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THE AGE OF THE GALAXY FROM THORIUM COSMOCHRONOMETRY

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RESUMEN

El torio, elemento radioactivo de larga duración, puede sevir como un reloj sencillo y directo para determinar la edad de nuestra galaxia. Las investigaciones espectroscópicas de torio en estrellas pobres en metales han dado resultados iniciales prometedores. Discutimos las mayores limitaciones observacionales y teóricas de la cosmocronometría del torio y señalamos formas para lograr que las edades derivadas de las abundancias de torio sean más exactas.

ABSTRACT

The long–lived radioactive element thorium can potentially provide a simple and direct clock to determine the age of our Galaxy. Spectroscopic investigations of thorium in metal–poor stars have yielded some promising initial results. We discuss the major observational and theoretical limitations in thorium cosmochronometry, and point out the ways in which the implied Galactic ages from thorium abundances can be made more accurate.

Key Words: **ATOMIC DATA — GALAXY: FUNDAMENTAL PARAMETERS — NUCLEAR REACTIONS, NUCLEOSYNTHESIS, ABUNDANCES — STARS: ABUNDANCES**

1. INTRODUCTION

Determination of the age of the universe has been a fundamental goal of astronomical research for centuries. Modern age–dating methods of varying degrees of directness attack both extragalactic objects (e.g., galaxies of all types, via the Hubble Law), and the older galactic objects (e.g., globular cluster main sequence turnoff stars, white dwarf stars). Every attempt to transform the observed properties of astronomical objects into their ages involves some estimates and assumptions; each of these leaps of faith inevitably increases the total derived age uncertainties.

Nuclear cosmochronometry begins with the determination of relative abundances of stable and long–lived radioactively unstable very heavy elements. The abundance ratios are used to determine the time since the synthesis of these elements, given that the half–lives of the unstable elements are known from laboratory studies. The elements involved in nuclear cosmochronometry are all neutron–capture (or n–capture) elements. They are in the atomic number domain $Z > 30$, and their isotopes are overwhelmingly created via bombardment of lighter target nuclei by free neutrons. The bombardment can be slow enough that almost any possible β–decays of too–neutron–rich nuclei has time enough to occur between successive neutron captures. This so–called "*s*–process" synthesis commonly occurs in helium fusion zones during the late quiescent stages of stellar evolution, as evidenced by the n–capture–rich asymptotic giant branch carbon stars. At the other neutron bombardment extreme, an extremely large neutron flux overwhelms the β–decay rates, pushing nuclei out to the "neutron drip line" in a matter of seconds, which then decay back toward the valley of β–stability after the neutron blast shuts off. The site of this "*r*–process" synthesis is not known with certainty, other than the realization that it must be at or near the point of stellar death; low–mass supernovae, neutron–star binaries, and other massive star sites have all been suggested (see Cowan et al. 1999 for a more detailed discussion and references).

Thorium ($Z = 90$) and uranium ($Z = 92$) are radioactive n–capture elements with at least three properties in common. First, they can be synthesized only in the *r*–process, because the heaviest completely stable element

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is bismuth (Z = 83). Elements in the atomic number domain $84 \leq Z \leq 89$ radioactively decay so quickly that *s*–process synthesis occurs too slowly to be able to bridge this six–element gap. Second, thorium and uranium decay on giga–year time scales, slowly enough that they can be used as chronometer elements for the solar system and the Galaxy. Third, these elements are spectroscopically detectable in the Sun and stars. For all of these reasons thorium and uranium will be the focus of the rest of the present paper. We first briefly review the history of thorium abundance studies in stars, with emphasis on the unique n–capture–rich very metal-poor star CS 22892-052 (§2), and then discuss the major uncertainties in thorium and uranium cosmochronometry, and how these uncertainties may be reduced with future work (§3).

