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Radioactive Ages of Metal-Poor Halo Stars *

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Abstract The abundances of long-lived radioactive elements Th and U observed in metal-poor halo stars can be used as chronometers to determine the age of individual stars, and hence set a lower limit on the age of the Galaxy and hence of the universe. This radioactive dating requires the zero-decay productions of Th and U, which involves complicated r-process nucleosynthesis calculations. Several parametric r-process models have been used to calculate the initial abundance ratios of Th/Eu and U/Th, but, due to the sharp sensitivity of these models to nuclear physics inputs, the calculations have relatively large uncertainties which lead to large uncertainties in the age determinations. In order to reduce these uncertainties, we present a simple method to estimate the initial productions of Th and U, which only depends on the solar system abundances and the stellar abundances of stable r-process elements. From our calculations of the initial abundance ratios of Th/Eu and U/Th, we re-estimate the ages of those very metal-poor halo stars with published abundances of Th and U. Our age estimates are consistent, within the errors, with the other age determinations derived from r-process models, and offer useful constrains for r-process theoretical calculations. The advantages and limitations of our simple method of radioactive dating are discussed.

Key words: stars: abundances — stars: Population II — Galaxy: abundances Galaxy: halo — Galaxy: evolution

1 INTRODUCTION

Long-lived radioactive nuclei, such as ^{232}Th and ^{232}U with half-lives of 14.05 Gyr and 4.47 Gyr, can be used as chronometers to determine the age of the Galaxy, and this possibility has been developed into an entire subject of nucleo-cosmochronometry since it was first defined and identified by Rutherford (1929) (for a review see Arnould & Takahashi 1990). However, until the first detection of Th in field stars reported by Butcher (1987), most determinations of the age of the Galaxy were made in the context of Galactic chemical evolution models (for a detailed review see Cowan et al. 1991a). In recent years, the radioactive elements Th and U

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have been detected in several very metal-poor halo field stars and globular cluster stars (e.g., CS 22892–052, Sneden et al. 1996, 2000a) and they have been used to determine the radioactive ages by comparing the Th and U abundances to those of stable neutron-capture (n-capture) elements, resulting in a range of age estimates of 11–15 Gyr for these halo stars (Truran et al. 2002; Sneden & Cowan 2003). This age estimate provides the most solid lower limits for the age of the Galaxy and the universe since the very metal-poor halo stars are the oldest objects of our Galaxy.

Radioactive dating is independent of the model of Galactic chemical evolution and is very simple in principle. However, there are practical difficulties when applying this technique to the age determination of halo stars (for detailed reviews see Arnould & Takahashi 1999; Arnould & Goriely 2001). The difficulty is related to the theoretical estimation of the initial (zero-decay) production ratios of Th to U or to some stable r-process nucleus such as Eu, because it requires theoretical calculations of the r-process, but unfortunately, the r-process remains the most complicated nucleosynthetic process to model from the point of view of both astrophysics and nuclear physics (Goriely & Clerbaux 1999). For this reason, several parametric approaches, such as the classical r-process model (Cowan et al. 1999) and the multi-event r-process model (Goriely & Arnould 2001), have been used to estimate the initial Th and U productions. However, because these models are very sensitive to the nuclear physics input, the initial abundance ratios they give have large uncertainties, leading to large uncertainties in the age estimates (Goriely & Clerbaux 1999; Arnould & Goriely 2001).

In this paper, we present a simple and direct method to predict the initial productions of Th and U in very metal-poor halo stars, which only depends on the solar abundances and the stellar observations. In Sect. 2, we give a brief review on the observational and theoretical studies of radioactive dating. In Sect. 3, we introduce our method and give our predictions for the abundances of n-capture elements in metal-poor stars. Then, in Sect. 4, we estimate the ages and the errors for the observed halo stars. Finally, in Sect. 5, we present our conclusions.

2 RECENT STUDIES ON THE Th AND U CHRONOMETERS

Thorium cosmochronometry was first applied to G-dwarf stars by Butcher (1987) who suggested using the abundance ratio Th/Nd to determine stellar ages. He found no detectable variation of the ratio Th/Nd with stellar ages and gave a rather young age of 9.6 Gyr for the galactic disk. This technique was later extended to metal-poor halo stars by François et al. (1993). They measured the Th/Eu ratio in stars and found a large star-to-star scatter, which weakened the use of this ratio as a chronometer. Sneden et al. (1996) made a breakthrough in thorium cosmochronometry: they measured 16 stable n-capture elements from Ba to Os and the radioactive element Th in the ultra-metal-poor halo star CS 22892–052. They found that the n-capture elements are extremely over-abundant relative to iron (e.g., [Eu/Fe] = +1.6[1]) but that their abundance distribution agrees well with a re-scaled solar system r-process abundance distribution, while the thorium abundance is lower than that given by the same re-scaled solar distribution. The authors assumed that the relative lower abundance of Th was due to its radioactive decay and obtained a lower limit of 15.2 ± 3.7 Gyr for the age of CS 22892–052. Since then, with the implementation of large telescopes and efficient high-resolution

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[1] We use the usual notation $[\mathrm{A/B}] \equiv \log_{10}(N_A/N_B)_{\mathrm{star}} - \log_{10}(N_A/N_B)_{\odot}$, and $\log_{10}\epsilon(A) \equiv \log_{10}(N_A/N_H) + 12.0$, for the elements A and B. Also, metallicity will be assumed here to be equivalent to the stellar [Fe/H] value.

spectrographs, thorium has been detected in a number of very metal-poor halo field stars and some halo giants in globular clusters. These include HD 115444 (Westin et al. 2000; Johnson & Bolte 2001), HD 186478, HD 108577, and BD +08°2548 (Johnson & Bolte 2001), CS 31082–001 (Cayrel et al. 2001; Hill et al. 2002), and BD +17°3248 (Cowan et al. 2002), as well as individual giants in the Galactic globular clusters M15 (Sneden et al. 2000b) and M92 (Johnson & Bolte 2001). Their observations showed a similar abundance distribution for the n-capture elements with $Z \geq 56$ in these stars as in CS 22892–052, which implies that the solar r-process pattern is universal in very metal-poor halo stars.

