R-process signatures

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Abstract

We compare r-process calculations with recent astronomical observations from the solar system and from ultra-metal-poor, neutron-capture-rich halo stars. These measurements include elemental as well as isotopic r-abundances. We deduce astrophysical conditions under which the observed r-patterns can be obtained, and derive criteria to determine Th/U chronometric ages.

1 Model calculations

The astrophysical r-process is responsible for the synthesis of half the solar system isotopic abundances beyond iron. As the site of the r-process has not been identified with certainty yet, we use the "classical r-process model", a largely model-independent, parametrized approach [1, 2, 3] which has been used extensively before in r-process studies [4, 5, 6, 7]. The calculations are performed within the waiting-point approximation assuming complete $(n,\gamma)\Leftrightarrow(\gamma,n)$ equilibrium as shown e.g. in detail by Freiburghaus et al. [3]. The abundance distribution within an isotopic chain is given by the Saha equation and is entirely determined by the neutron separation energies S_n for a given temperature T_9 and neutron density n_n [1, 2].

The nuclear-physics input needed for the classical r-process model comprises nuclear masses, β-decay rates $T_{1/2}$ and branchings for β-delayed neutron emission P_n. For the vast majority of these data no experimental information is available; hence, one has to rely mainly on theoretical predictions. For recent reviews of experimental information included in our steadily updated nuclear-data basis , see e.g. [6, 7]. The theoretical $T_{1/2}$ and P_n values are based on QRPA calculations of the Gamow-Teller (GT) strength function for allowed transitions [8] and an estimate for the first-forbidden strength from the Gross Theory [9, 10]. Nuclear masses to calculate S_n values have been taken from the ETFSI-Q model [11], which takes into account the possible "quenching" of neutron shell gaps far from stability, initially predicted by Hartree-Fock Bogolyubov (HFB) calculations [12].

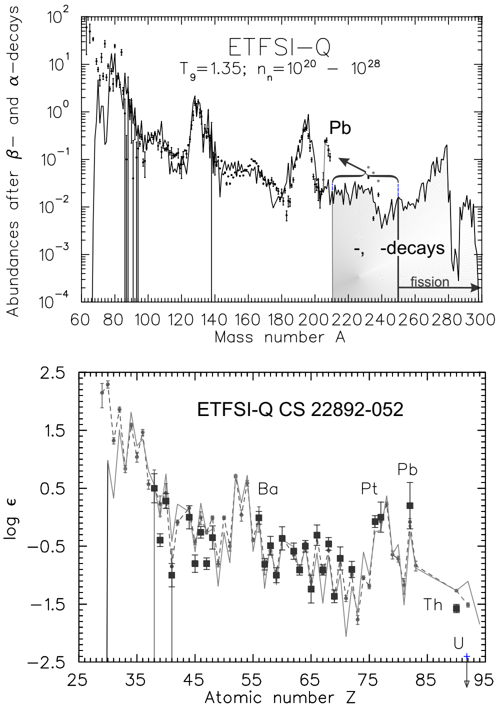

Figure 1: Upper part: Fit to solar r-process *isotopic* abundances ($N_{r,\odot}$) obtained as superposition of 16 equidistant n_n components. This result also shows a good fit to the r-process Pb and Bi contributions after summing up the α-decay chains of heavier nuclei. Lower part: Observed neutron-capture *elemental* abundances in the ultra-metal-poor (UMP) halo-star CS2298-052 (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.

Applying these input data, a single r-process component is calculated assuming irradiation of an Fe seed with constant neutron density and temperature for a time τ. The total r-abundances are then calculated as a superposition of a multitude of components with neutron densities in the range $10^{20} \leq n_n \leq 3\times10^{27}$ cm^{-3}, assuming power law distributions of the component weights $\omega(n_n)$ and irradiation timescales $\tau(n_n)$ and a freeze-out temperature of T_9=1.35 [5]. The *isotopic* abundances (see upper part of Fig. 1) can then be converted to *elemental* ones. After scaling to the lower metallicities of the halo stars, the calculated r-yields are then compared to the observed yields (see lower part of Fig. 1).

