

# R-Process Chronometers<sup>★</sup>

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## Abstract

We compare calculations of r-process abundances with recent astronomical observations from extremely metal-deficient, neutron-capture-rich halo stars. We derive criteria to determine Th and U chronometric ages, and deduce astrophysical conditions under which the observed abundance patterns can be obtained under r-like conditions.

*Key words:* Galaxy: halo, nuclear reactions, nucleosynthesis, abundances, stars: abundances, stars: Population II

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Historically, nuclear chronometers in terrestrial and meteoritic probes have always played an important role in the determination of the ages of the Solar System and our Milky Way Galaxy. Particularly useful in this context are the long-lived actinides  $^{232}\text{Th}$  ( $T_{1/2}=1.4 \times 10^{10}\text{a}$ ),  $^{235}\text{U}$  ( $7.0 \times 10^8\text{a}$ ) and  $^{238}\text{U}$  ( $4.5 \times 10^9\text{a}$ ) which are exclusive products of the astrophysical rapid neutron-capture process, i.e. the "r-process". Earlier attempts of age dating of the Galaxy were closely tied to theoretical models of star formation and Galactic chemical evolution and the primordial abundances of Th and U in Solar System matter. Over the past decade, spectroscopic studies of ultra-metal-poor (UMP), neutron-capture-rich stars made possible a quite different approach: age determinations for individual field-halo and globular-cluster stars from r-process chronometers. Since such stars were formed in the very early epoch of star formation and nucleosynthesis in our Galaxy, their ages provide a **direct** measure of the

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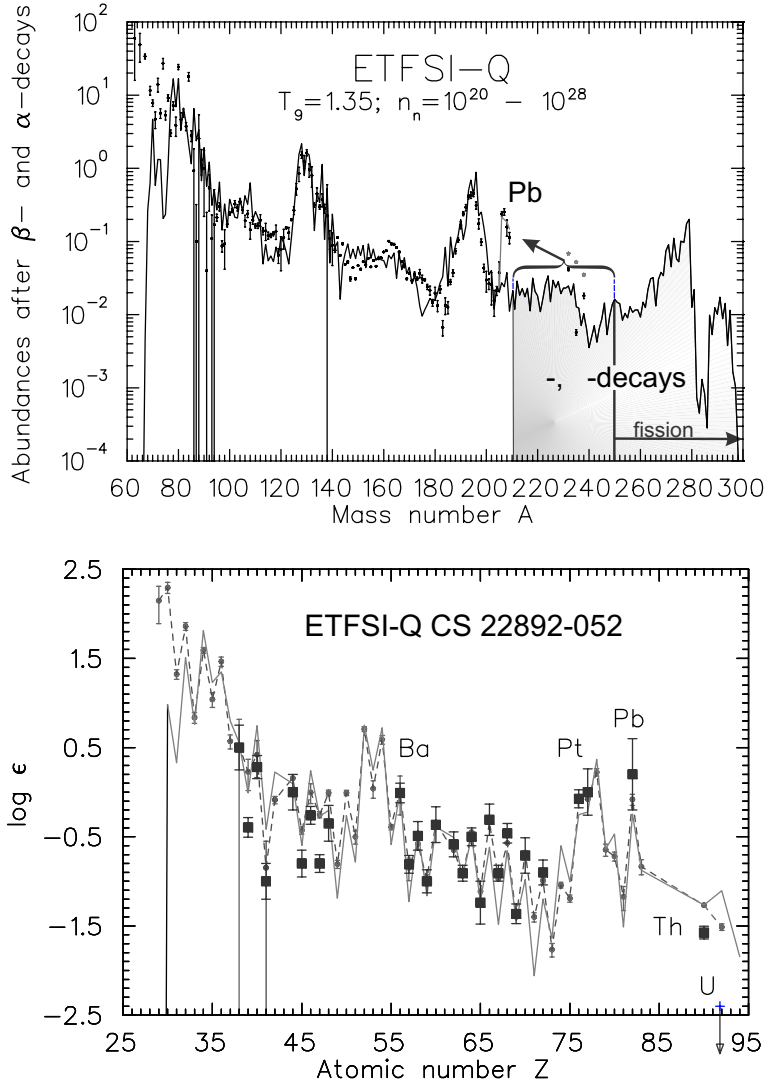