Recently, another long-lived radioactive element, uranium, has been discovered alongside thorium in two metal-poor halo stars CS 31082–001 (Cayrel et al. 2001; Hill et al. 20002) and BD+17°3248 (Cowan et al. 2002). This provides a second chronometer, U/Th, for estimating stellar ages. Since Th and U are near neighbors in mass number, the U/Th ratio might provide a more reliable age estimate than does the ratio Th/X, X representing a lower mass element such as Eu (Goriely & Clerbaux 1999).

The increasing detection of Th and U in metal-poor stars is paralleled by the progress in the theoretical studies of radioactive dating, particularly, in the prediction of the initial productions of Th and U. As the astrophysical site of the r-process has not been identified with certainty (see the earlier review by Cowan et al. 1991b, and the recent review by Truran et al. 2002), analytic calculations of r-process nucleosynthesis are unrealistic, and only a parametric approach can be used, as exemplified by the multi-event r-process model (e.g., Goriely & Arnould 2001; Goriely & Clerbaux 1999), and the classical r-process model (Cowan et al. 1991b, 1999; Kratz et al. 1998; Schatz et al. 2002). These r-process models are site-independent but they are very sensitive to nuclear physics input, especially to the nuclear mass models, so their predicted initial abundances have very large uncertainties. For example, Goriely & Clerbaux (1999) gave a large range of 0.25–1.55 for the Th/Eu ratio derived from their multi-event model depending on which nuclear mass model was adopted and which abundances of ^{206}Pb and ^{209}Bi were used as constraints in the calculation; they finally reported a large range of $7 - 39$ Gyr for the estimated age of CS 22892–052. A similar situation holds in the classical r-process model, for instance, Cowan et al. (1999) found that while a best fit between the model calculations and the solar r-process abundances for the stable n-capture elements can be obtained by the different nuclear mass models, the predicted Th/Eu ratio varied from 0.39 to 1.77, which led to a large range of $10 - 41$ Gyr for the estimated age of CS 22892–052.

Goriely & Arnould (2001) evaluated in great detail the production of actinides within the context of the multi-event r-process model. They recommended a range of $1.31 - 3.36$ for the production of Th/U ratio from 32 cases characterized by different astrophysical conditions and different nuclear mass models; this led to a range of $9 - 18$ Gyr for the estimated age of the very metal-poor halo star CS 31082–001. Schatz et al. (2002) recalculated the initial ratios of Th/Eu and U/Th based on updated nuclear physics input and a new analysis of the remaining uncertainties in the classical r-process model, their best predictions (in $\log \epsilon$) of the Th/Eu and U/Th ratios are -0.33 ± 0.12 and -0.22 ± 0.10, respectively. They derived an age estimate of 15.5 ± 3.2 Gyr for CS 31082–001 from the U/Th chronometer.

3 INITIAL PRODUCTIONS OF Th/Eu AND U/Th FROM A SIMPLE METHOD

Since nearly all the very metal-poor halo stars observed to date exhibit the solar r-process abundance pattern for n-capture elements with $Z \geq 56$, and the solar system abundances have been well determined in detail (e.g., Anders & Grevesse 1989; Grevesse & Sauval 1998), we can directly use the solar r-process abundances to estimate the overall abundances of heavy elements in very metal-poor halo stars (Zhang et al. 2002), including the radioactive elements Th and U.

$$N_i^*(Z) = C_h N_{i,r}^{\odot} \times 10^{[\mathrm{Fe/H}]}, \quad (Z \geq 56) \tag{1}$$

where N_i^* and $N_{i,r}^{\odot}$ are the i-th n-capture element r-process abundances scaled to $N(\mathrm{Si}) = 10^6$ in stars and in the solar system, respectively; C_h is a coefficient correlated with the r-process contributions to abundances in solar system material; [Fe/H] is the metallicity of stars.

Details of the solar r- and s-process fractions for each isotope have been identified and extracted in several works (Käppeler et al. 1989; Sneden et al. 1996; Burris et al. 2000; Arlandini et al. 1999), so the r-process abundances in metal-poor halo stars can be predicted via Eq. (1) if we know the coefficient C_h. We choose Eu as the reference element to determine the coefficient C_h, because Eu is nearly a pure r-process product both in solar material and in metal-poor stars (Sneden et al. 2002), and it is easily identified in stellar spectra. In this paper, we adopt the solar r-process abundances of Burris et al. (2000). Putting the the solar abundance of Eu into Eq. (1), we obtain the relation of C_h with the observed abundance ratio [Eu/Fe],

$$C_h = 1.03 \times 10^{[\mathrm{Eu/Fe}]}. \tag{2}$$

With Equations (1) and (2), we can calculate the overall abundances of the heavy n-capture elements in very metal-poor stars, using only the observed [Fe/H] and [Eu/Fe]. For example, for the very metal-poor halo star CS 22892–052, if we put [Fe/H] =−3.1 and [Eu/Fe] = 1.6 (Sneden et al. 2000a) in Eq. (2), we obtain $C_h = 45.65$ for this star. Then, putting this value of C_h in Eq. (1), we obtain the abundances of the heavy elements with $Z \geq 56$ in this star based directly on the solar r-process abundances. The calculated abundance distribution for CS 22892–052 is displayed in Fig. 1 by the solid line, to be compared with the observed abundances (filled circles with error bars). In the same way, the abundance distributions of the other metal-poor field halo stars HD 115444, CS 31082–001, BD +17°3248, HD 186478, HD 108577, and BD +08°2548, as well as three halo giants in globular clusters M15 and M92 can be obtained, the results are displayed in Figs. 1–5 by the solid lines.

