First Determination of the Actinide Thorium Abundance for a Red Giant of the Ursa Minor Dwarf Galaxy*

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Abstract

The thorium abundance of the red giant COS 82 in the Ursa Minor dwarf spheroidal galaxy was determined based on the high-resolution spectrum. This is the first detection of actinides in an extragalactic object. A detailed abundance pattern was determined for 12 other neutron-capture elements from atomic number 39 to 68. These elements are significantly over-abundant with respect to other metals, like Fe (> 1 dex), and their abundance pattern agrees well with those of the r-process-enhanced, very metal-poor stars known in the galactic halo, while the metallicity of this object ([Fe/H] ~ −1.5) is much higher than these field stars ([Fe/H] ~ −3.0). The results indicate that the mechanism and the astrophysical site that are responsible for neutron-capture elements in COS 82 are similar to that for field r-process-enhanced stars, while the condition of low-mass star formation is quite different. An estimate of the age of this object based on the Th abundance ratio is discussed.

Key words: galaxies: dwarf — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: individual (Ursa Minor COS 82)

1. Introduction

The rapid process (r-process) is known to be responsible for about half of the abundances of elements heavier than Fe in solar-system material. Since the reaction occurs through very neutron-rich, unstable nuclei, understanding the process is still a challenging issue in nuclear physics. The astrophysical sites of this process are still unclear, though numerical simulations have been made for many possibilities (e.g., Wanajo & Ishimaru 2006).

An important progress in this field during the past decade was discoveries of very metal-poor stars having large over-abundances of r-process elements. Such objects are expected to record the yields of nucleosynthetic events in the early Galaxy, including the r-process. Several objects having very large excesses of r-process elements (e.g., Eu) with respect to other metals ([Eu/Fe] > 1) are known to exist in the galactic halo (Sneden et al. 2003; Hill et al. 2002; Christlieb et al. 2004; Barklem et al. 2005), and are called ‘r-II’ stars (Beers & Christlieb 2005). A remarkable result for these stars is that the abundance patterns of neutron-capture elements are very similar. Objects having such large excesses of r-process elements are found even in stars with relatively high metallicity. Chemical abundance studies for individual stars in the local group dSph made much progress in the past several years, thanks to high-resolution spectrographs mounted at 8–10 m telescopes (e.g., Shetrone et al. 2001, 2003; Venn et al. 2004). One surprising result derived by these abundance studies is the existence of stars showing extremely large enhancements of heavy neutron-capture elements with relatively high metallicity. The most remarkable star is the red giant COS 82 in the Ursa Minor dSph. High-resolution spectroscopy of this object was first obtained by Shetrone et al. (2001; in their paper, this star is referred to as ‘199’), who reported that this star is moderately metal-poor ([Fe/H] ~ −1.5), but shows a large enhancement of heavy neutron-capture elements ([Eu/Fe] = 1.49). Our previous observation obtained a red spectrum of this star with higher quality, and successfully detected some other heavy elements (e.g., Dy, Er), confirming that the abundance pattern of elements heavier than Ba almost completely agrees with the r-process abundance pattern estimated from solar-system material (Sadakane et al. 2004). This result is surprising, because no moderately metal-poor star ([Fe/H] ≥ −2) in our Galaxy is known to date to have such a large excess of r-process elements. Tsujimoto and Shigeyama (2002) applied their supernova-driven star-formation model, and proposed that this phenomenon can be explained by assuming a large velocity dispersion of the gas from which low-mass stars like COS 82 formed.

In this letter, we report on the detection of a Th absorption line at 5989 Å for this object by a re-analysis of our high-resolution spectrum obtained by Sadakane et al. (2004).

* Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.
The actinide Th has an isotope whose half life is 14.05 Gyr, and is produced only by the r-process. The production of actinides is very sensitive to the environment of the sites (e.g., entropy, timescale of the explosion), according to model calculations for the r-process. Therefore, the Th abundance can be a very strong constraint on a study of the origin of the neutron-capture elements in this object. Although the Th abundance has been determined for more than ten field metal-poor stars and globular cluster stars, our measurement for COS 82 is the first determination of an actinide abundance for an extragalactic object. We also discuss the possibility to apply the Th abundance ratio to estimate the age of this object.

2. Observation, Analysis, and Results

A high resolution spectrum of COS 82 was obtained by Sadakane et al. (2004) with the Subaru Telescope High Dispersion Spectrograph (HDS, Noguchi et al. 2002). The spectrum covers 4400–7100 Å with a resolving power of 40000. The signal-to-noise ratio per 1.8 km s\(^{-1}\) pixel is 60 at 5900 Å. Standard data reduction procedures were carried out with the IRAF echelle package, as described by Aoki et al. (2005). The equivalent widths for isolated absorption lines were measured by fitting Gaussian profiles.

