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Uncertainties in the Th cosmochronometry

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Abstract. Recent observations of r-nuclei, and in particular of Th, in ultra-metal poor stars revived the old idea that the Th cosmochronometry could provide an age estimate of the oldest stars in the Galaxy, and therefore a lower limit to the age of the Galaxy. Unfortunately, some nuclear, astrophysics and observational uncertainties still affect the theoretical r-process models required to predict the original production of Th. The impact of these uncertainties on the prediction of the age of the Galaxy is analyzed and discussed.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: individual: CS 22892-052

1. Introduction

One of the methods called for estimating the age of the Galaxy is based on the analysis of observed abundance of some long-lived radionuclides. The most studied cosmochronometries involve $^{187}\mathrm{Re}$ or the actinides $^{232}\mathrm{Th}$, $^{235}\mathrm{U}$ and $^{238}\mathrm{U}$. Though some promising results have recently been achieved in decreasing the uncertainties affecting the $^{187}\mathrm{Re}$ cosmochronometry, the predictions based on the trans-actinides can still be regarded as relatively poor (Arnould & Takahashi 1999). Nevertheless, the recent observation of r-process elements, including Th, in ultra-metal-poor halo stars, such as CS 22892-052 or HD 115444 (Sneden et al. 1996, 1998) has brought some renewed excitement in the estimate of the age of the Galaxy on grounds of the Th cosmochronometry (Cowan et al. 1997; Pfeiffer et al. 1998). With a metallicity as low as [Fe/H] = –3 and a composition enriched in some pure r-elements, these stars provide strong evidence that the production of heavy elements by the r-process already took place early in the history of the Galaxy. Moreover, the abundance pattern of the 15 r-elements heavier than Ba at the surface of CS 22892-052 (or the 9 elements in HD 115444) shows a striking similarity with the solar system r-abundance distribution, leading to the tempting (though hazardous) conclusion that the r-process mechanism is "unique", i.e any astrophysical event producing r-elements gives rise to a solar-like abundance distribution. This conclusion has been critically analyzed by Goriely & Arnould (1997) who showed that this assumption may be valid indeed, but is by far *not the only possible one*, as the observations in the limited $56 \leq Z \leq 76$ range are equally compatible with an abundance distribution that does not fit the solar one outside the observed domain. This ambiguity is assigned to the fact that the observed CS 22892-052 pattern of abundances reflects primarily nuclear physics properties, and not one or another specificity of a blend of r-process events. This universality assumption is a fundamental prerequisite to build a Th cosmochronometry upon the abundance analysis of metal-poor stars at the present time. In principle, it could be possible to derive the abundance of Th ingested in these metal-poor stars from theoretical extrapolations based on direct fits to the observed abundances. However, in practice, this exercise is affected by uncertainties even greater than when basing the fits on the solar abundances, because of the restricted number of elements observed, the impossibility to distinguish isotopic ratios and the smaller precision in the abundance determination compared with the data available in the solar system. In particular, Goriely & Arnould (1997) showed that the r-elements distribution at the surface of CS 22892-052 could be reproduced satisfactorily by a random superposition of canonical r-process events. In this case, the theoretical extrapolation to the actinide region based on parametric r-process models is simply meaningless. Nevertheless, future accurate observations of r-elements in ultra-metal-poor star could change this situation.

For this reason, we will consider in the present paper the universality assumption to be valid in order to analyze if, despite this difficulty, the recent accurate observation of Th at the surface of ultra-metal-poor stars can indeed provide a reliable estimate of the stellar age by comparing it with the universal r-abundance of Th. Such a procedure requires the estimate of the Th by r-process models, which are known to suffer from very many astrophysics and nuclear physics problems, in spite of much recent theoretical and experimental effort. In this respect, the Th problem is particularly acute, since with U, Th is the only naturally-occuring nuclide beyond $^{209}\mathrm{Bi}$, so that the estimate of Th production relies on extrapolation procedures based on fits to the solar (or stellar) r-abundance distribution. In Sect. 2, a brief description of the adopted r-process models is given in relation to the Th cosmochronometry. In Sect. 3, the various uncertain-

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ties affecting the Th production are studied and their impact on the estimate of the stellar age is analyzed. In Sect. 4, it is shown by comparing the solar fits to the stellar r-element distribution observed that future observations of Pb, Bi or U could put the Th cosmochronometry on safer grounds.