We find that, for all of these metal-poor stars, our calculations are consistent with the observed abundances within error limits for n-capture elements with $56 \leq Z \leq 76$. Furthermore, for the four well observed stars CS 22892–052, HD 115444, BD +17°3248 and CS 31082–001, the agreement essentially extends to the third peak elements Os, Ir, and Pt, and probably to the heaviest element Pb. However, the observed thorium abundance is lower than the predicted abundance from the calculated distribution for all the stars except CS 31082–001, which indicates that thorium has decayed with respect to stable n-capture elements in the last case. This comprehensive level of agreement between the the predicted and observed abundances strongly confirms that the solar r-process pattern throughout the range $56 \leq Z \leq 78$ is universal in very metal-poor halo stars. This in turn argues for a common site for the r-process synthesis of these elements. In Qian & Wasserburg (2002), this site is called the high-frequency SN II (H) and is held to be responsible for the abundances of the second and third r-process peak elements (Ba and beyond). Therefore, we can safely extrapolate the predicted r-process pattern to the actinide region, and hence obtain the initial productions of Th and U. We find that the predictions for the absolute abundances of Th and U are different for different stars, but the predicted abundance ratios of Th/Eu and U/Th keep to the same values among the individual stars, at $\log(\mathrm{Th/Eu})_0 = -0.334$ and $\log(\mathrm{U/Th})_0 = -0.243$. This means that such an r-process operated in a fairly consistent manner over large periods of time during the evolution of the Galaxy.

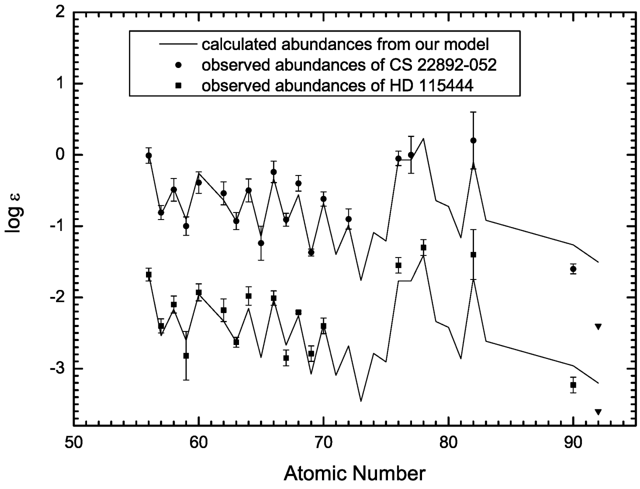

Fig. 1 Neutron-capture abundances in CS 22892–052 (filled circles; Sneden et al. 2000a) and HD 115444 (filled squares; Westin et al. 2000) are compared with the calculated abundance curve (solid line) from our method. The abundance values of HD 115444 have been vertically displaced arbitrarily by –1.0 for display purpose. The upper limit on the uranium abundance is marked by an inverted triangle.

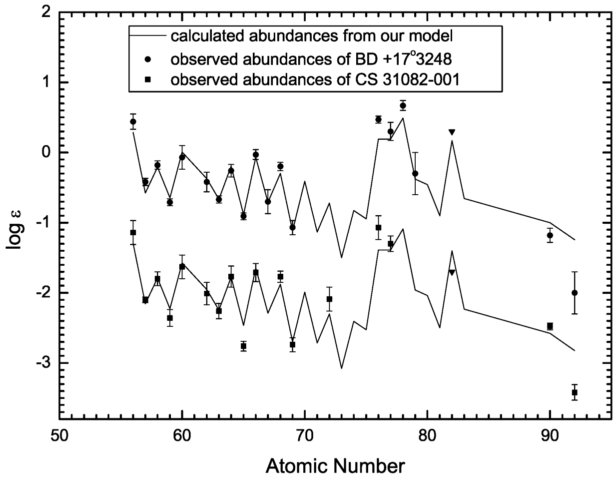

Fig. 2 Neutron-capture abundances in CS 31082–001 (filled circles; Hill et al. 2002) and BD +17°3248 (filled squares; Cowan et al. 2002) are compared with the calculated abundance curve (solid line) from our method. The abundance values of CS 31082–001 have been vertically displaced arbitrarily by –1.5 for display purpose. The upper limit on the lead abundance is marked by an inverted triangle.

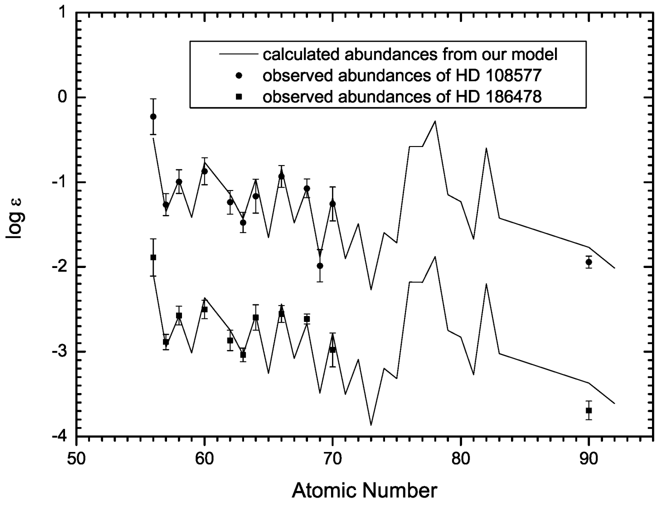

Fig. 3 Neutron-capture abundances in HD 108577 (filled circles) and HD 186478 (filled squares) (Johnson & Bolte 2001) are compared with the calculated abundance curve (solid line) from our method. The abundance values of HD 186478 have been vertically displaced arbitrarily by –1.5 for display purpose.