A standard abundance analysis was made for the measured equivalent widths using the model atmospheres of Kurucz (1993). The analysis was made primarily based on the line list of Sadakane et al. (2004). We added some weak Fe I lines, which enabled us to determine the micro-turbulence more accurately. The effective temperature (\(T_{\text{eff}}\)) of 4300 K, determined by Sadakane et al. (2004), was adopted in the analysis. The micro-turbulence (\(v_{\text{turb}}\)) and gravity (\(g\)) were determined so that the derived Fe abundance would not be dependent on the strengths of the Fe I lines nor on the ionization stage, respectively. The results (\(\log g = 0.6\) dex and \(v_{\text{turb}} = 1.7\) km s\(^{-1}\)) agree with those of Sadakane et al. (2004) within the estimated errors. The metallicity is assumed to be the Fe abundance ([Fe/H]). The Fe abundance derived by the present analysis is [Fe/H] = –1.42, adopting a solar abundance of \(\log \epsilon(\text{Fe}) = 7.45\) (Asplund et al. 2005). The results of the abundance analysis are given in Table 1.

The Th abundance was determined from the Th II 5989 Å line. The oscillator strengths of Th II lines, including the 5989 Å line, were obtained by Nilsson et al. (2002). This line was investigated by Yushchenko et al. (2005) for the field metal-poor star HD 221170. The line was measured for the same object, using a higher quality spectrum, by Ivans et al. (2006), who reported that the abundance determined from this line agrees with those from other Th II lines. We performed an analysis for HD 221170 using the spectrum obtained with the Subaru Telescope and the model atmosphere (Kurucz 1993) with the parameters adopted by Ivans et al. (2006), and confirmed that the derived Th abundance agrees very well with their result. We note that the partition function of Th II was calculated using the energy levels listed by Blaise and Wyart (1992).

Though telluric absorption lines, probably due to water vapor, exist in this wavelength range, we found that the Th II 5989 Å line of COS 82 is not distinctly affected by them. Figure 1 shows the observed spectrum along with the synthetic ones for three Th abundances. The data for spectral lines other than the Th II line were adopted from the list of Kurucz & Bell (1995). The wavelength of the observed spectrum was determined from 137 Fe I lines in the spectrum. We identified the absorption feature at 5989.3 Å as a Nd II line. Although a Nd II line at 5989.378 Å with a lower excitation potential of 6005.270 cm\(^{-1}\) is listed by Kurucz & Bell (1995), J. E. Lawler (private communication) suggests that the line should be the transition from 19758.540 to 30667.755 cm\(^{-1}\) at \(\lambda_{\text{air}} = 5989.312\) Å. Since the transition probability of this line is unknown, we assumed it to be \(\log gf = –2.05\). This \(gf\)-value

![Table 1. Elemental abundance results.](https://academic.oup.com/pasj/article-abstract/59/3/L15/1406308/1406308)

| Species | \(\log \epsilon_{\text{sun}}\) | \(\log \epsilon\) | [X/Fe] | \(N\) | \(\sigma_{\text{total}}\) | \(\sigma_{\text{FeH}}\) |
|---------|-----------------|----------|---------|---|----------------|----------------|
| Fe I    | 7.45            | 6.03     | ...     | 137 | 0.27           | ...            |
| Fe II   | 7.45            | 6.02     | ...     | 13  | 0.18           | ...            |
| O I     | 8.70            | 7.45     | 0.17    | 1  | 0.2            | ...            |
| Y II    | 2.21            | 1.22     | 0.42    | 6  | 0.23           | 0.14           |
| Zr II   | 2.59            | 1.82     | 0.65    | 1  | 0.24           | 0.19           |
| Ba II   | 2.17            | 1.36     | 0.60    | 3  | 0.30           | 0.21           |
| La II   | 1.13            | 0.52     | 0.81    | 8  | 0.16           | 0.06           |
| Ce II   | 1.63            | 0.76     | 0.55    | 4  | 0.20           | 0.14           |
| Pr II   | 0.80            | 0.20     | 0.82    | 7  | 0.19           | 0.11           |
| Nd II   | 1.45            | 1.00     | 0.97    | 41 | 0.17           | 0.05           |
| Sm II   | 0.98            | 0.90     | 1.34    | 2  | 0.21           | 0.13           |
| Eu II   | 0.98            | 0.34     | 1.24    | 3  | 0.17           | 0.11           |
| Gd II   | 1.09            | 1.10     | 1.43    | 3  | 0.16           | 0.12           |
| Dy II   | 1.17            | 1.13     | 1.38    | 3  | 0.17           | 0.10           |
| Er II   | 0.97            | 0.73     | 1.18    | 3  | 0.17           | 0.11           |
| Th II   | 0.09            | –0.25    | 1.08    | 1  | 0.15           | 0.08           |

![Fig. 1. Comparisons of synthetic spectra for the region including the Th II 5989 Å line with the observed spectrum. The Th abundances assumed in the calculations are \(\log \epsilon(\text{Th}) = –0.15, –0.25, –0.35\) (solid lines), and \(–\infty\) (dotted line).](https://academic.oup.com/pasj/article-abstract/59/3/L15/1406308/1406308)
and the Nd abundance determined from other spectral regions well reproduce the strength of the line for COS 82 as well as for HD 221170.