2. Th cosmochronometry and the r-process

Assuming that the whole r-abundance distribution observed in CS 22892-052 and HD115444 is essentially solar, it is straighforward to relate the star age T_* to the Th abundances,

$$\left(\frac{\mathrm{Th}}{\mathrm{Eu}}\right)_{obs} = \left(\frac{\mathrm{Th}}{\mathrm{Eu}}\right)_{r} \exp\left[-T_*/\tau(\mathrm{Th})\right] \quad (1)$$

where $\tau(\mathrm{Th}) = 20.27$ Gyr is the characteristic α-decay timescale of Th and the subscripts obs and r refer to the observed and universal r-process abundance ratios, respectively. As classically done, the Th abundance is here expressed relative to the spectroscopically relevant Eu r-dominant element. The recent accurate observation of Th at the surface of CS 22892-052 amounts to $\log(\mathrm{Th/Eu})_{obs} = -0.70 \pm 0.08$ (Sneden et al. 1996; Cowan et al. 1997). Th has also been observed at the surface of HD 115444, but its precise abundance remains to be determined (Pfeiffer et al. 1998). Assuming that a solar-like mix of the r-elements ingested in these halo stars originates from a small number of nucleosynthetic events that took place just before the formation of the stars, the age of the star can be estimated from Eq. (1) without calling for a complex model of the chemical evolution of the Galaxy. The only difficulty of the methodology is therefore related to the theoretical estimate of the r-production ratio $(\mathrm{Th/Eu})_r$.

Unfortunately, the r-process remains the most complicated nucleosynthetic process to model from the astrophysics as well as nuclear physics point of view (for a review see Arnould & Takahashi 1999). On the nuclear physics side, the nuclear structure properties (such as the nuclear masses, deformation, ...) of thousands of nuclei located between the valley of β-stability and the neutron drip line have to be known, as well as their interaction properties, i.e the (n,γ) and (γ,n) rates, α- and β-decay half-lives and the fission probabilities. Despite much recent experimental effort, those quantities for most of the nuclei involved in the r-process remain unknown, so that they have to be extracted on theoretical grounds and are subject to the associated uncertainties. On top of these nuclear difficulties, the question of the astrophysical conditions under which the r-process can develop is far from being settled. The site(s) of the r-process is (are) not identified yet, all the proposed scenarios facing serious problems. For this reason, only parametric approaches, such as the so-called canonical model (Seeger et al. 1965) can be used to estimate the Th production. We use in the present study the multi-event model[1] (Bouquelle et al. 1996; Goriely & Arnould 1996) in which the best fit to the solar abundances is derived from a superposition of canonical events with the aid of an iterative inversion procedure. Compared with other treatments of the canonical model (e.g Pfeiffer et al. 1998), a major advantage of the multi-event approach is to provide an efficient tool for a systematic study of the various uncertainties affecting the model (Goriely 1999). The iterative inversion method works in such a way that the modification of a given (nuclear or astrophysics) input in the r-process model leads to an automatic renormalization of the thermodynamic conditions necessary to optimize the fit to the solar r-abundance distribution. Therefore, the uncertainties affecting the input data of the parametric model, as well as their impact on the Th production can be studied systematically within the multi-event approach, as shown in the next section.

Our standard calculation is performed under the following thermodynamic conditions: $1.3 \leq T[10^9\mathrm{K}] \leq 1.7$, $10^{22} \leq N_n[\mathrm{cm}^{-3}] \leq 10^{29}$ and $10 \leq n_{cap} \leq 200$ (where T is the temperature, N_n the neutron density and n_{cap} the number of neutrons captured per seed nucleus). Note that the r-process calculations are performed making use of the waiting point approximation, since under the thermodynamic conditions considered here, an almost complete $(n,\gamma)-(\gamma,n)$ equilibrium is established (Goriely & Arnould 1996). When not available experimentally, the nuclear data are taken from the ETFSI nuclear masses of Aboussir et al. (1995) and from the gross theory (GT2) of β^- decay (and β-delayed neutron emission) of Tachibana et al. (1990). In addition, α-decay and fission processes are also considered (before and after the neutron irradiation freeze-out). The fission processes include spontaneous, β-delayed and neutron-induced fission, the probabilities of which are calculated according to the prescriptions of Kodoma & Takahashi (1975) with the ETFSI fission barriers (Mamdouh et al. 1998). The procedure used to fit the solar r-abundance distribution is similar to the one described in Bouquelle et al. (1996) though each isotope is now given a weight inversely proportional to the error affecting its solar r-abundance (Goriely, 1999). Since we are mainly concerned with Th cosmochronometry, no details are given for the representative thermodynamic conditions required to fit the solar system r-abundance distribution (Such details can be found in Goriely & Arnould, 1996).

3. Uncertainties in the predicted Th abundance

The r-process production of Th is obviously model dependent. However, for cosmochronological purposes, it is of fundamental importance to know to what extent the remaining uncertainties in the r-process modelling can affect the Th synthesis. From Eq. (1), it can be seen that the Th abundance has to be determined within less than 16% if we hope to predict the age of star within less than 3 Gyr. A high accuracy has already been achieved observationally with errors reduced to $\log\epsilon = 0.08$ affecting the stellar age by about 3.7 Gyr. Unfortunately, other uncertainties still need to be solved. These mainly concern the r-process modelling, but before focussing on this subject, it is of interest to stress that the normalization to the Eu abundance is