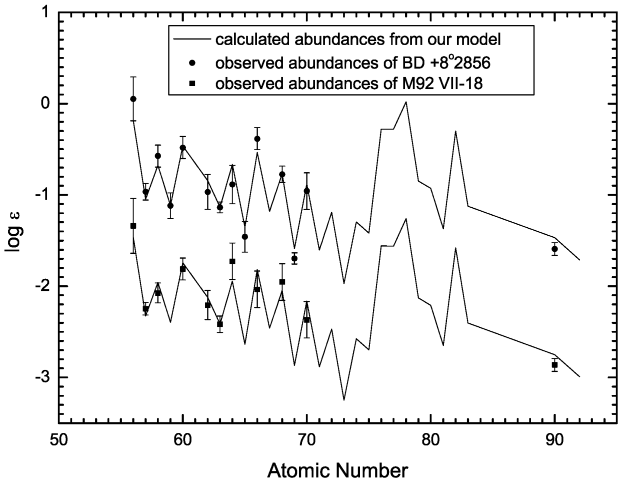

Fig. 4 Neutron-capture abundances in BD +8°2856 (filled circles) and M92 VII–18 (filled squares) (Johnson & Bolte 2001) are compared with the calculated abundance curve (solid line) from our method. The abundance values of M92 VII–18 have been vertically displaced arbitrarily by –1.0 for display purpose.

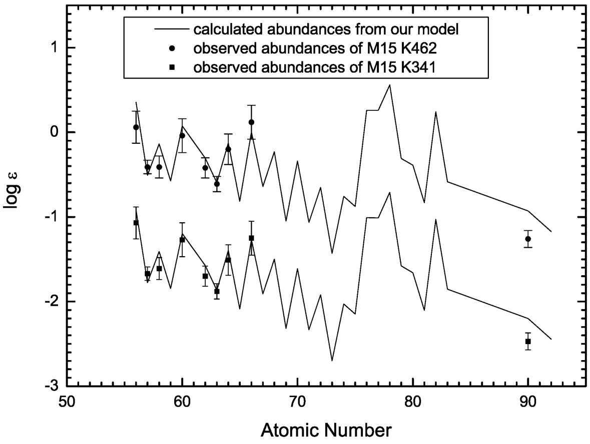

Fig. 5 Neutron-capture abundances in M15 K462 (filled circles) and M15 K341 (filled squares) (Sneden et al. 2000b) are compared with the calculated abundance curve (solid line) from our method. The abundance values of M15 K341 have been vertically displaced arbitrarily by –1.0 for display purpose.

In Table 1 we list the initial productions of the Th/Eu and U/Th ratios given by different papers using different methods and models. We note that our predicted abundance ratios are in agreement with those derived from the parametric *r*-process models within error limits. For example, our prediction of $\log(\mathrm{Th/Eu})_0 = -0.334 \pm 0.02$ agrees well with the that of -0.32 ± 0.07 predicted by Cowan et al. (1999) from their classical *r*-process model and clearly falls within the range of $-0.65 \leq \log(\mathrm{Th/Eu})_0 \leq -0.19$ recommended by Goriely & Clerbaux (1999) using the multi-event *r*-process model. In addition, our predicted ratio $\log(\mathrm{U/Th})_0 = -0.243 \pm 0.044$ also agrees well with that of -0.22 ± 0.1 (Schatz et al. 2002) and -0.255 (Cowan et al. 1999) within error limits. More interestingly, the prediction of -0.334 ± 0.02 for $\log(\mathrm{Th/Eu})_0$ from our simple method coincides with that of -0.33 ± 0.12 estimated by Schatz et al. (2002) from the classical *r*-process model with updated nuclear physics input. This indicates that our simple method is a valid tool for predicting the abundances of *n*-capture elements in very metal-poor stars, and our predictions of the initial productions of Th/Eu and U/Th are as reliable as those by the *r*-process models.

Table 1 Initial Productions of Th/Eu and U/Th from Different Works

Work	Model	$\log(\mathrm{Th/Eu})_0$	$\log(\mathrm{U/Th})_0$
Present work	...	-0.334 ± 0.02	-0.243 ± 0.044
Schatz et al. (2002)	classical *r*-process model	-0.33 ± 0.12	-0.22 ± 0.10
Goriely & Arnould (2001)	multi-event *r*-process model	...	$-0.53 \sim -0.12$
Cowan et al. (1999)	classical *r*-process model	$-0.32 \sim -0.26$	-0.255^*
Goriely & Clerbaux (1999)	multi-event *r*-process model	$-0.65 \sim 0.19$	$-0.22 \sim 0.05$
Toenjes et al. (2001)	classical *r*-process model	...	-0.16 ± 0.18, -0.37 ± 0.18

$*$ This value of $\log(\mathrm{U/Th})_0$ is cited by Cayrel et al. (2001).

The advantage of our method is that it is independent of theoretical r-process models, hence it is free of the theoretical uncertainties in the latter. In addition, errors in the observed abundances of Eu translate into uncertainties in the predicted absolute abundances, but these uncertainties are eliminated completely in the relative abundance ratios (e.g., Th/Eu). Therefore, the overall errors in our predicted Th/Eu and U/Th ratios only depend on the errors of the Th and U abundances in solar material. According to the standard solar composition reported by Grevesse & Sauval (1998), the errors in Th and U solar abundances are 0.02 dex and 0.04 dex in $\log \epsilon$, respectively. So these are also the errors in our calculated values of $\log(\mathrm{Th/Eu})_0$ and $\log(\mathrm{U/Th})_0$.