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2. PAST AND PRESENT THORIUM ABUNDANCE STUDIES

The first extensive study of stellar thorium cosmochronometry was published by Butcher (1987), who synthesized the 4019 Å line of Th II, and compared the derived thorium abundances to those of neodymium derived from a neighboring Nd II line. This analysis was refined and extended by Morell, Källander & Butcher (1992). One significant limitation of these pioneering studies was the use of neodymium as a comparison element: it is made in solar–system material in roughly equal measure by the *s*– and *r*–process (Burris et al. 2000, and references therein), but the fractional contributions to its abundance in the target stars was not assessed. Additionally, these studies only considered relatively metal–rich disk stars, whose ages compared with the oldest halo stars cannot easily be determined. A major step forward was achieved by François, Spite & Spite (1993), whose thorium abundance study targeted very metal–poor halo field giants, and used europium (a 97% *r*–process element in solar–system material; Burris et al. 2000) as a more appropriate comparison stable element. That investigation found a large star–to–star scatter in derived [Th/Eu][3] ratios, but there were heterogeneous sources for the europium abundances, and no definitive statements could be made sources of the [Th/Eu] scatter. They noted that at the time of their paper, "The complex variation of the Th/Eu ratio weakens the use of this ratio as a radiochronometer as long as no detailed yields will be available for these elements" (see §3.2).

Included as a target star in a large spectroscopic survey of abundances in newly–discovered very metal–poor giants (McWilliam et al. 1995), the star CS 22892-052 was serendipitously discovered to have extremely large relative overabundances of all detectable n–capture elements, and the abundance pattern among these elements was consistent with a scaled solar–system *r*–process pattern (Sneden et al. 1994). The spectrum of the star was subjected to further scrutiny with better spectra (more extensive wavelength coverage, higher S/N and resolution) by Sneden et al. (1996), and Norris, Ryan, & Beers (1997a), and recently Sneden et al. (2000) have published a new abundance study that includes about half of the elements in the periodic table. In Figure 1 we summarize the results of that work. The abundances of CS 22892-052 clearly exhibit a non–solar pattern. The parts of the abundance distribution relevant to the present discussion are: *(a)* the very low metallicity ([Fe/H] = –3.1) which ensures that the abundances of CS 22892-052 were created near the nucleosynthetic beginning of the Galaxy; *(b)* the extreme overabundances most n–capture elements (roughly peaking at [Dy/Fe] $\simeq$ +1.8), suggesting that a single nucleosynthesis event was responsible for the creation of this star's n–capture elements; *(c)* the steady increase in overabundances from barium to europium, and the flat abundance distribution of the stable n–capture elements beyond europium, indicating a dominant *r*–process synthesis mechanism for (at least) the heaviest n–capture elements; and *(d)* the relatively lower abundance of thorium and the even lower abundance upper limit for uranium. This latest study reaffirms that for elements with $Z \geq 56$, there is an almost perfect abundance match between the observed CS 22892-052 and a scaled solar–system *r*–process–only abundance distribution.

CS 22892-052 has the largest set of n–capture elemental overabundances with a distinct *r*–process signature ever found in a metal–poor halo star. But it stands alone only in the magnitude of the n–capture overabundances, not in the *r*–process nature of these abundances. For example, a recent detailed study (Westin et al. 2000) of the very metal–poor giant star HD 115444 reveals a nearly identical n–capture abundance pattern. More generally, Burris et al. (2000) show that the dominance of the *r*–process is very general among halo stars with [Fe/H] $\lesssim$ –2.5. The interpretation of *r*–process synthesis of n–capture elements in the early Galactic halo seems reasonably secure. The apparently uniform production of the heavier *r*–process elements throughout the Galaxy's history is not well understood, but with this fairly uniform observational result we can now turn attention to observation and interpretation of thorium abundances.