2 Comparisons

2.1 Two r-processes?

Recent astrophysical results indicate the existence of (at least) two types of the r-process. Although the evidence is based on a variety of observations in different fields (e.g. extinct radionuclides present in the early solar [13], and isotope abundance anomalies observed in presolar diamonds [14]), the strongest indication for more than one r-process comes from the heavy neutron-capture element abundances in UMP halo stars. The observed yield pattern in these old stars, which are assumed to be produced by only a single or at most a few r-process events, seems to be quite robust. Whereas on the one hand the abundances of elements from $_{56}$Ba onwards are in remarkable agreement with the solar r-process pattern, on the other hand the elements between $_{39}$Y and $_{48}$Cd are lower than solar and exhibit a pronounced odd-even Z staggering (see lower part of Fig. 1 for the star CS22892-052 and Fig. 2 for BD+17°3248). This distribution will be called the *"main"* r-process in the following. The residuals to the solar r-abundances at "low Z" require a second r-process component, in the following called the *"weak"* r-process ($N_{r,weak} \simeq N_{r,\odot}$-$N_{r,main}$; see. e.g. lower part of Fig. 15 in Ref. [7]).

Taking our waiting-point approach, we have investigated under which stellar conditions these two r-processes have to run. The *"main"* component, as observed in the UMP stars, can be well reproduced with neutron-densities of $n_n \geq 10^{22}$ cm^{-3}, even reproducing the odd-even Z pattern of the under-solar "low-Z" elements. Consequently, the residual "weak" r-component is limited to moderate neutron densities. Another outcome of our calculations is that the *"weak"* r-process does not make a significant contribution to the A$\simeq$130 abundance peak, in agreement with recent calculations of Truran and Cowan for an explosive shell-burning scenario [15]. Therefore, our results do not support the suggestions of two supernova r-process sources occuring at different frequencies [16], which should be responsible for the observed abundance level of the extinct radionuclides ^{129}I and ^{182}Hf in the early solar system.

2.2 Nuclear chronometry

Historically, nuclear chronometers have played an important role in the determination of the ages of our solar system and our Milky Way Galaxy, thus providing lower limits on the age of the Universe itself. Particularly useful in this regard are the long-lived actinide radionuclides ^{232}Th and ^{238}U, which are

exclusive products of the r-process. Early attempts of age dating were closely tied to theoretical models of star formation and Galactic chemical evolution. The boundary conditions for these studies were, of course, the primordial abundances of ^{232}Th and ^{238}U in solar-system matter.
Spectroscopic studies of UMP halo stars have, over the past decade, made possible a quite different approach: age determinations for individual field-halo and globular-cluster stars from nuclear chronometers. This has resulted from the increasing availability of abundance data for Th, and more recently also U, in these stars. Since such stars were formed in the very earliest epoch of star formation and nucleosynthesis in our Galaxy, their ages are expected to provide a measure of the age of the Galaxy itself. The approach has been to use the abundance of Th in the star relative to the abundance of the stable r-process (only) element Eu as the appropriate chronometer [17, 4, 5]. Such Th/Eu ages are now available for six field halo stars (as for CS22892-052, Ref. [5]) and two stars in the globular cluster M15.
The observation of U and the determination of its abundance in the UMP star CS31082-001 (Ref. [18]), the tentative detection of U in the halo star BD+17°3248 (Ref. [19], see Fig. 2), and the estimation of U upper limits in a couple other UMP stars now make it possible to use the U/Th pair as a chronometer. Ages of (13.8±4.0) Gyr for BD+17°3248 and (15.5±3.2) Gyr for CS31082-001 (Ref. [20]) are in agreement with the Th/Eu ages as well as with other, independent age determinations for the Universe.