Fig. 1. Upper part: Fit (curve) to solar r-process *isotopic* abundances (dots;  $\text{Si} \equiv 10^6$ ) obtained as superposition of 16 equidistant  $n_n$  components. This result also shows a good fit to the r-process Pb and Bi contributions after summing up the  $\alpha$ -decay chains of heavier nuclei. Lower part: Observed neutron-capture *elemental* abundances in the ultra-metal-poor halo-star CS 22892-052 (squares) compared to scaled  $N_{r,\odot}$  values (dots) and our calculated r-abundances (full line). The upper limit of the U abundance is denoted by an arrow.

age of the Galaxy and a lower limit of the age of the Universe itself. The observed relative abundance ratio of radioactive Th to a stable r-process-”only” rare-earth element (REE), in most cases Eu, was commonly used as the appropriate chronometer (see, e.g. [1,2]). More recently, in several field halo stars, observational data of a wider range of heavy elements beyond  $Z \simeq 50$  (up to the 3<sup>rd</sup> r-process abundance peak elements Os, Ir, Pt and Au) have become available [3–5] to determine an ”average” cosmochronological Th age. Moreover, the observation of U in the two UMP stars CS 31082-001 and BD +17°3248 and the estimation of upper limits of U in a couple of other halo stars now

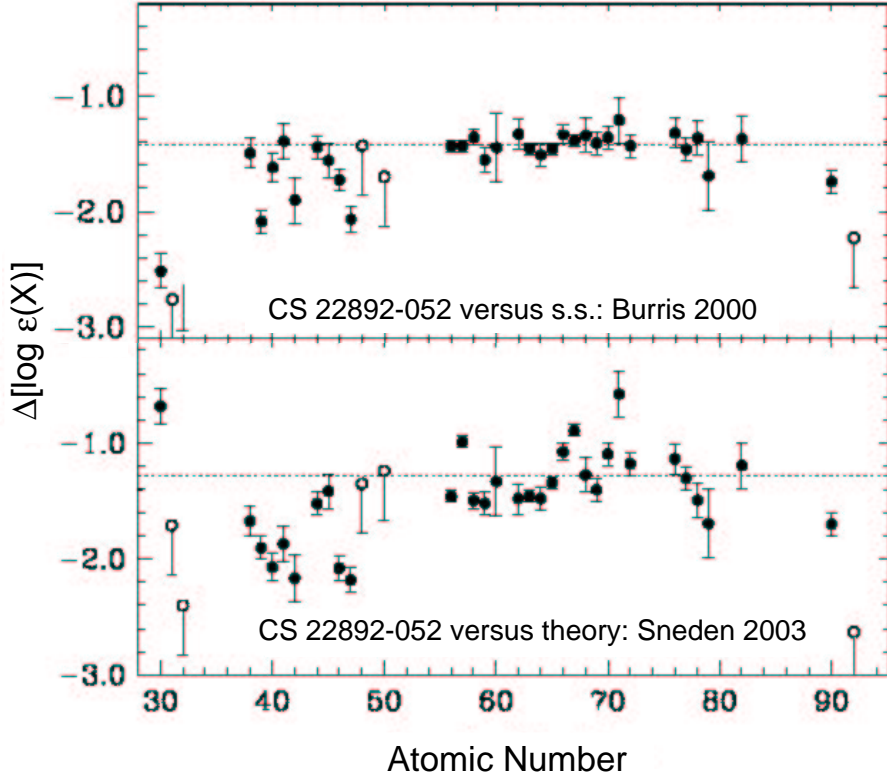


Fig. 2. Upper part: Differences between CS 22892-052 abundances [3] and the metallicity-scaled  $N_{r,\odot}$  distribution from [11]. The dotted line indicates the unweighted mean difference for elements in the range  $56 \leq Z \leq 79$ . Detected elements are shown as filled circles with error bars, and upper limits are with open circles with only the lower part of an arbitrary-length error bar. Lower part: Differences between CS 22892-052 abundances and our scaled theoretical r-process predictions [9].

makes it possible to use the radioactive Th/U pair as a chronometer in addition to the Th/REE pairs.

