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Thorium (Th) Enrichment in the Milky Way Galaxy

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We have been determining abundances of the actinide element Th, as well as of other heavy neutron-capture elements, based on high resolution spectroscopy with Subaru Telescope High Dispersion Spectrograph (HDS) and Gunma Astronomical Observatory Echelle Spectrograph (GAOES). Our sample covers wide metallicity range ($-2.5 <$[Fe/H]$< +0.3$). The Th abundances are determined mostly using the Th 5989 Å line, which is less affected by blending of other elements than the 4019 Å one that has been used in previous studies of very metal-poor stars. The preliminary results of our measurements are presented. The Th/Eu abundance ratios of our sample show no significant scatter, and the average is slightly lower than the solar-system value. This result suggests that the actinide production by the r-process does not show large dispersion, or mixing of interstellar matter before formation of these metal-poor stars is very efficient. The Th/Eu ratios in relatively metal-rich ([Fe/H]> -1) stars show some scatter, and the average is higher than found in metal-poor stars. This suggests that these metal-rich stars include young objects where decay of Th is less significant.

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1. Introduction

The actinide Th is a key element to understand the production of heavy elements by r-process neutron-capture reactions. Indeed, model calculations of the r-process predict that the production of r-process elements is sensitive to the model parameters corresponding to the condition of r-process site (e.g. Wanajo & Ishimaru [1]).

The difficulties in observational studies of Th abundances are the weakness of spectral lines in the optical range, and also contaminations of spectral features of other elements and molecules, in particular to the Th 4019 Å line that has been used in most of previous studies. For this reason, measurements of Th have been limited to very metal-poor stars with large enhancements in neutron-capture elements (see Roederer et al.[2] and references therein). We note that efforts to measure Th abundance from the 4019 Å line have been made for objects with solar metallicity [3], but the uncertainty due to the blending is inevitable in the analysis.

In order to investigate the enrichment of Th in the Milky Way Galaxy covering a wide metallicity range, we have been extending the measurements to higher metallicity than previously studied. The Th 5989 Å line is useful for this purpose, because the line is detectable in cool giants (with effective temperatures lower than 4500 K), and the line is little blended with other features [4]. This article presents the preliminary results of our measurements obtained from high resolution spectra with the Subaru Telescope High Dispersion Spectrograph (HDS) and Gunma Astronomical Observatory Eschelle Spectrograph (GAOES).

2. Measurements of Th abundances

Our targets are bright red giants (most of them have $V < 10$) with low effective temperature ($\lesssim 5000\ K$). The Subaru spectra were obtained in a service program in 2008 with a resolving power (R) of 90,000, or in observing runs of other programs during twilight or in poor weather conditions with $R > 50,000$. The GAOES spectra were obtained with $R = 70,000$ for bright and less metal-poor stars.

Standard abundance analyses have been made for Fe and other elements. The effective temperatures are estimated from colors ($V-K$) or adopted from literature. We note that the abundance ratios between Th and other neutron-capture elements (e.g. Eu) are not sensitive to the adopted stellar parameters, while the metallicity (Fe abundance) is rather dependent on the estimate of effective temperature.

Th abundances have been measured from the Th II 4019 Å line for most of metal-poor stars in previous studies. This line is, however, severely blended with other absorption lines in mildly metal-poor stars studied in the present work (upper panel of Figure 1). In such stars (in particular cool red giants), the Th II 5989 Å line is sufficiently strong for abundance measurements. This line is almost free from contaminations of other species in metal-poor stars (lower panel of Figure 1; see also Aoki et al. [6]). We measured Th abundances for X stars from the Th 5989 Å line. The atomic line data of Nilsson et al. [5] are adopted. The Eu abundances are also measured from the lines in the red region (e.g. Eu II 6036 Å, 6645 Å).

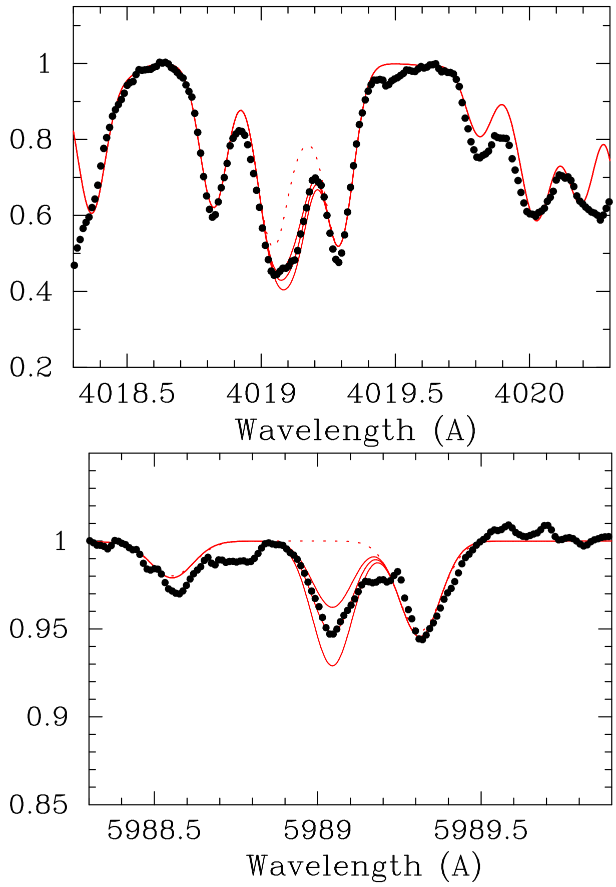

Figure 1: Examples of Th II lines at 4019 Å and 5989 Å detected in the Subaru spectra of BD+30°2611 (filled circles). The solid lines are calculated spectra for three different Th abundances ($\Delta \log \varepsilon = 0.15$ dex), while the dotted line means that for no Th contribution. The Th II 5989 Å line is sufficiently strong for measurements in this cool metal-poor giant (effective temperature of 4250K, [Fe/H]=-1.4), while the Th II 4019 Å is highly contaminated by other species.