[1] Note that, in the case of r-processes responsible for elements observed in ultra-metal-poor stars, the denomination "multi-event" does not refer to numerous astrophysical events, such as supernova explosions, but rather to numerous components of a given astrophysical event characterized by different thermodynamic conditions, for example in the different layers of a given supernova.

not free from uncertainties. As shown by Goriely (1999), even if the r-process models would be able to reproduce exactly the Eu solar r-abundance, this value is still uncertain by about 20% (the observed abundance in the ultra-metal-poor stars is known within 35%) leading to an error in T_* of about 6.6 Gyr. Note that with respect to normalization procedure, it might be safer to use the Ho abundance, since Ho is made of one stable isotope only and the s-contribution to its solar abundance is even smaller than for Eu, i.e the error bars on its solar abundance (about 13%) are smaller than in the Eu case. The additional uncertainties related to the predicted Eu r-abundance are neglected in the present study by normalizing the calculated Th abundance to the solar r-abundance of Eu. The complete absence of correlation in the production of Th and Eu in the canonical approach of the r-process justifies this choice.

The sensitivity of the calculated r-process abundances, and in particular of the Th abundance, to the different crucial inputs used in the multi-event model is now examined and the impact of such uncertainties on the age of the CS 22892-052 star (T_*^{CS}) is discussed.

3.1. Sensitivity to astrophysics conditions

Among the different thermodynamic parameters entering the canonical model, the most critical one affecting the Th synthesis is obviously the maximum number of neutrons captured by the initial seed nuclei, n_{cap}^{max}, which defines the strong component of the r-process. In analogy with the s-process nucleosynthesis, we can define a main r-process component responsible for the production of all the elements up to the $A = 195$ peak and part of the Pb peak. This main component requires a value of n_{cap} up to about 140. Till now, there is no constraint from realistic models on the largest value that n_{cap} can take, i.e in analogy with the s-process, on a strong r-component responsible for the bulk production of Pb and Bi. Considering canonical events with values of $n_{cap} > 140$ would lead to the production of the Pb-peak elements, as well as Th, without affecting the synthesis of the lower-mass elements. To illustrate such a sensitivity, multi-event calculations are performed considering canonical events with a maximum number of neutrons captured of n_{cap}^{max} =140, 145, 150 and 200 (Fig. 1). An excellent fit is obtained for all isotopes with $A \lesssim 204$ and seen not to be affected at all by the change in the maximum value of n_{cap}^{max} considered. On the contrary, increasing the n_{cap}^{max} above 140 leads to an increase in the production of the Pb-peak, Th and U elements. The large uncertainties in the Pb-peak r-abundances cannot favour one or another fit. The complete absence of a strong r-component, i.e a maximum value of $n_{cap} = 140$, leads to a negative age (when derived from Eq. 1) of the CS 22892-052 star, and can obviously be rejected. Including a strong r-component with $n_{cap} = 145$, 150 and 200 leads to a Th abundance that implies a star age $T_*^{CS} = 12.2$, 22.9 and 28.9 Gyr, respectively. Since the fit is constrained by the upper value of the Pb and Bi abundances, increasing n_{cap}^{max} above 200 does not affect the upper value of the Th abundance. More precisely, no event with a value of $n_{cap} > 170$ contributes to the fit to the solar system abundances with our adopted nuclear inputs. In summary, any age below about 29 Gyr can thus be obtained just by adjusting the strength of such a strong r-process component, unless the s- or r-origin of the Pb and Bi can be determined with a greater accuracy.

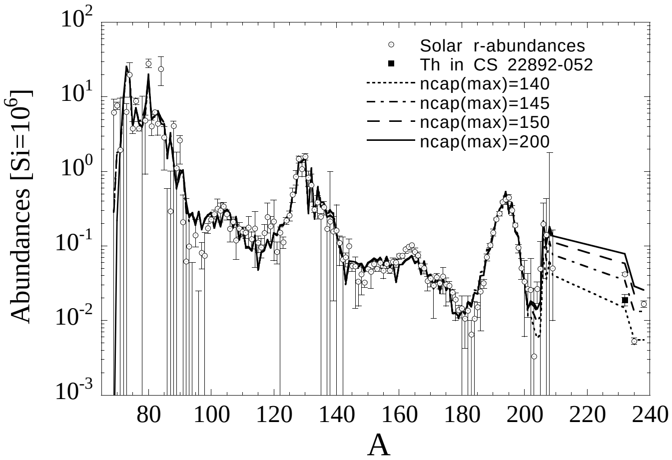

Fig. 1. Comparison between the solar system r-abundances (Goriely 1999) and the distribution predicted by our standard multi-event superposition of events characterized by maximum values of n_{cap}^{max} =140 (dashed), 145 (dot-dash), 150 (dotted) and 200 (full curve). The square corresponds to the Th abundance observed in CS 22892-052 (Sneden et al. 1996). The Bi and Th abundance are connected by a straight line to visualize the extrapolation predicted by the respective models. The vertical lines correspond to error bars in the solar system abundances taken from Goriely (1999).