[3] $[A/B] \equiv \log_{10}(N_A/N_B)_{star} - \log_{10}(N_A/N_B)_{\odot}$

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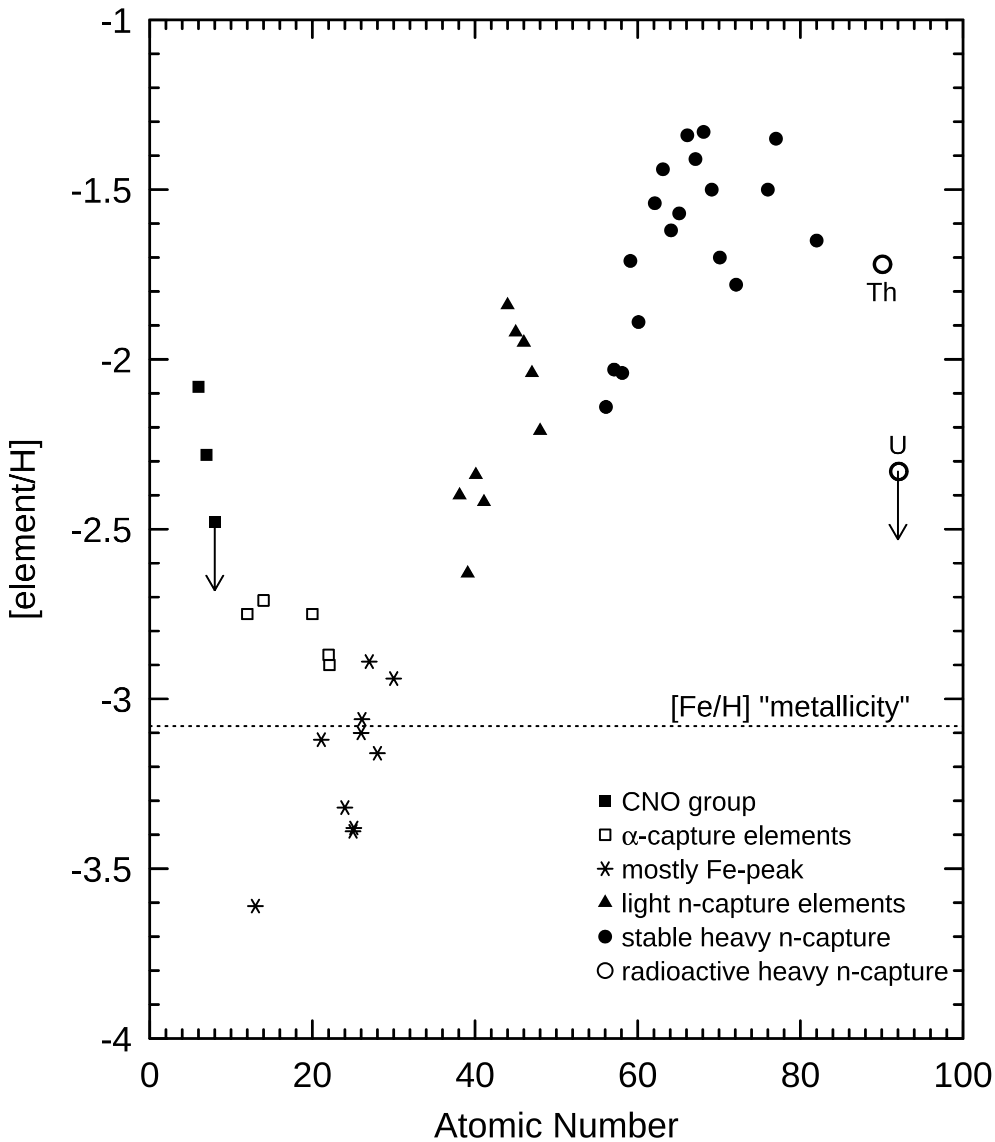

Fig. 1. Abundances of 46 elements in the very metal–poor giant star CS 22892-052. Note the extreme overabundances of the n–capture elements, which grows with increasing atomic number with the conspicuous exception of the radioactive elements thorium and uranium. See Sneden et al. (1996; 2000) and Cowan et al. (1999) for additional discussion of the elemental abundances not discussed here.

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3. THORIUM ABUNDANCES AND COSMOCHRONOMETRY

3.1. *Observational Aspects of Thorium and Uranium*

The ionization potential of Th I is low, and so thorium is essentially totally ionized in stellar atmospheres. There are many lines of Th II spectrum, but the relatively low thorium abundance renders most of the transitions undetectably weak in low metallicity stars. Until recently, the only Th II line studied in cool stars has been the 4019.12 Å feature. Analysis of this line is very difficult for a number of reasons. First and foremost, it is severely blended with a number of atomic and molecular (^{13}CH) features (e.g. Morell, Källander & Butcher 1992; François, Spite & Spite 1993; Norris, Ryan & Beers 1997b). The blending agents are of comparable strength or greater than that of the Th II line in metal–poor giants with [Fe/H] $\lesssim$ 0.0 (and they totally dominate the thorium feature in higher metallicity disk main sequence stars; see Figure 1 of Morell, Källander & Butcher (1992), so this feature is useless for reliable age estimates unless [Th/Eu] $\gtrsim$ +0.5 (e.g., see Figure 7 of Westin et al. 2000).

