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Universality and the Astrophysical Sites for the r-Process

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Abstract

Several observations of r-process elements in metal-deficient halo stars have been reported which show a Z> 56 abundance distribution pattern similar to the Solar-system r-process distribution. It was believed that r-process elements for $Z > 56$ formed in the same ratio and their astrophysical origin is unique because of this. However, quite recently, several controversial observational results have been reported. We calculated r-process nucleosynthesis in various environments using a dynamical code. We find it is possible to reproduce the observed universal abundance distribution for stable $Z > 56$ elements in various environments. Our results do not support a unique astrophysical site for $Z > 56$ elements. These results significantly affect nuclear chronology using actinide elements.

1.1 Introduction

The investigation of the origin of rapid neutron-capture (i.e., r-process) elements is an important current topic in astronomy and astrophysics. These elements are probably made in an explosive astrophysical environment like type II supernovae. Study of such elements prove quite useful for probing the formation and evolution of the Galaxy. In addition, the long-lived unstable nuclei, Th and U, are generated in the r-process; and, their half-lives are of the same order as the cosmic age (14.5 Gyr for Th, 8 Gyr for U). We can therefore use them as cosmochronometers to estimate the age of the Galaxy. Furthermore, these elements are quite important in nuclear physics because they were formed via extremely neutron-rich unstable nuclei.

It has been assumed that the $56 \leq Z$ r-process elements are always formed in the same initial production ratio. This is because the abundance distribution for $Z \leq 56$ elements in metal-deficient stars shows the same pattern as that of Solar r-process material (e.g., Sneden et al. 2000). This feature is called "the universality of the r-process". Hence, the astrophysical site for r-process elements $56 \leq Z$ has been thought to be unique.

However, the extremely r-process enhanced, metal-deficient star CS31082-001 was reported to show an extremely high Th/Eu ratio (Cayrel et al. 2001). Although it shows a similar abundance distribution for 56<Z< 80 elements, the Th/Eu ratio is higher than in the Sun. Japanese Subaru/HDS group recently observed six other metal-deficient stars. All of them show a similar abundance distribution for $56 \leq Z$ stable elements, but two of them show a high Th/Eu ratio (Honda 2002). These observations imply that the heaviest r-process elements in these stars were generated with different production ratios and these elements could be formed in different nucleosynthesis environments.

In this study, we investigated r-process nucleosynthesis in various environments. We found that "the universality of the r-process" can be reproduced in different environments. Our results imply that the astrophysical site for $56 \leq Z$ r-process elements is not unique. This result is consistent with the observation of CS31082-001 mentioned above. We also discuss how these results affect the use of nuclear cosmochronometers.

1.2 Universality in Theoretical Calculations

1.2.1 Model

For this study, we assume a spherical steady-state flow as a quite general model for the r-process nucleosynthesis environment. We calculated r-process nucleosynthesis in various combinations of $\tau_{\rm dyn}$, S, Ye, and boundary temperature T_b (e.g., Woosley et al. 1996, Otsuki et al. 2000, Terasawa et al. 2002). Differences in these parameters mean different density and temperature profiles, which result in different neutron-to-seed ratios and/or different paths of the r-process. We used a dynamical network code based on Meyer et al.(1992) which was extended by Terasawa and Orito (Orito et al. 1997, Terasawa et al. 2001). For details of our calculation, see Otsuki et al. (2003).

1.2.2 Results

Our results are shown in Fig. 1.1. The figure shows the abundance distribution for the $56<Z<80$ elements is almost independent of the nucleosynthesis environment as long as there are enough neutrons to form the 3rd peak elements. In addition, the Eu isotope ratios in such cases are consistent with the observational data (Aoki et al. 2002). The universality in the theoretical calculation also holds at the isotope level. We can not be convinced that the nucleosynthesis site for the heaviest r-process elements is unique even if a universal abundance distribution for $56<Z<80$ elements is observed. We also find that the observed universality does not mean a unique Th/Eu production ratio.