3.2. Sensitivity to nuclear physics input

The most fundamental nuclear input to r-process models is well known to be the nuclear masses. Various mass models are available, but for practical reasons we only consider here in addition to the ETFSI model, the ETFSI-Q model (Pearson et al. 1996) which takes into account the strong shell-quenching found in some microscopic calculations on highly neutron-rich nuclei, the popular FRDM model of Möller et al. (1995) and the recently-developed model of Duflo & Zuker (1995), hereafter DZ, based on a very different approach than the previously cited models and which has proven its remarkable ability to predict experimentally known masses. Many studies have compared the quality of these models and their differences in the prediction of masses far away from the valley of β-stability. Their impact on the r-process nucleosynthesis has also been analyzed in various papers (e.g Goriely & Arnould 1992), so that we will restrict ourselves to analyze their respective predictions of the Th abundance.

Multi-event calculations are now performed making use of the 4 above-cited mass models. The resulting fits are shown in Fig. 2. The fits to the stable nuclei are of the same quality, and in particular in the Pb region, no major differences in the predicted r-abundances can be observed. In particular, it should be emphasized that no major deficiency in the fit is obtained in the pre-peak regions at $A \simeq 120$ and $A \simeq 180$ whatever mass

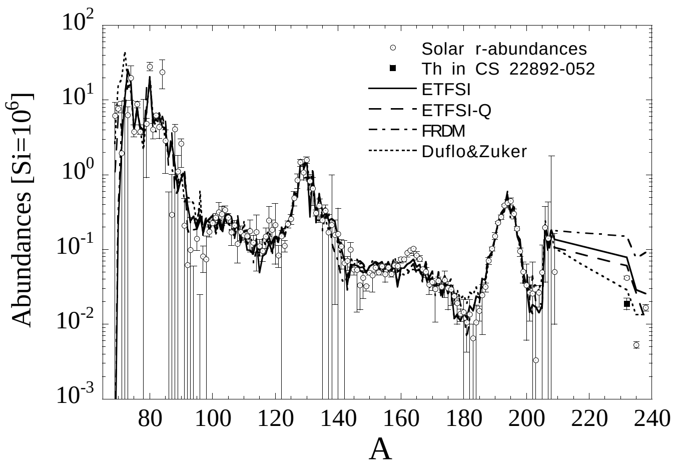

Fig. 2. Same as Fig. 1 where the predictions are obtained with the ETFSI (full), ETFSI-Q (dashed), FRDM (dot-dash) and Duflo & Zuker (dotted) mass models.

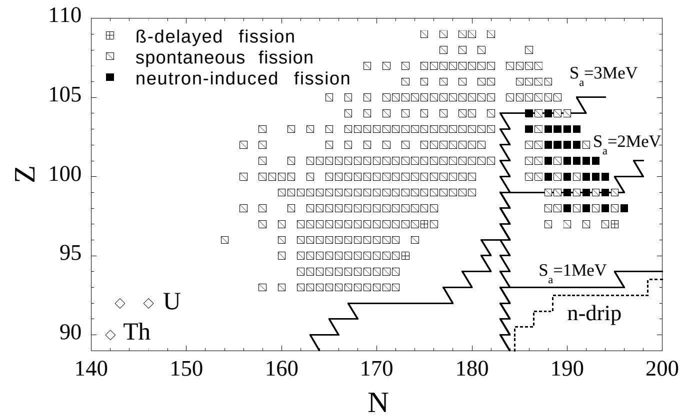

Fig. 3. Representation in the nuclear chart of the dominating fission modes affecting the r-process flow, as given by the legend in the figure. Three r-process paths at $S_a = 1$, 2 and 3 MeV (full line) are drawn for illustrative purposes, as well as the neutron drip line (dashed line).

model is used. Given the absence of realistic r-process models, there is obviously no reason to favour one or another mass formula on grounds of parametric fits to the solar r-abundance distribution, especially when dealing with the Th abundance predictions which exclusively depend on the r-process paths in the $A \geq 232$ region. The extrapolation to the Th abundance appears to be highly affected by the mass model used. The estimate of the star age amounts to $T_*^{CS} = 28.9$, 23.8, 42.2 and 8.7 Gyr for the ETFSI, ETFSI-Q, FRDM and DZ models, respectively. Such differences are not surprising, since it is well known that the r-process paths for these mass models are significantly different, in particular in the $Z > 82$ region where the strength of the shell correction energy around the $N = 184$ shell closure can be very different. This is not the case for the ETFSI and ETFSI-Q models, because the shell quenching introduced in the ETFSI-Q model in the vicinity of the $N = 184$ shell closure is small. Therefore, the abundance predictions in the Pb and actinide regions, and consequently the stellar age predictions, are globally similar when making use of ETFSI or ETFSI-Q. Compared with the other models, the DZ formula is characterized by a steep slope of the mass parabola and a weak shell effect around $N = 184$, so that the progenitors responsible for the final Pb abundance are found in a lower mass region by-passing partially Th and U. The Th abundance obtained with FRDM model is higher than with the ETFSI mass models, because of a more widely spread shell effect in the vicinity of the $N \leq 184$ shell closure affecting the r-process path down to $N = 170$. The abundance peak around $N = 184$ before freeze-out is consequently flattened to lower masses than in the ETFSI case and is less affected by fission processes after freeze-out. A higher Th abundance predicted with the FRDM model leads to a higher age estimate. The high sensitivity of the predicted Th abundance to the mass model will not be resolved before improving our mass predictions in the heavy ($Z > 82$) neutron-rich region.