We note from Fig. 2 that the prediction of Th is strangely lower than the observed Th abundance in CS 31082–001. This unusual result can be understood if an initial enhancement of Th and U is assumed (Schatz et al. 2002; see discussion in Sect. 4.2).

4 AGE ESTIMATES AND UNCERTAINTIES

Radioactive dating is simple in principle, provided that the initial abundance ratios of $(\mathrm{Th/X})_0$, $(\mathrm{U/X})_0$, and $(\mathrm{U/Th})_0$ have been determined, where X is a stable r-process element (e.g., Eu). Assuming that their changes with respect to the present ratios of $(\mathrm{Th/X})_{\mathrm{obs}}$, $(\mathrm{U/X})_{\mathrm{obs}}$, and $(\mathrm{U/Th})_{\mathrm{obs}}$ observed in stars only depend on the simple exponential decay of Th and U, the time Δt (in Gyr) elapsed since the production of these elements can be determined from the following equations (Cayrel et al. 2001):

$$\Delta t = 46.7[\log(\mathrm{Th/X})_0 - \log(\mathrm{Th/X})_{\mathrm{obs}}], \quad (3)$$

$$\Delta t = 14.8[\log(\mathrm{U/X})_0 - \log(\mathrm{U/X})_{\mathrm{obs}}], \quad (4)$$

$$\Delta t = 21.8[\log(\mathrm{U/Th})_0 - \log(\mathrm{U/Th})_{\mathrm{obs}}]. \quad (5)$$

In fact, Δt is an upper limit. The reason of using the relative abundance ratios rather than the absolute abundances is to reduce the errors, particularly in the Th and U determinations.

4.1 Th/Eu Ages

Up to now, the ratio Th/Eu has been available in a number of very metal-poor halo stars. The names of these stars as listed in column (1) of Table 2. The [Fe/H] and observed abundances of Th and Eu follow in columns (2)–(4). Column (5) lists the initial ratio $(\mathrm{Th/Eu})_0$ used in our age calculations. The age estimates for these individual stars, obtained from Eq. (3), are listed in column (6). For the purpose of comparison, the Th/Eu ages given in the literature are listed in column (7).

According to Eq. (3), the error in the Th/Eu age comes from the observational error in the measurement of $(\mathrm{Th/Eu})_{\mathrm{obs}}$ and the theoretical error in the initial ratio $(\mathrm{Th/Eu})_0$. We have given the errors in our predicted $(\mathrm{Th/Eu})_0$ ratios in Sec. 3. The error in the observed ratio $(\mathrm{Th/Eu})_{\mathrm{obs}}$ mainly depends on the error in the Th abundance determination (Sneden et al. 1996), so we simply take the error in the Th abundance as the error of $(\mathrm{Th/Eu})_{\mathrm{obs}}$. Thus, the total uncertainty in our Th/Eu age, δt, is evaluated by adding the two uncorrected errors $\delta \log \epsilon(\mathrm{Th/Eu})_{\mathrm{obs}}$ and $\delta \log \epsilon(\mathrm{Th/Eu})_0$ in quadrature.

$$\delta t = 46.7\sqrt{(\delta \log \epsilon(\mathrm{Th/Eu})_0)^2 + (\delta \log \epsilon(\mathrm{Th/Eu})_{\mathrm{obs}})^2}\,. \quad (6)$$

For example, with the errors of $\delta \log \epsilon(\mathrm{Th/Eu})_0 = 0.02$ dex and $\delta \log \epsilon(\mathrm{Th/Eu})_{\mathrm{obs}} = 0.07$ dex in CS 22892–052 (Sneden et al. 200a), an age uncertainty of $\delta t = 3.4\,\mathrm{Gyr}$ was obtained from Eq. (6), leading to the final age estimate of 15.7 ± 3.4 Gyr for CS 22892–052 as listed in Table 2. The age uncertainties for the other stars were determined in the same way.

Table 2 The Th/Eu Ages of Metal-poor Halo Stars

Star	[Fe/H]	Observed Abundances		$\log(\mathrm{Th/Eu})_0$	Age(Gyr)	
		$\log \epsilon(\mathrm{Eu})$	$\log \epsilon(\mathrm{Th})$	from our method	Present work	In literature
(1)	(2)	(3)	(4)	(5)	(6)	(7)
CS 22892–052	-3.1[1]	-0.93 ± 0.09	-1.60 ± 0.07	-0.334 ± 0.02	15.7 ± 3.4	16 ± 4[1]
HD 115444	-3.0[2]	-1.63 ± 0.07	-2.23 ± 0.11	-0.334 ± 0.02	12.4 ± 5.2	14.2 ± 4[2]
BD +17°3248	-2.1[3]	-0.67 ± 0.05	-1.18 ± 0.10	-0.334 ± 0.02	8.2 ± 4.7	10 ± 4[3]
HD 186478	-2.6[4]	-1.54 ± 0.08	-2.26 ± 0.07	-0.334 ± 0.02	18.0 ± 3.4	18.3 ± 4.2[4]
HD 108577	-2.4[4]	-1.43 ± 0.12	-1.99 ± 0.07	-0.334 ± 0.02	10.6 ± 3.4	9.8 ± 4.2[4]
BD +8°2856	-2.1[4]	-1.14 ± 0.06	-1.66 ± 0.07	-0.334 ± 0.02	8.7 ± 3.4	8.9 ± 4.2[4]
M92 VII-18	-2.3[4]	-1.42 ± 0.07	-1.95 ± 0.07	-0.334 ± 0.02	9.15 ± 3.4	8.8 ± 4.2[4]
M15 K341	-2.2[5]	-0.88 ± 0.09	-1.47 ± 0.10	-0.334 ± 0.02	12.0 ± 4.7	13.8 ± 4[5]
M15 K462	-2.2[5]	-0.61 ± 0.09	-1.26 ± 0.10	-0.334 ± 0.02	14.8 ± 4.7	15.8 ± 4[5]

References: [1] Sneden et al. 2000a; [2] Westin et al. 2000; [3] Cowan et al. 2002; [4] Johnson & Bolte 2001; [5] Sneden et al. 2000b.