One obvious way to increase the reliability of thorium abundances would simply be to detect other Th II transitions in metal–poor stars. But all other lines have smaller transition probabilities than the already weak 4019 Å line, so the task is not easy. The n–capture–rich star CS 22892-052 is the obvious target to search for secondary Th II lines. Sneden et al. (2000) report detection of a line at 4086.52 Å, suggesting that the thorium abundance derived from this feature is in good agreement with the abundance from the 4019 Å line. In Figure 2 we show these two lines, as well as two additional ones that lie at the wavelengths of predicted Th II lines, appear to be largely free of blending, and have strengths roughly consistent with ones expected from extrapolation of the strengths of the 4019 and 4086 Å lines. Further investigation is needed before these suggested new thorium transitions can yield reliable abundances. Unfortunately, it is clear from the spectra shown here that the three weakest Th II lines will be undetectable in stars with much smaller thorium abundances; the spectrum of CS 22892-052 remains the best "laboratory" for n–capture studies in metal–poor stars.

Even with Th II line detection(s), derivation of accurate thorium abundances requires careful consideration of data and analysis assumptions. The transition probabilities of Th II transitions appear to be reasonably well determined. The standard 4019.12 Å line has received the most attention in laboratory studies. Lawler et al. (1990), drawing from the data of Simonsen et al. (1988), suggest that the log gf value of this transition has an uncertainty of only ±0.04 dex. The more Th II lines (with accurate gf values) that are identified in stellar spectra, the less such transition probability uncertainties will matter in the overall error budget for thorium chronometry; the averaging of abundances from several lines would certainly help here.

Continuum placement errors and line contamination probably contribute another ±0.02 dex to the total thorium abundance errors. Many metal–poor stars now have been observed with very high resolution and S/N spectra, and the general line weakness of these stars yields relatively well–defined continua even in the blue–violet spectral regions where the Th II lines occur. But the known blending of the usually–employed 4019 Å line (discussed above), and the rudimentary current knowledge of blending for the other thorium lines are the limiting factors here. Again, the best way to deal with continuum and line contamination problems is to analyze stars with the largest n–capture overabundances.

Little if any investigation has been made of the effects on thorium abundances of various stellar atmospheric uncertainties. The use of different model atmosphere grids (e.g., MARCS, Gustafsson et al. 1975; ATLAS, Kurucz 1992; 1999) certainly alters the derived [Th/H] values, but does so equally to the abundances of almost all of the usual comparison elements (europium, dysprosium, etc.), since transitions of all of these arise from low excitation levels of their ionized species. And to our knowledge there are no statistical equilibrium studies that drop the simplifying assumption of LTE for any of the elements considered here. Such studies should be attempted, but the atomic data for the elements considered here simply may be inadequate at present for meaningful insights into the magnitude of the abundance changes that could occur.

Finally, even if the n–capture abundances of CS 22892-052 and HD 115444 are in excellent agreement with each other, and the derived [Th/Eu] abundances also agree well, how do we know that these abundance ratios represent the typical values for Galactic halo material? If the [Th/Eu] values have significant star–to–star scatter, then they cannot be interpreted in terms of stellar ages (e.g. Goriely & Clerbaux 1999). Resolution of this question is simple in principle, yet it will require the derivation of detailed n–capture abundance patterns in many metal–poor stars. If the derived [Th/Eu] ratios of a large set of very metal–poor stars turn out to be all the same within observational errors, then the observed thorium abundances undoubtedly are the radioactive