Another important ingredient in the Th nucleosynthesis concerns the fission processes, i.e the spontaneous, neutron-induced and β-delayed fission. Most of the r-process calculations do not include the fission processes at all or only partially. However, when dealing with Th cosmochronometry, fission processes must be included in the most careful way in order to describe the competing processes responsible for the final Th abundance (namely α-decays, β-decays and fissions) correctly. The recent large scale calculation of ETFSI fission barriers (Mamdouh et al. 1998) up to $A = 295$ is used to test the significance of fission on the Th cosmochronometry. The spontaneous, neutron-induced and β-delayed fission probabilities are determined in the same way as in Kodoma & Takahashi (1975). It should, however, be stressed that when not available experimentally, the spontaneous fission rates are derived from a new regression fit to experimental data based on our fission barrier predictions. Fig. 3 shows the nuclear regions where the different fission modes influence the r-process flows. Because of the strong ETFSI shell effect on the fission barriers around $N = 184$, no fission recycling is found during the neutron irradiation, at least before crossing the $N = 184$ closure. Only r-process paths characterized by an astrophysical parameter $S_a \gtrsim 2$ MeV (for more details about the astrophysical parameter, see Goriely & Arnould 1992) are stopped by neutron-induced fission. Spontaneous fission can also affect such r-process paths before neutron freeze-out. β-delayed fission is found to be of small importance compared with the other decaying modes, even after freeze-out. On the contrary, the spontaneous fission is found to be faster than the β-decay for almost all isobaric chains above $A = 250$ and crucial in estimating the final r-abundances in the Pb and actinide region. In the specific fits studied in the present paper, the fission fragments do not affect the low-mass abundance distribution. Obviously, all the above conclusions should be taken with care, because of the uncertainties remaining in the determination of the fission barriers and fission probabilities, which are to be studied in a forthcoming paper.

In order to quantify the impact of the fission processes on the Th cosmochronometry, a multi-event calculation is reiterated switching off all the fission processes. This numerical test just aims at illustrating the largest error possibly made when

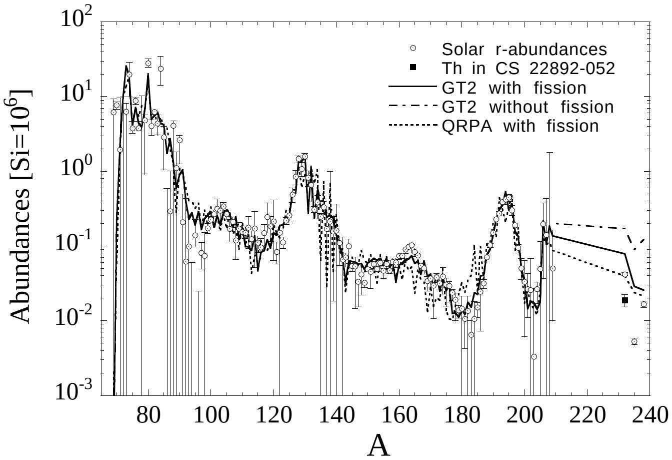

Fig. 4. Same as Fig. 1 where the predictions are obtained using the GT2 β-decay and β-delayed neutron emission rates with (full) or without (dash-dot) fission processes. The dotted curve corresponds to the use of the QRPA β-decay and β-delayed neutron emission rates including fission.

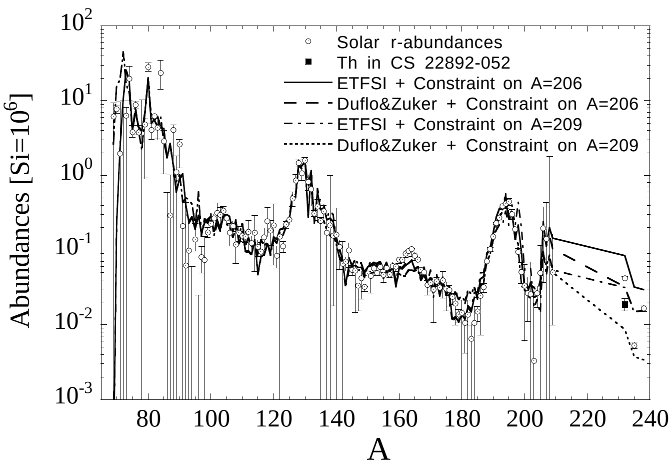

Fig. 5. Same as Fig. 1 when the fit is constrained on $^{204}\mathrm{Hg}$ and $^{206}\mathrm{Pb}$ solar abundances with the ETFSI (full) or DZ (dashed) mass models. The dash-dot and dotted lines correspond to the constrain on $^{204}\mathrm{Hg}$ and $^{209}\mathrm{Bi}$ abundances with ETFSI and DZ mass models, respectively.

