4.1 \times 10^8$ cm^{-3} [18] are out of range of not only the possible neutron sources of $^{13}C(\alpha, n)^{16}O$ and $^{22}Ne(\alpha, n)^{25}Mg$, but also of the extended region of Figure 1 (5–35 keV and 10^6–10^{11} cm^{-3}). This discrepancy is possibly due to the different reaction rate previously used for ^{151}Sm(n,γ).

Both the recent theoretical studies [4] and the analysis of individual presolar grains [11] shows that *s*-process elements in the solar system are derived predominantly from $^{13}C(\alpha, n)^{16}O$ sources. It should be noted that our data closely match the current ^{13}C-pocket model (<10 keV at about 10^7 cm^{-3}), but the neutron source of $^{22}Ne(\alpha, n)^{25}Mg$ is still possibly about 10^{10} cm^{-3}. For tighter constraints on the *s*-process conditions, much higher precision analyses of ^{153}Eu/^{151}Eu ratios, coupled with analyses of isotopic compositions of other heavy elements sensitive to s-process branchings in the same grains, would be required.

References:

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