2.3 Isotopic abundances in UMP stars

So far, only *elemental* abundances could be determined in UMP, neutron-capture-rich halo stars and were compared with their values in the solar system. However, very recently Sneden et al. [21] have succeeded to measure the *isotopic* abundances of the rare-earth element (REE) Eu in three of these metal-poor giant stars. Europium consists of only two, nearly "r-only" isotopes, i.e. ^{151}Eu and ^{153}Eu. In all three stars, the authors found a consistent abundance ratio of ^{153}Eu/^{151}Eu$\simeq$1.0, in agreement with the $N_{r,\odot}$ ratio of 1.13. Motivated by the above authors, we have used our r-process model to investigate under which astrophysical conditions (in particular the n_n regimes at freeze-out) **detectable** abundances of ^{151}Eu and ^{153}Eu can be produced. Roughly equal amounts of both isotopes are formed over a wide r-process n_n-range. However, measurable quantities (at the 1% level of the strongest n_n-component) can only be obtained for $n_n \geq 5\times10^{24}$ cm^{-3} (see Ref. [22]). These are typical conditions of the *"main"* r-process, under which the matter flow

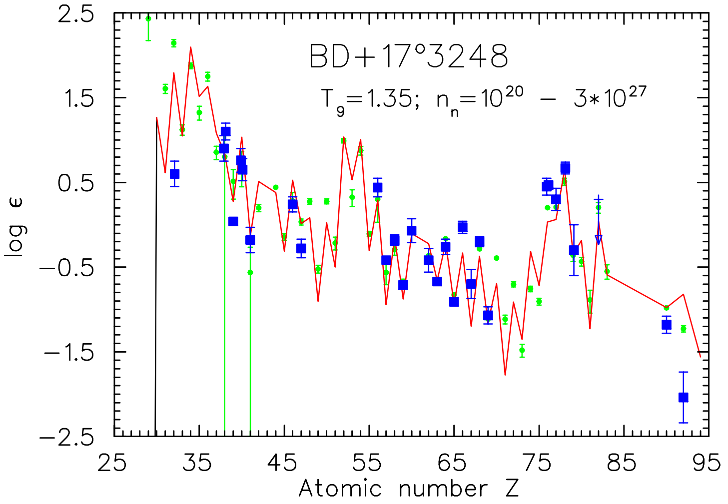

Figure 2: Observed neutron-capture element abundances in BD+17°3248 (squares) compared to scaled $N_{r,\odot}$ values (dots) and our calculated r-abundances (full line). The upper limit on the Pb abundance is denoted by an arrow. Note also the Th and U detections.

has already passed the A≃130 abundance peak and forms the REE region. One problem astronomers want to solve by the study of these stars is the relation between the two distinct neutron-capture nucleosynthesis processes, the s- and r-process, and especially the question at which time in the course of the Galactic chemical evolution these processes begin to contribute to the inventory of the interstellar medium. However, as the Eu isotopes are essentially products of the r-process, their abundance ratio is "insensitive" to this problem. A much better candidate would be the element Ba, as its odd isotopes ^{135,137}Ba are predominantly r-isotopes whereas the s-process mainly contributes to the even isotopes. The absorption lines of the odd isotopes exhibit a pronounced hyperfine splitting, whereas the even ones do not show this effect. Hence, the s/r-isotope mixture is thus reflected by the absorption line widths, and the ratio f_{odd}=(^{135}Ba+^{137}Ba)/(^{135}Ba+^{137}Ba+^{138}Ba) should be much more sensitive to the underlying nucleosynthesis processes than the above Eu isotopic ratio. Applying this method to the metal-poor subgiant HD140283 (see Ref. [23] and Refs. therein), have led, however, to contradictory results in the past. Actually, new measurements of the isotopic abundance fractions of Ba in metal-poor halo stars have been performed [24]. From high-resolution, high signal-to-noise spectra of HD140283, Lambert et al. [25] claim that a solar-like r-process mixture provides a fair fit to the observed line profile, although the