However, for all chronometric pairs theoretical modeling of r-process nucleosynthesis is required to determine the "initial" isotopic or elemental abundances. As the site of the r-process has not been identified with certainty yet, we use a largely model-independent approach of the classical canonical r-process (see, e.g. [6–10]). Fig. 1 shows a typical fit to the Solar System *isotopic* r-abundances ( $N_{r,\odot}$ , see upper part), which then can easily be converted to *elemental* ones, here for the UMP halo-star CS 22892-052 (see lower part). A detailed element-by-element difference comparison between the  $N_{r,\odot}$  curve from Burris et al. [11] and the abundances in CS 22892-052 is presented in the top panel of Fig. 2 (from Sneden et al. [3]). In the bottom panel of Fig. 2 we make a similar comparison between the abundances in this UMP star and our theoretical predictions based on the "waiting-point" approximation for the r-process [9]. It is quite evident from Fig. 2 that both comparisons reveal and confirm three important features that are common to extremely metal-deficient stars: (i) the robustness of the goodness of the fit to the  $N_{r,\odot}$  values

Table 1

Abundance ratios of r-chronometer pairs using different fit criteria and seed compositions. *New fit A, B* are least-square fits for  $N_{r,\odot}$  in the mass ranges A=83-209 and A=125-209, respectively.

R-chronom. pair	Fe-seed				Zr-seed
	Old fit [2]	New fit A	New fit B	Th(B)/X <sub>⊙</sub>	New fit
Th/U-238	1.805(3)	1.557(11)	1.568(11)		1.475(1)
U-235/U-238	1.602(6)	1.464(14)	1.464(14)		1.758(2)
Th/Os	0.0990(24)	0.0980(11)	0.0927(14)	0.0750	0.0735(16)
Th/Ir	0.0923(19)	0.0948(30)	0.0890(31)	0.0703	0.0676(11)
Th/Pt	0.0239(6)	0.0255(11)	0.0235(11)	0.0360	0.0316(5)
Th/3 <sup>d</sup> peak	0.0159(4)	0.0167(6)	0.0155(6)	0.0181	0.0166(3)
Th/Eu	0.481(23)	0.530(23)	0.453(17)	0.422	0.479(18)

for elements in the range from Ba to Pb, which corresponds to a primary *"main"* r-process (requiring high neutron densities), (ii) the underproduction and pronounced odd-even-Z staggering of elements in the region below Ba relative to the REE and 3rd peak elements, which indicates the need for a secondary *"weak"* r-process (with moderate neutron densities) [9,12,13], and (iii) the good agreement between observations and our theoretical predictions. This gives us some confidence in proceeding to utilize the Th and U chronometers to provide age estimates not only for CS 22892-052, but also for other UMP halo stars.

However, it is still true, that r-process calculations require nuclear-physics input data of thousands of unstable nuclei, in general not available from experiment. Hence, far reaching theoretical extrapolations from known isotopes near  $\beta$ -stability to the neutron drip-line are needed, which may affect the calculated initial production ratios of the chronometric nuclei. This may well introduce considerable uncertainties in the age determinations that are not easy to quantify. Therefore, the more recent observations of the main 3rd-peak elements ( $^{76}\text{Os}$ ,  $^{77}\text{Ir}$ ,  $^{78}\text{Pt}$ ) and in particular  $^{92}\text{U}$  were quite welcome in the sense that the  $^{90}\text{Th}/^{63}\text{Eu}$  chronometer pair can now be replaced by abundance ratios of elements with smaller difference in atomic number. This is particularly true for the radioactive Th/U pair, where, in addition, a quite sensitive consistency check for the calculated *"initial"* abundances of this latter actinide pair can be given by a successful reproduction of the observed Pb and Bi r-abundances, which originate to more than 80 % from  $\alpha$ -decay of the Th and U isotopes (for details, see e.g. [2]).