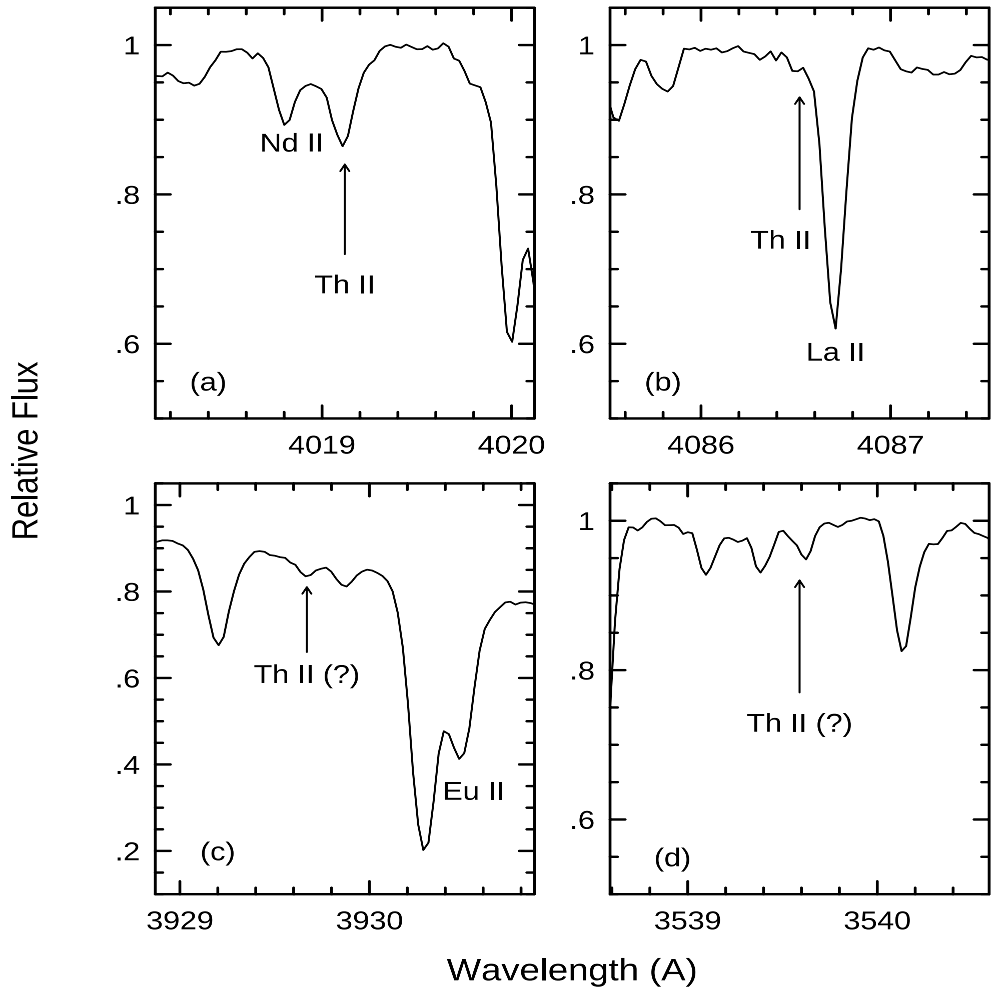

Fig. 2. Small spectral regions surrounding four of the strongest Th II lines. Panel (a) displays the 4019 Å feature used exclusively in past thorium abundance studies, panel (b) shows the newly-detected 4086 Å line, and panels (c) and (d) have the spectra of two proposed new Th II lines. Attribution of the features in panels (c) and (d) solely or mostly to thorium is tentative at present.

remnants of the thorium that the early Galaxy synthesized — with identical but higher [Th/Eu]. On the other hand, if the observed [Th/Eu] ratios end up having significant scatter among very metal–poor stars, then thorium will lose its attractiveness for stellar cosmochronometry. Only future n–capture abundance studies can adequately address this question.

The situation is less promising for uranium. The one strong U II line in a conveniently observable spectral region lies at 3859.5 Å, and thus its presence in cool stars is normally swamped by CN molecular absorption. Moreover, its long–lived isotope ^{238}U has a half–life of 4.468 Gyrs, meaning that even if in the early Galaxy uranium was created in reasonable amounts compared to thorium (as predicted by r–process theoretical calculations) then its abundance will have been greatly attenuated after the 12–15 Gyr history of the Galaxy. In the most favorable case of CS 22892-052, an upper limit to the uranium abundance could be derived that was of interest; do not expect the same meaningful abundance limit in many other stars.