The Th abundance was determined by χ²-fitting of synthetic spectra to the observed one from 5988.9 to 5989.2 Å, which is not severely affected by the 5989.3 Å feature. The derived abundance is log ε(Th) = −0.25. The 2ν level of the fitting error was 0.07 dex. The continuum level was estimated for the spectrum around the absorption features. The uncertainty of the continuum placement (∼0.5%) resulted in a possible error of 0.03 dex in the Th abundance. We estimated the line broadening for relatively clean lines in the spectrum, and found that the line widths are primarily determined by the instrumental broadening, and no significant broadening by macro-turbulence nor rotation was detected. The possible error in the Th abundance due to the adopted broadening parameter (±0.5 km s⁻¹) is 0.03 dex.

The abundances of other elements were determined using the line list of Sadakane et al. (2004) with some modifications. The transition probabilities of Nd II, Sm II, and Gd II were updated, adding several new lines to the list, using the data of Den Hartog et al. (2003), Lawler et al. (2006), and Den Hartog et al. (2006), respectively. The effects of the hyperfine splitting for Ba, La, Eu, and Pr were included, using the line data obtained by McWilliam (1998), Lawler, Bonvallet, and Sneden (2001), Lawler et al. (2001), and Ginnibre (1989), respectively. We also measured the O abundance from the [O I] 6300.3 Å line. The results are listed in table 1. An upper limit of the Os abundance was derived from the Os I 5584 Å line. Estimates of the upper limits for other neutron-capture elements were also attempted, but no meaningful result was derived from our spectrum. The abundances of Fe and most neutron-capture elements derived by the present analysis agree with the results of Sadakane et al. (2004) within the errors (see below). Exceptions are Eu and Gd abundances, for which the differences between the two measurements are about 0.25 dex. This would be due to the difference of the spectral features and line data adopted in the analysis. The abundances of Fe and some neutron-capture elements determined by Shetrone, Cote, and Sargent (2001) agree well with our results, while their Ce and Sm abundances are more than 0.3 dex higher than ours. We suspect that their results are uncertain because of the low S/N ratio in the blue region of their spectrum, where Ce and Sm lines used in their analysis exist.

The abundance uncertainties for elements for which more than 10 lines are measured are estimated by σN⁻¹/², where σ is the standard deviation of the abundances from individual lines and N is the number of lines used. A typical uncertainty of the equivalent width measurement from our spectrum is 6 mÅ. We performed abundance analyses for Fe I lines with equivalent widths from 30 to 200 mÅ, changing the equivalent widths by 6 mÅ. The effects of the change of the equivalent widths on the derived abundances are 0.15–0.20 dex, which agree with the σ (0.18 dex) for Fe I (σFeI). For elements whose abundances are determined from less than 10 lines, the random error is estimated by σFeI N⁻¹/². Errors due to the uncertainty of atmospheric parameters are estimated by calculating the abundances changing the atmospheric parameters by ∆(T_eff) = 150 K, ∆(log g) = 0.3 dex, ∆([Fe/H]) = 0.2 dex, and

\[ \Delta(v_{turb}) = 0.3 \text{ km s}^{-1}. \]

These errors are added, in quadrature, to the random errors estimated above, and are given in table 1 (σ_total). We found, however, that the abundances of the neutron-capture elements determined from the ionized species systematically scales by changes of the adopted atmospheric parameters. For a discussion based on the abundance pattern, we calculated the average of the abundance changes for heavy neutron-capture elements (La–Er) by changing the atmospheric parameters, and adopted the deviation from this systematic abundance change for individual elements as the errors due to the uncertainties of the atmospheric parameters. This resulted in quite small errors (≤0.05 dex). These errors and the random errors were added in quadrature, and are also given in table 1 as σ_in-cap.

3. Discussion and Concluding Remarks

The upper panel of figure 2 shows the abundance patterns of the neutron-capture elements for COS 82, the solar-system r-process component (Simmerer et al. 2004), and the two r-process-enhanced field stars, CS 22892–052 (Sneden et al. 2003) and CS 31082–001 (Hill et al. 2002). The abundances were normalized to the average of Ba–Er ones. As reported by Sadakane et al. (2004), the overall abundance pattern of heavy neutron-capture elements (Ba–Er) in COS 82 agrees well with the r-process abundance pattern. In the lower panel, the abundance differences between COS 82 and the solar-system r-process component, as well as that between COS 82 and CS 22892–052, are shown. The Th abundance of COS 82 is lower than the normalized value of the solar-system r-process component, but agrees very well with the value of CS 22892–052. This point is discussed below in more detail. The abundance of the light neutron-capture element Y in COS 82 is also lower than the normalized value in the solar-system r-process component, as found in field r-process-enhanced stars.