neglecting fission, but should not be regarded as a sensible test case for the Th prediction. It is found that the neglect of fission gives rise to an increase of the age of CS 22892-052 by 12.3 Gyr on grounds of the abundance distribution shown in Fig. 4. It can also be seen that when including fission processes, the fission fragments do not modify the global abundance distribution. Obviously, a complete and consistent treatment of the fission processes (especially spontaneous fission) is required to build a reliable cosmochronometry on the actinides.

Fig. 4 also presents uncertainties associated with β-decays and β-delayed neutron emission by comparing the solar fits obtained with the GT2 model and the QRPA model of Möller et al. (1997). Both models have been extensively used in previous works dedicated to the r-process nucleosynthesis, so that it is of interest to study their influence on the Th cosmochronometry. If use is made of the QRPA model instead of the GT2 model, a reduction from 28.9 Gyr down to 15.1 Gyr is obtained for the age of CS 22892-052.Once again, it should be added that although the fit to the solar distribution obtained with the QRPA model is slightly worse than the one obtained with the GT2 approach, it cannot be rejected *a priori*, since other nuclear or astrophysics shortcomings of the model can be responsible for the observed discrepancies (for example in the $A = 180$ region). As stated previously, given our poor understanding of the r-process nucleosynthesis (especially of the astrophysical site) the quality of nuclear models should not be tested on astrophysics arguments like fits to the solar abundance distribution.

3.3. Uncertainties in the solar r-abundance

The uncertainties still affecting the s-process model are responsible for non-negligible imprecisions in the determination of the residual r-abundances of the solar system content (Goriely 1999), in particular for the so-called s-dominant isotopes and Pb-Bi isotopes (see the large error bars in Fig. 1). The principal source of uncertainty in the solar r-abundance of Pb and Bi lies in our ignorance of the relative s- and r-contribution to their production. Both processes can produce Pb-Bi almost entirely, so that the r-contribution cannot be estimated in a reliable way on grounds of s-process calculations. This problematic aspect of the solar abundance splitting in the Pb region can only be resolved through realistic modelling of the s-process (or accurate abundance determination of Pb at the surface of ultra-metal-poor stars provided the assumption of the r-process universality be confirmed). It should be kept in mind that the prediction of the Th and Pb-Bi abundances are strongly correlated, so that any uncertainty in the solar r-abundances of the Pb and Bi elements is translated into the exponentially dependent uncertainty in the star age. Among the $A > 200$ r-isotopes, $^{204}\mathrm{Hg}$, $^{206}\mathrm{Pb}$ and $^{209}\mathrm{Bi}$ play an important role since their r-abundances are better determined than for their neighbours. The solar r-abundance of $^{204}\mathrm{Hg}$ is indeed well determined, so that it seems logical to constrain the fit in such a way as to reproduce the $^{204}\mathrm{Hg}$ solar r-abundance. As regards $^{206}\mathrm{Pb}$ and $^{209}\mathrm{Bi}$, they are characterized by a relatively well-determined abundance to which the Th production is directly correlated. However, reproducing the recommended solar abundance of $^{204}\mathrm{Hg}$, $^{206}\mathrm{Pb}$ and $^{209}\mathrm{Bi}$ simultaneously appears to be impossible without strongly deteriorating the fit to the $A = 195$ peak. For this reason, we reiterate multi-event calculations in which the fitting procedure is constrained (with an extra statistical weight) to the solar abundance of $A = 204$ and 206 in one case and $A = 204$ and 209 in the other case, using two different mass models, namely the ETFSI and DZ models (Fig. 5). Although a negative age is obtained with the DZ masses when constraining the fit to $^{209}\mathrm{Bi}$, the other predicted ages are 30.4 Gyr for the ETFSI calculation constrained to $^{206}\mathrm{Pb}$ and 10.5 Gyr in the two remaining cases. So, in addition to the large sensitivity of the stellar age to the mass models as studied in the previous section, the uncertainties in the solar r-abundances appear to affect the age determination by about 20 Gyr. As long as the s- or r-origin of the Pb and Bi solar abundance is not determined with high accuracy, the Th cosmochronometry will not provide any reliable age estimate.

