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The Eu Isotopic Ratios in CEMP Stars

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Abstract

Understanding the chemical evolution of galaxies requires accurate abundances of chemical elements in various stellar populations, which are then compared with theoretical predictions to probe their nucleosynthetic origin. However, most of the elements have several stable isotopes which are produced by different nucleosynthetic reactions, thus making multiple contributors to their overall abundance. The situation will be more complex in the case of heavy elements produced by different neutron capture processes. Hence, the abundances at the isotopic levels are more important to constrain the conditions at which the nucleosynthesis takes place and also to identify the actual isotopic path followed by the different neutron capture processes. This will help us identify the relative contribution of different neutron capture processes to the abundance of individual elements, and it is an essential ingredient of the GCE models. Moreover, the contribution of different astrophysical sites, such as AGB stars, to the overall chemical enrichment of our Galaxy can be estimated with greater accuracy. Here we present the preliminary results of our attempt to measure the Eu isotopic abundance in a sample of s-process-enhanced stars at various metallicities. The purpose of this analysis is primarily to demonstrate the feasibility of the technique and a detailed quantitative analysis will be presented in a future paper.

Keywords: Metal poor stars, Nucleosynthesis, Neutron capture process, Abundance, AGB, Isotopic ratios

1. Introduction

The stars within a mass range of $0.8\,M_\odot$ to $10\,M_\odot$, the so-called low- and intermediate-mass stars, are the predominant members of all the galaxies. They are found at different metallicities and show a variety of abundance patterns in their atmospheres. Thus they can provide immense information about the formation of chemical elements in their host galaxies. The longest-lived low-mass stars can synthesize half of the elements heavier than iron when they are at the Asymptotic Giant Branch phase (AGB) through the slow-neutron capture process.

Recent studies (Hampel et al., 2019, 2016; Karinkuzhi et al., 2021b,a) indicate the occurrence of the intermediate neutron capture process in very low-mass low-metallicity AGB stars.

Our comprehension of the different nucleosynthesis processes is currently reliant on the abundance of chemical elements they produce. Despite Ba being used as the hallmark element for the s-process, several of its stable isotopes are primarily produced during the rapid neutron-capture process, another nucleosynthetic process responsible for the other half of the heavy elements (Arlandini et al., 1999; Burris et al., 2000; Lodders et al., 2009). This situation becomes more complex after the identification of the i-process in AGB stars (Choplin et al., 2021; Denissenkov et al., 2017; Hampel et al., 2016). Currently, the differentiation between the s-process and the i-process is very difficult. The majority of elements have several stable isotopes originating from various neutron-capture processes. Consequently, isotopic abundances can provide more information about the contribution of various nucleosynthesis processes to the origin of chemical elements. For example, during their investigation of heavy element isotopes under i-process conditions, Choplin et al. (2021) predicted that certain isotopes of Ba, Nd, Sm, and Eu are excessively produced during the i-process. Hence, it is essential to identify the fraction of various isotopes contributing to the overall abundance of their parent elements. Despite this importance, even with very high-resolution spectrographs, it remains challenging to measure the abundances at the isotopic level as the shift produced by them is very small. But the elements such as Ba and Eu exhibit relatively significant isotopic shifts making it possible to measure them at moderately high resolution. Moreover, some of their atomic lines are less affected by the changes in atmospheric parameters thus making the measurements relatively free from uncertainties.

Our aim here is to derive Eu isotopic ratios for a sample of carbon-enhanced metal-poor (CEMP) stars that have been found to be enriched in heavy elements from our previous study (Karinkuzhi et al., 2021b). Our study includes two abundance classes of CEMP stars; CEMP-s with enrichment of s-process elements and CEMP-rs stars with enrichment of both s-and r-process elements. The element Eu has two stable isotopes, ^{151}Eu and ^{153}Eu, and has a comparatively high isotopic shift which can be measured with a resolution ($R \approx 80,000$). The Eu isotopic ratios are an important constraint for the different nucleosynthesis processes. A few studies already derived the isotopic ratios of Eu in CEMP-stars (Sneden et al., 2002; Aoki et al., 2003a,b; Roederer et al., 2008). Sneden et al. (2002) and Aoki et al. (2003a) studied the Eu isotopic ratios in four CEMP-r stars and found that the Eu isotopic ratios in these stars agree well with that in the solar system materials. Aoki et al. (2003b); Roederer et al. (2008) explored this ratio in CEMP-s stars.

2. Data and Analysis

We derive the Eu isotopic ratios in a sample of CEMP stars studied by Karinkuzhi et al. (2021b). We adopted the same atmospheric parameters and abundance as these authors; they are given in Table 1. The high-resolution spectra of the program stars were acquired using HERMES Spectrograph connected to a 1.2 m Mercator telescope ($R \approx 86,000$). We used the Eu line at 6437.640 Å to derive the isotopic ratios comparing the synthetic spectra generated

Table 1: Programme stars.