3. Enrichment of Th in the Galactic halo

We here discuss the Th/Eu abundance ratios in metal-poor stars. Eu in metal-poor stars represents the yields of r-process by progenitors. Hence, the Th/Eu abundance ratio is determined by the production of these two elements by r-process and the decay of Th. We note that, while these heavy elements in extremely metal-poor ([Fe/H]~ -3) stars might be supplied by a single r-process event, those of less metal-poor stars ([Fe/H]> -2) would be integration of the products of many events.

Figure 2 shows a preliminary result of the Th/Eu abundance ratios as a function of metallicity for our sample (filled symbols) and those determined by previous studies (open circles). Our study covers the metallicity range of [Fe/H]> -2.5. The red solid line indicates the average of Th/Eu for 0.5 dex metallicity bins and the bars mean their standard deviations.

We found that the Th/Eu ratios at the metallicity around [Fe/H]$= -2$ are slightly lower than the solar value. This suggests that the Th/Eu ratio produced by the r-process statistically agrees

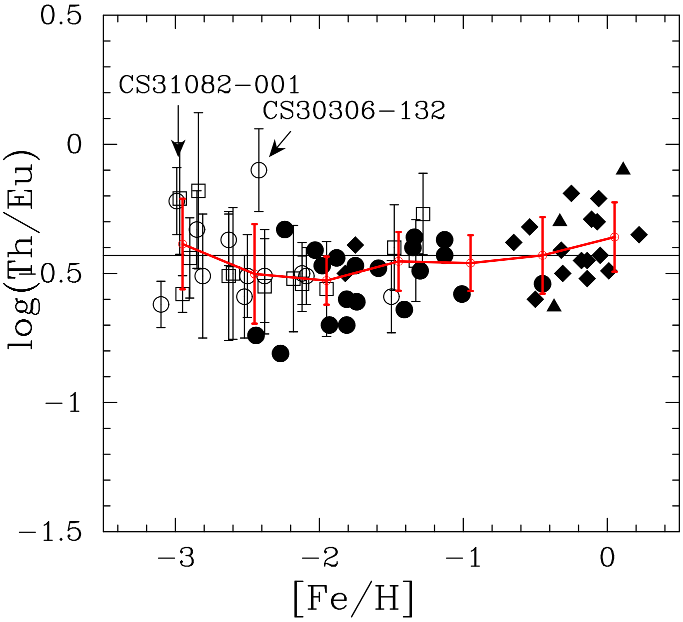

Figure 2: A preliminary result of the abundance ratios of Th/Eu are shown for our sample (filled circles and triangles: Subaru/HDS results; filled diamonds: GAOES results) and others (open circles: Roederer et al. [2] and references therein). The filled triangles are objects suggested to be thick disk stars. The solid horizontal line is the Th/Eu ratio of solar-system material. The red solid line indicates the average of Th/Eu for 0.5 dex metallicity bins and bars mean the standard deviations.

with the value estimated for the initial solar composition, but larger amount of Th has decayed in these stars. This is an expected result because these metal-poor stars are believed to be formed in the early phase of the Milky Way formation. It should be noted that, for detailed comparisons between our results from the Th II 5989 Å line and previous ones based on the 4019 Å line, more careful calibration of the abundance measurements from the two lines is required.

The small scatter of Th/Eu in the metallicity range $-2 <$[Fe/H]< -1 possibly implies that mixing of interstellar matter in the Milky Way halo was already efficient. By contrast, some star-to-star scatter of Th/Eu is found in extremely metal-poor ([Fe/H]< -2.5) stars studied by previous work. This would indicate that the chemical abundances of these extremely metal-poor stars reflect the yields of a limited number of r-process events (or even a single event). Interestingly, the average of Th/Eu ratios in such extremely metal-poor stars is higher than that at [Fe/H]$= -2$: objects that have particularly high Th/Eu are sometimes called as "actinide-boost" stars [7]. We note that, however, the scatter of Th/Eu found in extremely metal-poor stars is still much smaller than that expected from r-process models [1], which predict that the actinides production is very sensitive to the environment and can vary by one order or more by changes of model parameters.

The Th/Eu ratio becomes higher at higher metallicity ([Fe/H]> -1) on average, and the scatter becomes slightly larger than found in $-2 <$[Fe/H]< -1. Our sample of this metallicity range should include some objects of the Galactic disk population, which are not as old as halo population stars. Hence, the Th/Eu ratios and their scatter can be interpreted as a result of a wide distribution of ages of metal-rich stars in our sample.

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We are conducting more detailed abundance analyses for our sample. In the analysis of metal-rich stars, measurements of Eu are sometimes more uncertain than the Th measurements because of blending of other species to the absorption lines. Further efforts are required to make more careful calibration of the abundance measurements from the two lines as mentioned above. Measurements for larger sample covering wide metallicity range will improve the statistics and contribute to the understanding of enrichment of actinides in the Milky Way Galaxy.

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