Table 2 shows that the age estimates derived from our calculation of $(\mathrm{Th/Eu})_0$ for metal-poor stars are consistent, within error limits, with those based on the other r-process model calculations. However, strictly speaking, our age estimates for the metal-poor halo stars are lower limits, because the initial value of $(\mathrm{Th/Eu})_0$ ratio calculated from our method is just a lower limit of the zero-age r-process abundance ratio of Th/Eu, — since Eu is stable and so had remained unchanged, while Th had partially decayed when the solar system formed (Seneden et al. 2000b).

4.2 U/Th Ages

The very recent detections of both of the elements Th and U in metal-poor stars provide a more reliable chronometer, U/Th, more reliable than Th/Eu, because the two elements are close in mass (Goriely & Clerbaux 1999; Cayrel et al. 2001). In addition, the U/X ratio as a chronometer could in principle provide a more accurate age determinations than does Th/X, due to the much shorter half-life of U relative to Th. Thus, we can use the three chronometers, Th/X, U/X, and U/Th to estimate the ages of stars with published Th and U abundances.

In Table 3 we list the predictions of the various chronometers by our method and the corresponding observations in CS 31082–001 (Schatz et al. 2002) and BD +17°3248 (Cowan et al. 2002), as well as the age estimates for these two stars. The errors in the observations of CS 31082–001 are adopted from Schatz et al. (2002). For BD +17°3248, we take the errors of observed Th and U abundances as the errors of the observed Th/X and U/X ratios. The errors in our predictions of Th/X and U/X are adopted from the errors of Th and U abundances in solar system material. Hence, the uncertainties in our age estimates can be estimated via Eq. (6). Finally, the U/X and Th/X ages are determined from an average of all the different ages.

For the very metal-poor star CS 31082–001, we find that the average ages of 9.3 ± 2.2 Gyr and -5.3 ± 4.5 Gyr from U/X and Th/X are inconsistent; particularly, the negative age based on Th/X ratios is unacceptable. In fact, Schatz et al. (2002) also found the same result, their Th/Eu age of -5.1 ± 5.8 Gyr is nearly the same as our Th/Eu age of -5.3 ± 5.7 Gyr. They assumed that CS 31082–001 had a different initial r-process abundance distribution than the other *r*-process enhanced metal-poor halo stars, and found that an enhancement of U and Th by a factor of 2.5, compared to their *r*-process model predictions, would resolve the problem. With the same supposition, we find that the average ages of Th/X and U/X would be 13.3 Gyr and 14.5 Gyr, respectively, which are consistent with the U/Th age of 15.0 Gyr, within error limits. At present, it is not clear whether CS 31082–001 is an unusual case or whether it represents a different class of stars (Hill et al. 2002). However, the results for this star do suggest caution in using only Th/Eu for chronometric estimation of stellar ages, and more observations of metal-poor stars are needed to verify the reliability of Th/Eu ages. We note that our U/Th age of 15.0 ± 2.6 Gyr for CS 31082–001 is in good agreement with the 15.5 ± 3.2 Gyr estimated by Schatz et al. (2002) based on *r*-process model prediction of Th/U. This indicates that U/Th ages are more reliable than Th/Eu ages.