4. The age of the stars

So far, we have been evaluating the stellar ages on the basis of a fit to the solar r-abundance distribution. Such a procedure is obvioulsy based on our initial fundamental assumption that the r-process site is unique in the Galaxy. This basic assumption is a fundamental prerequisite to build a Th cosmochronometry upon the abundance analysis of metal-poor stars at the present time, since, as explained above, a direct fit to the abundance distribution observed at the surface of metal-poor stars would present even larger uncertainties, because of the restricted number of elements observed, the impossibility to distinguish isotopic ratios and the much smaller accuracy in the abundance data as compared with our solar system. However, in the specific case of Pb, the uncertainties still affecting the solar abundance might be greater than the ones found in the observation at the surface of HD 115444 or HD 126238 (Sneden et al. 1998), so that the Pb abundance in such stars could probably be more constraining on the Th predictions than the solar value. Unfortunately, the Th abundance has not been determined yet in such stars, so that in this case, we limit the discussion on the relative stellar age. Compared with CS 22892-052, only a small number of r-elements are observed in HD 115444, but it is at the moment the only metal-poor star in which Pb and Th lines are detected simultaneously. All the physically sound (i.e leading to a positive age T_*^{CS}) calculations presented in the previous section are compared, in Fig. 6, with the elemental abundance distribution observed in HD 115444 and CS 22892-052. We only retain calculations which provide a good fit to the observed $Z \geq 55$ abundances, and in particular to the Pb abundance in the case of HD 115444. In order to achieve a good fit to all elements observed and to optimize the extrapolation to the Th region, a normalization of the abundance curves is done on the heaviest elements accurately observed, i.e Pt and Os for HD 115444 and CS 22892-052, respectively. In this case, the age of CS 22892-052 is found to lie in the $7 \leq T_*^{CS}[\mathrm{Gyr}] \leq 39$ range, and a similar error range of about 32 Gyr is predicted for the age of HD 115444. The different predictions of the stellar age, as well as the elemental abundances of Eu, Pb, Bi, Th and U are summarized in Table 1. The stellar age can be determined in two different ways. If normalized to the calculated Eu abundance, the age T_*^1 has the advantage of beeing free from uncertainties in the normalization procedures on the observed abundances, but is sensitive to the theoretical uncertainties made in the r-process predictions. In particular, it is well known that the origin of the r-nuclides in the $A \simeq 160$ region is not easily explainable (e.g Meyer & Mullenax 1998). The impact of such errors remains to be estimated. On the contrary, normalizing the calculated Th abundance on the observed Eu avoids theoretical complications inherent in the origin of the $A \simeq 160$ nuclides, but gives rise to additional errors of the order of ± 0.1 dex on the abundances (as seen in Fig. 6), i.e of ± 4.7 Gyr on the age T_*^2.

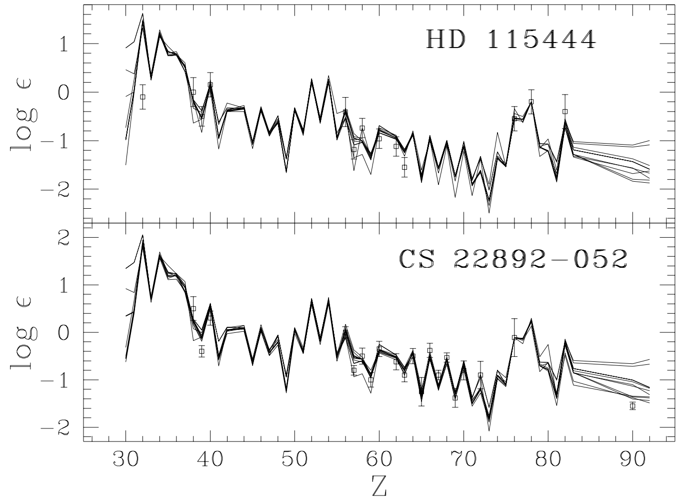

Fig. 6. Elemental abundance distributions observed in HD 115444 and CS 22892-052 (open squares) compared with multi-event r-abundance predictions (see text).

Although the present study suggests that at the moment great care should be taken in estimating the age of the stars on the basis of observed Th abundance, new accurate observations of heavy r-elements could put the Th cosmochronometry on safer grounds, especially if Th and U lines could be observed accurately and simultaneously in metal-poor stars, as already stressed by Arnould & Takahashi (1999). As a matter of fact, if the Th and U lines are available, an age estimate could be derived from the expression

$$\log\left(\frac{\mathrm{Th}}{\mathrm{U}}\right)_{obs} = \log\left(\frac{\mathrm{Th}}{\mathrm{U}}\right)_r + \log\mathrm{e}\left(\frac{1}{\tau(\mathrm{U})} - \frac{1}{\tau(\mathrm{Th})}\right) T_* \quad (2)$$

where $\tau(\mathrm{U}) = 6.41$ Gyr is the characteristic α-decay timescale of U. As seen in Fig. 6 and Table 1, $\log(\mathrm{Th}/\mathrm{U})_r$ is found to lie within an 0.1 range, whatever theoretical inputs are used in the r-process model. Such an accurate estimate is principally bound to the fact that Th and U are neighbour nuclei, and consequently their production ratio is not strongly affected by unreliable extrapolation procedures, but rather by local nuclear uncertainties, such as nuclear masses or fission processes in the actinide region.