Name	$T_{\rm eff}$ (K)	$\log g$ (cgs)	ξ (km s^{-1})	[Fe/H]	Class	$\log\varepsilon$ (lit.)	$\log\varepsilon$
HD 5223	4650 ± 120	1.03 ± 0.30	2.16 ± 0.14	-2.00 ± 0.08	rs	-0.30	-0.30
HD 145777	4443 ± 57	0.50 ± 0.10	2.63 ± 0.10	-2.32 ± 0.10	rs	-0.83	-0.83
HD 198269	4458 ± 15	0.83 ± 0.08	1.64 ± 0.09	-2.10 ± 0.10	s	-0.91	-0.90
HE 0507-1653	5035 ± 53	2.39 ± 0.16	1.53 ± 0.14	-1.35 ± 0.10	s	0.30	0.40

by TURBOSPECTRUM (Plez, 2012) radiative transfer code using MARCS model (Gustafsson et al., 2008) atmospheres at local thermodynamic equilibrium (LTE) conditions. In Fig. 1, we present the spectral synthesis of the Eu II region at 6437.640 Å for the adopted Eu abundance as given in Table 1 to show the continuum affects and blending in the region. Both these Eu isotopes ^{151}Eu and ^{153}Eu, have hyperfine splitting and have also been taken care of while doing the synthesis.

2.1. Derivation of isotopic ratios

We discuss the derivation of isotopic abundance using the Eu II line at 6437.640 Å. To ensure utmost accuracy and precision, we conducted a reanalysis of the high-resolution spectra, with our primary emphasis placed on the targeted line at 6437.640 Å. While Karinkuzhi et al. (2021b) reported the average abundance of Eu from all the lines in Table 1 in their paper, we acknowledge the possibility of a potential variation of up to ± 0.3 dex specifically regarding the abundance associated with this particular line. The Eu abundance adopted for deriving the isotopic abundances is presented in column 8 of Table 1 along with the average Eu abundance from all other lines in column 7. Upon confirmation of Eu abundances, the spectral synthesis is repeated with different isotopic ratios.

3. Preliminary Results and Conclusion

We derived the Eu isotopic ratios for four CEMP stars from Karinkuzhi et al. (2021b). Figure 2 presents the spectral fitting after adopting different isotopic fractions for ^{151}Eu and ^{153}Eu for two CEMP-rs stars. The similar spectral synthesis for a sample of two CEMP-s stars is shown in Fig. 3.

In a recent study conducted by Choplin et al. (2021), the contribution of s- and i-processes to stable isotopes of certain elements was investigated under a low-metallicity regime. The theoretical predictions from their model show that for the isotopes such as ^{137}Ba, ^{144}Nd, ^{154}Sm, and ^{151}Eu, higher production is noted through the i-process than the s-process in the studied conditions. A similar trend is shown by our CEMP-rs stars (see Fig. 2), where the observed abundances can be well reproduced by the i-process occurring in low-mass low-metallicity thermally pulsing AGB stars (Karinkuzhi et al., 2021b). The preliminary results here demonstrate the feasibility of this technique and the sensitivity of the Eu line at 6437 Å to the isotopic abundances, but the final conclusion should be drawn ideally after using 3D NLTE models for synthesis.

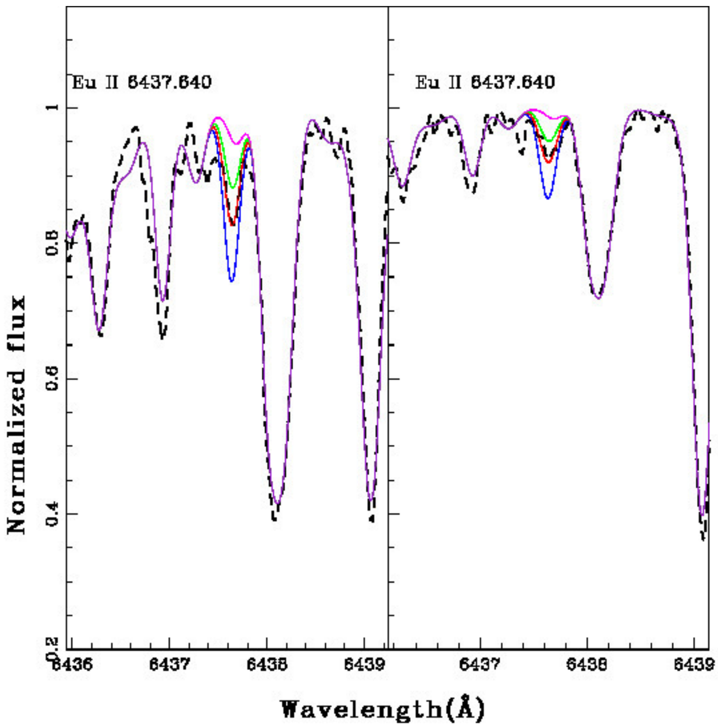

Figure 1: Spectral fitting of the Eu II line at 6437.640 Å is shown for HD 5223 (*left*) and for HD 198269 (*right*). The red curve corresponds to spectral syntheses with the adopted abundance for Eu. The blue and green curves correspond to syntheses with abundances deviating by ±0.3 dex from the adopted abundance. The black dashed line represents the observed spectrum. The magenta line corresponds to the synthesis with a null abundance for the corresponding element.