A recent occasion to question the robustness and universality of a *"main"* r-

Table 2

Comparison of  $(N_{\odot}-N_s)\simeq N_{r,\odot}$  "residuals" [2,16,17] of  $^{206-208}\text{Pb}$  and  $^{209}\text{Bi}$  with our calculated r-abundances.

Isotope	Pb-206	Pb-207	Pb-208	Bi-209	$\Sigma\text{Pb}$	$\Sigma\text{Pb,Bi}$
$N_{\odot}(\text{s+r})$	0.593	0.644	1.828	0.146	3.065	3.211
$N_{r,\odot}$						
Ref. [2]	0.240	0.254	0.158	0.144	0.652	0.766
Ref. [16]	0.178	0.171	0.133	0.101	0.482	0.583
Ref. [17]	0.178	0.116	0.091	0.118	0.385	0.503
$N_{r,calc.}$						
Ref. [2]	0.158	0.146	0.135	0.103	0.439	0.542
Fe-seed	0.163	0.151	0.138	0.111	0.452	0.564
Zr-seed	0.213	0.163	0.142	0.132	0.518	0.650

process pattern in UMP halo stars has been the observation of an enhancement of the Th and U abundances in CS 31082-001 relative to the REE by about a factor 2.5, together with an inconsistently low upper limit for Pb of  $\log \epsilon = -0.2$  [4,14]. With an age of this star of about 15.5 Gyr [14] deduced from the Th/U pair, the generic relationship between Th, U and their Pb  $\alpha$ -decay products would in our calculations require a minimum Pb abundance of  $\log \epsilon = -0.02$ , which should have been measurable. The only possibility of resolving this problem, while still upholding the assumption of a universal r-process pattern in UMP stars, would be to assume that at least part of the heavy r-elements including Th and U in CS 31082-001 were implanted long after the formation of this star.

We have therefore examined in great detail problems and constraints associated with the Th/3rd peak and Th/U chronometric pairs, such as uncertainties in the underlying atomic and nuclear physics (see, e.g. [12,15,14]). Table 1 summarizes our recent results of Th/X ratios from r-abundance calculations assuming two different seed compositions, (i) the classical Fe-seed, and (ii) an  $A \simeq 90$  seed (here denoted "Zr-seed"). The latter simulates the possible r-process seed composition after the  $\alpha$ -rich freeze-out of the high-entropy wind scenario of a core-collapse SNII [7]. Table 2 compares the Solar System r-process "residuals" ( $N_{r,\odot} \simeq N_{\odot} - N_{s,\odot}$ ) [2,16] for the Pb and Bi isotopes with our theoretical predictions. It is clear from this table, that – at least within our present r-process model parameterization – we consistently obtain Pb and Bi abundances, which are lower than the old recommended solar values (used e.g. in [2]), but agree better with the recent evaluations of Beer et al. [16] and Gallino et al. [17]. Further progress in the understanding of r-process chronometry of Th/U may soon be obtained from the determination of Pb abundances

with the Hubble Space Telescope. Measurements for the star CS 31082-001 are underway [18].

Summarizing, from recent Th/REE and Th/U observations in several UMP halo stars chronometric ages of about  $(14 \pm 3)$  Gyr have been determined [4,14,12,15,3], which are in good agreement with other, independent age determinations of the Universe (see, e.g. [19]). Further progress in r-chronometric age determinations are expected from a combination of improved astrophysical calculations and high-resolution optical spectroscopy of **isotopic** abundance ratios [20]. Such data would also allow to determine r/s-mixtures and with this the onset of s-process nucleosynthesis in the early Galaxy.

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