Further observations of metal-deficient stars are needed to decide whether the three high Th/Eu ratio stars are peculiar or not. However, at least, the heaviest r-process elements in these stars could be formed in a different environment from other metal deficient stars.

1.3 Discussion

In our present calculations, the beta-decay flow into stable nuclei occurs after almost all neutrons have been depleted. Hence, the final abundance distribution was controlled by beta-delayed neutron emission rather than the neutron-capture path. This seems to be the main reason of the universality which holds in theoretical calculations. If the dynamical timescale is longer than ~ 1.5 seconds, this universality does not hold. More detailed discussion is in Otsuki et al. (2003).

We have shown that the coincident abundance distribution for $Z>56$ stable r-process elements in metal-deficient stars does not mean the same nucleosynthesis environment. Both observational and theoretical results indicate that the astrophysical site for $Z \leq 56$ r-process elements is not unique.

Finally, we briefly mention about nuclear cosmochronology. The application of the Th/Eu chronometer to metal-deficient stars was believed to be a useful method to estimate Galactic age. However, as can be seen in Fig. 1.1, the Th/Eu production ratio strongly depends upon the nucleosynthesis environment. It is difficult to find an initial Th/Eu production ratio for each metal-deficient star. Our results suggest that application of the Th/Eu chronometer to metal-deficient stars is questionable. On the other hand, the U/Th chronometer seems to be a good chronometer. We found the U/Th production ratio is almost independent of the nucleosynthesis environment if there were enough neutrons to reproduce the observed abundance distribution when they formed. Unfortunately, there are several uncertainties in the nuclear physics models. More experimental, observational, and theoretical studies for r-process nucleosynthesis are desired.

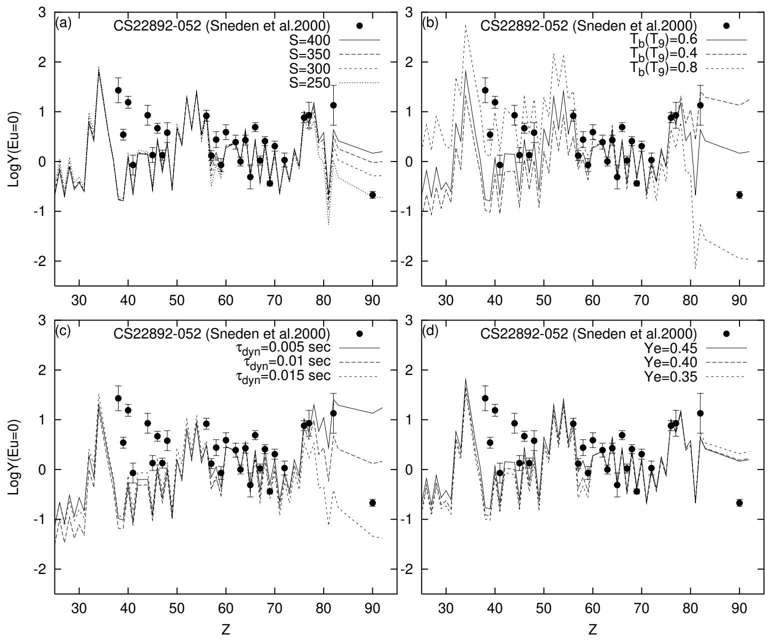

Fig. 1.1. Dependence of the nucleosynthesis yields upon various parameters of the astrophysical environment. Closed circles show observed elemental abundances in CS22892-052 (Sneden et al. 2000). In (a) the entropy per baryon for each model is S/k = 400, 350, 300, and 250 as labeled, and the dynamical time scale is fixed at 0.005 sec. In (b) the asymptotic temperature is 0.4, 0.6, 0.8 in units of T_9 as labeled. In (c) dynamical timescales of 0.015, 0.010, and 0.005 sec are shown for fixed S=400 and Y_e=0.45. In (d) the electron fraction is varied.

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