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3.2. *Transforming Thorium Abundances into Age Estimates*

From the observed thorium abundances in a metal–poor halo star we estimate the "age" of its n–capture material via a simple procedure. An underlying assumption is behind this calculation: that the abundances of the n–capture elements observed in the most metal–poor of these stars match the solar–system *r*–process abundances. Observational evidence supporting this assumption has been reviewed in §2. The age is derived by comparing the observed stellar abundance ratio N_{Th}/N_{Eu}[4] With theoretical estimates of the initial value of N_{Th}/N_{Eu} at the time of formation of these elements in an *r*–process synthesis event. Since the radioactive element thorium has a known decay half–life, the difference in the abundance ratios gives a direct age estimate of the stars containing the n–capture material. For both CS 22892-052 and HD 115444, thorium decay ages of about 14–16 Gyr are obtained. Repeating the calculation for uranium, the lack of a detectable U II line in CS 22892-052 suggests an age of greater than 11 Gyr.

The primary theoretical factor affecting these age estimates involves uncertain nuclear physics. Nuclei involved in the *r*–process are far from β–stability and therefore the necessary nuclear data for reliable *r*–process predictions are in most cases not obtainable by experimental determination. There have, however, been major recent advances in theoretical prescriptions for very neutron–rich nuclear data that have been strengthened by recent experimental results for very neutron–rich isotopes (see Cowan et al. 1999 and references therein for a discussion of this.) One assessment of the reliability of any nuclear mass formulae is how well the abundance predictions match the observed, stable solar system *r*–process nuclei. Cowan et al. (1999) found that the best agreement with solar system *r*–process abundances – with deviations typically in the 10%–20% range – was obtained when they employed the nuclear mass predictions from an extended Thomas Fermi model with quenched shell effects far from stability (i.e., "ETFSI–Q", Pearson, Nayak & Goriely 1996).

There is an additional level of uncertainty involved in the zero–decay age abundance predictions of the chronometers thorium and uranium, simply due to their radioactive nature. In other words, while the stable heavy solar system elements, such as Pt, can be compared directly with theoretical predictions, no such comparison is possible with thorium or uranium. However, their decay is responsible for the production of the stable lead and bismuth isotopes, which can be observed and thus compared with theoretical estimates. Based upon a number of tests, examining the nuclear physics input which best reproduced all observables, Cowan et al. (1999) suggested that the theoretical errors, when employing a nuclear mass models that are reliable far from stability, are of the order of 10-20%, resulting in theoretical age uncertainties of $\simeq$ 3–4 Gyr. Reducing that uncertainty further will require great theoretical and experimental nuclear physics efforts to determine reliable values of the properties of nuclei far from stability.

A final, more encouraging comment is warranted. The derivation of ages of metal–rich disk stars from their thorium abundances is made more complicated by the multiple generations of n–capture producers that were necessary to build these elements to their present relatively high abundances. This means that the radioactive elements like thorium and uranium have multiple clocks ticking: individual atoms of these elements that exist in metal–rich stars may have been synthesized near the start of the Galaxy, or relatively recently. There is a confusion of decay times at work. This source of age uncertainty does not apply to very metal–poor halo stars. All of their elements were produced in the first wave of Galactic nucleosynthesis, and effectively only one clock is at work for the whole ensemble of radioactive atoms observed in very metal–poor stars.

4. CONCLUSIONS

Thorium cosmochronometry is a promising method to derive the age of our Galaxy, and application of it to the spectra of very metal–poor halo stars has recently yielded ages that are in good agreement with determinations from other methods (e.g., Pont et al. 1998; Riess et al. 1998; Perlmutter et al. 1999). Reliable abundances of both thorium and a number of other n–capture elements are now available for a handful of very metal–poor stars. Unfortunately, uncertainties in the age estimates for each of these cases remains large, of order ±4 Gyr. Improvement in this situation depends on a number of factors. First, it is very important to continue probing the Galactic halo population for more examples of very metal–poor yet n–capture–rich

[4] Alternatively, one could consider N_{Th}/N_{Dy}, or N_{Th}/N_{Pt}, or indeed the abundance ratio of thorium to any other predominantly *r*–process element (to minimize synthesis uncertainties). However, europium is the most commonly employed stable *r*–process comparison element because its spectral features are easily observed in most metal–poor stars.

stars. Second, for those 30 or so metal–poor stars now known to possess [n–capture/Fe] $\gtrsim +0.5$, more complete n–capture abundance studies (obviously including very careful attention to thorium) must be carried out. Complementary theoretical investigations of r–process synthesis must be carried out, for the crucial question in deriving a thorium–based age of a star is not "what is the observed [Th/Eu] ratio", but rather "what was the time–zero [Th/Eu]"?

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