Table 3 Chronometers and Age Estimates for CS 31082–001 and BD +17°3248

Chronometer	Calculation	Observation		Age estimate (Gyr)	
		CS 31082-001[1]	BD +17°3248[2]	CS 31082-001	BD +17°3248
log(U/Th)	-0.24 ± 0.04	-0.93 ± 0.11	-0.82 ± 0.11	15.0 ± 2.6	12.6 ± 2.6
$\log\overline{(U/X)}$	...	...	...	9.3 ± 2.2	12.4 ± 4.5
log(U/Ba)	-1.52 ± 0.04	-2.32 ± 0.12	-2.44 ± 0.30	11.8 ± 1.9	13.5 ± 4.5
log(U/La)	-0.66 ± 0.04	-1.32 ± 0.12	-1.58 ± 0.30	9.7 ± 1.9	13.5 ± 4.5
log(U/Ce)	-1.03 ± 0.04	-1.61 ± 0.12	-1.82 ± 0.30	8.6 ± 1.9	11.6 ± 4.5
log(U/Pr)	-0.54 ± 0.04	-1.06 ± 0.12	-1.29 ± 0.30	8.0 ± 1.9	10.3 ± 4.5
log(U/Nd)	-1.24 ± 0.04	-1.79 ± 0.12	-1.93 ± 0.30	8.1 ± 1.9	10.3 ± 4.5
log(U/Sm)	-0.87 ± 0.04	-1.41 ± 0.12	-1.58 ± 0.30	8.0 ± 1.9	10.5 ± 4.5
log(U/Eu)	-0.57 ± 0.04	-1.16 ± 0.17	-1.33 ± 0.30	8.6 ± 2.6	11.1 ± 4.5
log(U/Gd)	-1.05 ± 0.04	-1.65 ± 0.13	-1.74 ± 0.30	8.9 ± 2.0	10.3 ± 4.5
log(U/Tb)	-0.36 ± 0.04	-0.67 ± 0.11	-1.09 ± 0.30	4.6 ± 1.8	10.8 ± 4.5
log(U/Dy)	-1.18 ± 0.04	-1.71 ± 0.13	-1.97 ± 0.30	7.9 ± 2.0	12.0 ± 4.5
log(U/Ho)	-0.53 ± 0.04	...	-1.30 ± 0.30	...	11.4 ± 4.5
log(U/Er)	-0.94 ± 0.04	-1.65 ± 0.15	-1.80 ± 0.30	10.4 ± 2.3	12.7 ± 4.5
log(U/Tm)	-0.12 ± 0.04	-0.68 ± 0.14	-0.93 ± 0.30	8.3 ± 2.2	11.9 ± 4.5
log(U/Hf)	-0.52 ± 0.04	-1.33 ± 0.20	...	12.0 ± 3.0	...
log(U/Os)	-1.43 ± 0.04	-2.35 ± 0.19	-2.45 ± 0.30	13.6 ± 2.8	15.1 ± 4.5
log(U/Ir)	-1.43 ± 0.04	-2.12 ± 0.15	-2.30 ± 0.30	10.2 ± 2.3	12.8 ± 4.5
log(U/Pt)	-1.43 ± 0.04	...	-2.67 ± 0.30		13.8 ± 4.5
$\log\overline{(Th/X)}$	...	...	...	-5.3 ± 2.4	10.2 ± 5.2
log(Th/Ba)	-1.28 ± 0.02	-1.38 ± 0.11	-1.62 ± 0.10	$+4.4 \pm 5.2$	13.5 ± 4.5
log(Th/La)	-0.42 ± 0.02	-0.38 ± 0.06	-0.76 ± 0.10	-2.0 ± 3.0	15.8 ± 5.2
log(Th/Ce)	-0.79 ± 0.02	-0.67 ± 0.04	-0.79 ± 0.10	-5.6 ± 2.1	9.7 ± 5.2
log(Th/Pr)	-0.35 ± 0.02	-0.12 ± 0.06	-1.29 ± 0.30	-8.4 ± 3.0	10.3 ± 4.5
log(Th/Nd)	-0.99 ± 0.02	-0.85 ± 0.05	-1.11 ± 0.10	-7.0 ± 2.5	5.4 ± 5.2
log(Th/Sm)	-0.63 ± 0.02	-0.47 ± 0.06	-0.76 ± 0.10	-7.3 ± 3.0	6.3 ± 5.2
log(Th/Eu)	-0.33 ± 0.02	-0.22 ± 0.12	-0.51 ± 0.10	-5.3 ± 5.7	8.2 ± 5.2
log(Th/Gd)	-0.80 ± 0.02	-0.71 ± 0.06	-0.92 ± 0.10	-4.2 ± 3.0	5.3 ± 5.2
log(Th/Tb)	-0.11 ± 0.02	$+0.28 \pm 0.04$	-0.27 ± 0.10	-18.2 ± 2.4	7.3 ± 5.2
log(Th/Dy)	-0.93 ± 0.02	-0.77 ± 0.07	-1.15 ± 0.10	-7.5 ± 3.4	10.2 ± 5.2
log(Th/Ho)	-0.29 ± 0.02	...	-0.48 ± 0.10	...	8.9 ± 5.2
log(Th/Er)	-0.70 ± 0.02	-0.71 ± 0.09	-0.98 ± 0.10	$+0.5 \pm 4.3$	13.0 ± 5.2
log(Th/Tm)	$+0.12 \pm 0.02$	$+0.26 \pm 0.08$	-0.11 ± 0.10	-6.5 ± 3.8	10.6 ± 5.2
log(Th/Hf)	-0.28 ± 0.02	-0.39 ± 0.17	...	-5.1 ± 8.0	...
log(Th/Ir)	-1.19 ± 0.02	-1.18 ± 0.11	-1.48 ± 0.10	-0.5 ± 5.2	13.6 ± 5.2
log(Th/Pt)	-1.49 ± 0.04	...	-1.85 ± 0.10	...	16.8 ± 5.2

[1] Schatz et al. (2002); [2] Cowan et al. (2002)

For BD +17°3248, we find the average ages of U/X (12.4 ± 4.5 Gyr) and Th/X (10.2 ± 5.2 Gyr) are consistent with the U/Th age (12.6 ± 2.6 Gyr) within error limits. In fact, it is a certain result of the basic hypothesis of radioactive dating that the solar r-process pattern is universal in very metal-poor halo stars. Conversely, consistency among the various Th/X, U/X, and U/Th ages can be used as a test for the r-process models or to identify particular stars such as CS 31082–001. Furthermore, the individual U/X (or Th/X) ages are in general agreement among themselves, which indicates that any observed stable element can be used as the element X to estimate the stellar age if the observed abundance distribution follows perfectly the solar r-process pattern.

The third r-process peak elements (e.g., Ir and Pt) are closer in mass number to Th and U, and offer a direct comparison with ratios of Th or U to less massive n-capture elements: the ratios of Th or U to these heaviest elements should provide more reliable age estimates than to the lighter elements such as Eu. Noting this point, Cowan et al. (2002) derived an average age estimate of 13.8 ± 4 Gyr for BD +17°3248 with the Th/Ir, Th/Pt, U/Ir, U/Pt, and U/Th chronometers, using the theoretical calculations of the classical r-process model (Cowan et al. 1999). Using the same chronometers as in Cowan et al. (2002), we obtain a mean age of 13.9 ± 4.6 Gyr for BD +17°3248 with our calculations. Thus, we obtain the same age estimate as Cowan et al. (2002), using a different approach. This confirms again that our simple method is reasonable.

5 SUMMARY AND CONCLUSIONS

So far, we have proposed a simple method to predict the initial productions of radioactive elements Th and U, based only the observed stellar abundances and the solar r-process abundances. The advantage of our method is that it is independent of any r-process model, and hence its calculations are free from the theoretical uncertainties associated with the r-process models. Using our predictions for the initial productions of Th/Eu and U/Th, we re-estimated the ages of some well observed metal-poor halo stars. Our age estimates are consistent, within error limits, with the other age determinations derived from the theoretical r-process models.