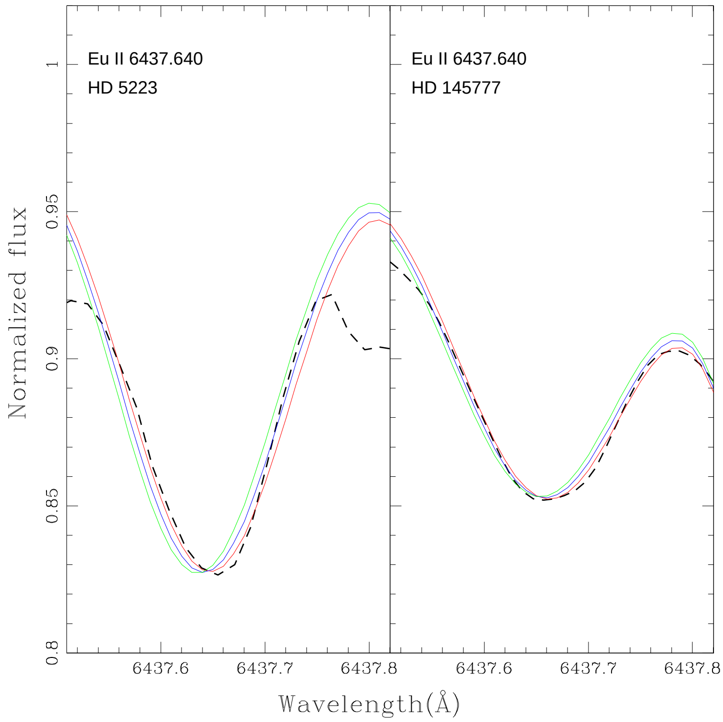

Figure 2: Spectral synthesis of Eu II line at 6437.640 Å for two CEMP-rs stars. The red line represents 90% contribution from ^{151}Eu, the blue line for 50% of ^{151}Eu, and the green line represents 10% contribution from ^{151}Eu compared to ^{153}Eu. The black dashed line represents the observed spectra.

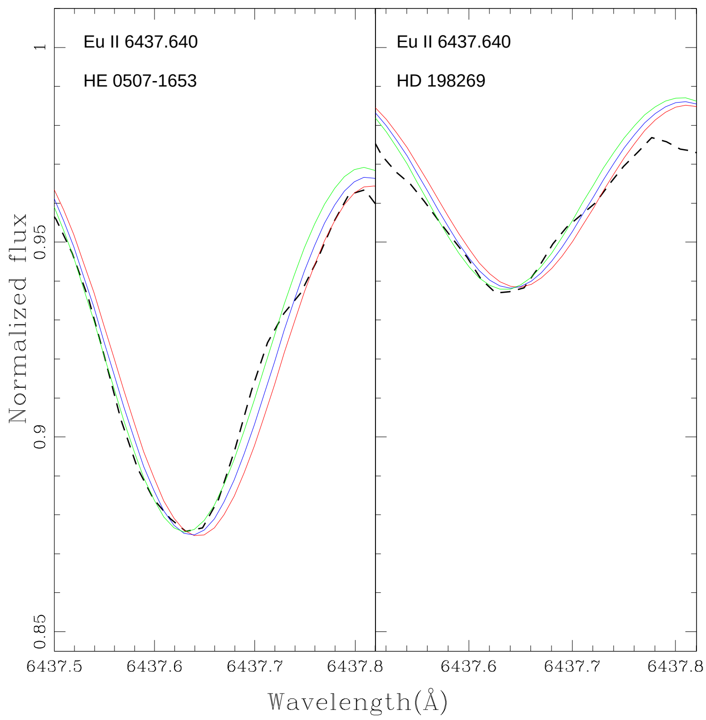

Figure 3: Same as Fig. 2, but for two CEMP-s stars.

Similarly, given the horizontal shift of all synthesis with respect to the Eu line, the technique is very sensitive to radial velocity correction. The detailed quantitative analysis of the results will be discussed in a forthcoming paper.

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Further Information

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Author contributions

D. K. and S. V. E. initiated this project. F. A. A. did the analysis. The manuscript was prepared by D. K and S. V. E.

Conflicts of interest

The authors declare no conflict of interest.

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