From Eq. (2), it is found that a ± 0.1 error on the observed or predicted production ratio of Th/U gives rise to a ± 2.1 Gyr error on T_*. A future simultaneous observation of Th and U lines in ultra-metal-poor stars could therefore open the way to an accurate age determination in contrast to the still complicated Th cosmochronometry based on Th lines only. Eq. (2) is shown in a graphical form in Fig. 7 for 3 possible values of the Th/U production ratio. Note, however, that a deeper analysis of the Th/U production ratio would be required before rushing into an age determination. In particular, uncertainties in the fission processes have not been included in the present study, but could possibly affect the predicted Th/U ratio.

Table 1. Ages T_* (in Gyr) of CS 22892-052, elemental abundances (in logϵ) for Eu, Pb, Bi, Th, U and log(Th/U) predicted by the different theoretical calculations shown in Fig. 6 and analyzed in Sect. 3. T_*^1 (T_*^2) corresponds to the age calculated with a Th abundance normalized to the calculated (observed) Eu abundance.

Comment (see Sect. 3)	Eu	Pb	Bi	Th	U	Th/U	T_*^1	T_*^2
Standard ($n_{cap}^{max} = 200$, ETFSI, GT2)	-0.79	-0.20	-0.76	-1.00	-1.16	0.16	22.9	25.5
$n_{cap}^{max} = 145$	-0.82	-0.43	-1.03	-1.38	-1.49	0.11	6.6	8.2
$n_{cap}^{max} = 150$	-0.80	-0.27	-0.85	-1.13	-1.23	0.10	17.3	19.5
ETFSI-Q masses	-0.79	-0.26	-0.86	-1.10	-1.32	0.22	18.2	21.0
FRDM masses	-0.91	-0.14	-0.64	-0.72	-0.67	-0.05	41.6	38.9
DZ masses	-0.75	-0.19	-0.85	-1.40	-1.44	0.04	2.4	6.9
ETFSI + constraint on $A = 206$	-0.86	-0.22	-0.81	-1.04	-1.18	0.14	24.3	23.8
DZ + constraint on $A = 206$	-0.75	-0.20	-0.85	-1.36	-1.38	0.02	4.3	8.9
ETFSI + constraint on$A = 209$	-0.74	-0.48	-1.11	-1.34	-1.36	0.02	4.7	9.6

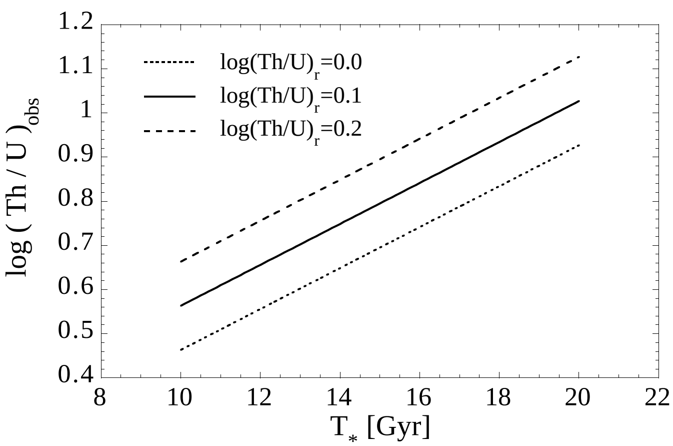

Fig. 7. Relation between the observed Th/U ratio and the age of the star T_* for 3 different estimates of the production ratio.

5. Conclusions

The present paper analyzes critically the impact of the remaining uncertainties in the existing r-process models on the determination of the age of the Galaxy derived on grounds of the Th cosmochrometry. Although the direct and accurate observation of the Th abundance in ultra-metal-poor stars provides a possible method to date the age of the star without calling for complex model of the chemical evolution of the Galaxy, the Th cosmochronometry remains affected by all the difficulties associated with our poor understanding of the r-process nucleosynthesis. Even if we disregard the difficulty associated with the fundamental assumption relative to the unicity of the r-process site in the Galaxy, it is impossible at the present stage reliably to determine the age of a ultra-metal-poor star from parametric models of the r-process. The major difficulties lie in the very s- or r-origin of the Pb and Bi isotopes, in addition to the unavoidable problem related to the prediction of nuclear data (principally masses) and the still unknown thermodynamic conditions in which the r-process takes place (in particular concerning the maximum neutron irradiations that can be reached). New accurate observations including Pb and Th lines in ultra-metal poor stars could shed light on the ability of the r-process to produce the Pb-peak elements, and consequently constrain the Th cosmochronometry. In particular, the Th cosmochronometry could be put on safer grounds, especially if Th and U lines could be observed accurately and simultaneously in ultra-metal-poor stars. As regards nuclear uncertainties, only theoretical as well as experimental effort to come can help us achieve the required accuracy to pretend to derive the age of the Galaxy on the basis of the actinides cosmochronometry.

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