We conclude that our simple method is a reasonable and valid approach for calculating the n-capture element abundances of very metal-poor halo stars, and for giving lower limits for the initial productions of Th/Eu and U/Th ratios, thereby providing certain constraints on the r-process model calculations. In addition, our simple method can be used to identify halo stars with unusual abundance distributions such as that of CS 31082–001, so we can make further studies of such unusual distributions, which may provide important information on the early nucleosynthesis in our Galaxy.

Even though we have obtained reasonable age estimates with a very simple method, there are some important problems that have to be kept in mind. First, the age calculation relies on an exponential model, so that any small error in the observed Th abundance will lead to a large uncertainty in the age determinations. Secondly, the long-standing question that whether the solar r-process pattern is 'universal' remains in doubt (e.g., Arnould & Goriely 2001). This universality is an essential hypothesis for bringing the observed Th and U to the status of chronometers. Fortunately, almost all the metal-poor halo stars observed up to now exhibit a unique solar r-process abundance pattern for elements with $56 \leq Z \leq 76$. Of course, further observations for more metal-poor stars are needed to settle the dispute on this question. Thirdly, another crucial question is whether this r-process pattern can be extrapolated to the

Th and U region. Our results indicate that such an extrapolation is reasonable for most of the very metal-poor stars found so far with the only exception of CS 31082–001. In addition, radioactive dating suffers from some difficulties in both observational and theoretical aspects. On the observational side, it is difficult to determine accurate Th and U abundances because the lines of Th and U in cool stars are very weak and are severely blended with a number of atomic and molecular features. On the theoretical side, how to accurately estimate the initial productions of radioactive elements is still a thorny problem. Nonetheless, radioactive dating still provide a promising independent approach to estimating the age of the Galaxy and providing some important constraints for the Galactic chemical evolution models.

In future, additional stellar spectra with high resolution and high signal-to-noise ratio and accurate stellar atmosphere models for metal-poor halo stars are required to reduce the errors in the abundance determinations. Further theoretical and experimental nuclear physics studies on the r-process nucleosynthesis are needed to reduce the uncertainties in the r-process predictions for the Th and U chronometers. Work along these lines will increase the accuracy of age determination for the metal-poor halo stars and will give tighter limits on the age of the Galaxy.

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References

Anders E., Grevesse N., 1989, Geochim. Cosmochim. Acta, 53, 197

Arlandini C., Käpeler F., Wisshak K., 1999, ApJ, 525, 886

Arnould M., Goriely S., 2001, In: von Hippel T., Simpson C., eds., Astrophysical Ages and Time Scales, ASP Conf. Ser., p.252

Arnould M., Takahashi K., 1990, In: Sanchez F., Vasquez M., eds., New Windows to the Universe, Cambridge: Cambridge University Press, 355

Arnould M., Takahashi K., 1999, Rep. Prog. Phys., 62, 393

Burris D. L., Pilachowski C A., Armandroff T E. et al., 2000, ApJ, 544, 302

Butcher H. R. 1987, Nature, 328, 127

Cayrel R., Hill V., Beers T G. et al., 2001, Nature, 409, 691

Cowan J. J., McWilliam A., Sneden C., Burris D. L., 1997, ApJ, 480, 246

Cowan J. J., Pfeiffer B., Kratz K.-L. et al., 1999, ApJ, 521, 194

Cowan J. J., Sneden C., Burles S. et al., 2002, ApJ, 572, 861

Cowan J. J., Thielemann F.-K., Truran J., 1991a, ARA&A, 29, 447

Cowan J. J., Thielemann F.-K., Truran J., 1991b, Phys. Rep., 208, 267

François P., Spite M., Spite F., 1993, A&A, 274, 821

Goriely S., Arnould M., 2001, A&A, 379, 1113

Goriely S., Clerbaux B., 1999, A&A, 346, 798

Grevesse N., Sauval A. J., 1998, Space Sci. Rev., 85, 161

Hill V., Plez B., Cayrel R. et al., 2002, A&A, 387, 560

Johnson J. A., Bolte M., 2001, ApJ, 554, 888

Käppeler F., Beer H., Wisshak K., 1989, Rep. Prog. Phys., 52, 945

Kratz K.-L., Pfeiffer B., Thielemann F.-K., 1998, Nucl. Phys. A, 630, 352

Li J., Zhao G., 2003, Progress in Astronomy (in Chinese), 21, 70

Qian Y.-Z., Wasserburg G. J. 2002, ApJ, 567, 515

Rutherford E., 1929, Nature, 123, 313

Schatz H., Toenjes R., Pfeiffer B. et al., 2002, ApJ, 579, 626

Sneden C., Cowan J. J., Ivans I. I. et al., 2000a, ApJ, 533, L139

Sneden C., Johnson J., Kraft R. P. et al., 2000b, ApJ, 536, L85

Sneden C., McWilliam A., Preston G. W. et al., 1996, ApJ, 467, 819

Sneden C., Cowan J. J., Lawler J. E. et al., 2002, ApJ, 566, L25

Truran J. W., Cowan J. J., Pilachowski C. A., Sneden C., 2002, PASP, 114, 1293

Toenjes R., Schatz H., Kratz K.-L. et al., 2001, In: von Hippel T., Simpson C., eds., Astrophysical Ages and Time Scales, ASP Conf. Ser., p.376

Westin J., Sneden C., Gustafsson B., Cowan J. J., 2000, ApJ, 530, 783

Zhang B., Li J., Wang Y. X. et al., 2002, Ap&SS, 280, 325