Although such a small deviation exists, an important result derived from the comparison is that the abundance pattern of neutron-capture elements, including Th, in COS 82 agrees with the pure r-process abundance pattern. According to model calculations for the r-process, the actinide abundances with respect to other neutron-capture elements are very sensitive to the model parameters (e.g., electron fraction, entropy; Wanajo et al. 2002). The agreement of the Th abundance ratio to other neutron-capture elements in COS 82 with that of CS 22892–052 indicates that the mechanism and astrophysical sites that are responsible for the heavy elements in COS 82 are common with those for the r-process-enhanced field stars. Recent abundance studies for r-process-enhanced stars suggest that the r-process occurs under a quite limited condition (e.g., supernova explosions whose progenitors have mass in a very narrow range). Our result shows that this can also be applied to stars even in dSph.

The metallicity of COS 82 is more than one order of magnitude higher than that of the field r-II stars ([Fe/H] ∼−3). The chemical composition of field stars with such metallicity is believed to be affected by a number of nucleosynthesis events. However, the metallicity, as well as the amount of neutron-capture elements, should be related to how the yields
from the abundance ratio between Th and other stable elements, which could be an independent calibration for age measurements for this galaxy. If the age of this star is shown to be quite long (> 10 Gyr), the star formation of this dSph should be completed with a short time scale. Th has a half life of 14.05 Gyr, and the age of the object (more strictly, the duration from the r-process event) is estimated from the Th abundance ratio to other stable elements, if its initial abundance ratio is given. Here, the average of the abundances of the nine elements from La to Er is used as a reference. The Th/E_{\text{stable}} ratio of COS 82 agrees very well with that of CS 22892–052, while it is 0.3 dex lower than the value in the r-process component in solar-system material (figure 2).

Unfortunately, the abundance ratio of Th/E_{\text{stable}} produced by the r-process is not constant. Indeed, the actinides including Th are significantly enhanced with respect to other neutron-capture elements, in the r-II star CS 31082–001, compared to that of the solar-system r-process component (Hill et al. 2002; see also Honda et al. 2004). However, studies of Th abundances for a number of r-process enhanced field stars show that the abundance ratios distribute in a rather narrow range (−0.6 ≤ Th/E_{\text{stable}} ≤ −0.1), and CS 22892–052 is one of the objects that have the lowest ratio. Assuming that the initial abundance ratio of Th/E_{\text{stable}} for COS 82 is within the range for field stars, and that the field halo stars including CS 22892–052 are quite old (their ages are around 12–13 Gyr), COS 82 is also an old object. (If a higher value of the initial Th/E_{\text{stable}} ratio is assumed, the derived age becomes longer).

The error (σ_{n-cap}) in the determination of the Th abundance ratio is 0.08 dex, while the scatter of the abundances of the above nine stable elements around those of the solar-system r-process component, as well as of CS 22892–052, is 0.11 dex. We estimate the error of the Th/E_{\text{stable}} to be 0.13 dex, which results in the uncertainty of the age estimate to be 6 Gyr. Hence, though the object is suggested to be as old as field halo stars, the age estimate using the Th chronometer gives only a weak constraint. A measurement of the U/Th ratio, which is a more sensitive chronometer, for this object will enable one to estimate the age with a much smaller error (< 2 Gyr).

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References

Aoki, W., et al. 2005, ApJ, 632, 611
Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in ASP Conf. Ser. 336: Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, ed. T. G. Barnes III & F. N. Bash (San Francisco: ASP), 25
Blaise, J., & Wyart, J.-F. 1992, Energy Levels and Atomic Spectra of Actinides, International Tables of Selected Constants 20, Paris
Barklem, P. S., et al. 2005, A&A, 439, 129
Beers, T. C., & Christlieb, N. 2005, ARA&A, 43, 531
BLAG W. Aoki et al. [Vol. 59, NUL
Den Hartog, E. A., Lawler, J. E., Sneden, C., & Cowan, J. J. 2003, ApJS, 148, 543
Den Hartog, E. A., Lawler, J. E., Sneden, C., & Cowan, J. J. 2006, ApJS, 167, 292
Evolution and Nucleosynthesis, ed. T. G. Barnes III & F. N. Bash (San Francisco: ASP), 25
Honda et al. 2004, A&A, 428, 1027
Honda et al. 2004, A&A, 428, 1027