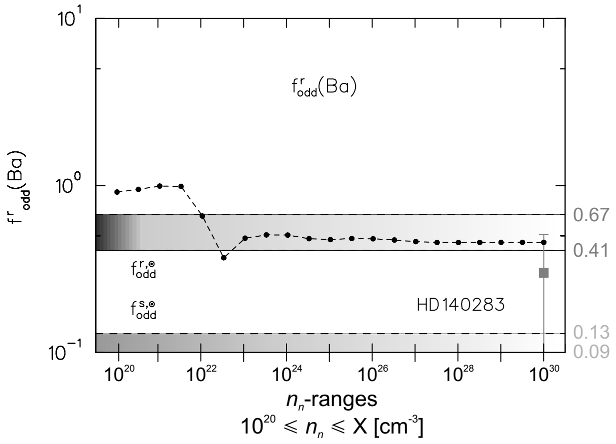

Figure 3: Calculated r-process abundance ratio f_{odd} as compared to solar s- and r-values and the observation in HD140283 (Ref. [25]).

given uncertainty is quite large.

In order to check the above statement about the s/r-mixture in HD140283, we have calculated the r-process yields of ^{135}Ba, ^{137}Ba and ^{138}Ba, which lie just beyond the 2^{nd} r-abundance peak. Fig. 3 shows our model predictions of f^r_{odd} as a function of partial sums of the 16 n_n-components. Similar to the case of Eu, the solar-system r-process ratio $f^{r,\odot}_{odd}$ for Ba can only be reproduced for $n_n \geq 10^{22}$ cm^{-3}. However, given the large uncertainty of the observation (f_{odd}=(0.30±0.21) which overlaps with both $f^{r,\odot}_{odd}$=(0.54±0.13) and $f^{s,\odot}_{odd}$=(0.11±0.02), we conclude that the abundance ratio f_{odd} alone cannot give an unambiguous answer about the s/r-mixture in HD140283.

Therefore, a second observational quantity, in this case the elemental abundance ratio of Ba to Eu normalized to the respective solar values, i.e. [Ba/Eu] = (Ba$_{obs}$/Ba$_{\odot}$)/Eu$_{obs}$/Eu$_{\odot}$), has to be considered. And indeed, the value observed in HD140283 (Ref. [25]) clearly excludes the $s,\odot$-ratio and indicates that the r-process has been the main contributor in this star. This is shown in Fig. 4, where the observed [Ba/Eu] value is compared to the solar-system ratios for pure s-process ($s,\odot$) and pure r-process ($r,\odot$) and to our r-process calculations [Ba/Eu]$_{r,calc}$ as a function of n_n-ranges. In these calculations, the solar r-process value ($r,\odot \simeq 1.0$) can only be obtained for $n_n \geq 10^{24}$ cm^{-3}. These are the conditions under which the *"main"* r-process is just forming the full A≃130 peak and the matter flow starts to overcome this bottle-neck. On the other hand, Fig. 4 shows that for low n_n-ranges ($n_n < 10^{24}$ [cm^{-3}]) the predicted r-process [Ba/Eu] ratio may "mimic" different s/r-mixtures, even up to

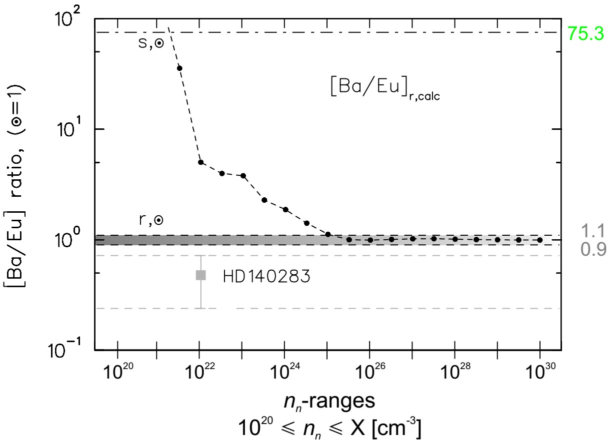

Figure 4: Calculated r-process abundance ratios [Ba/Eu] compared to the solar s- and r-values, as well as to the observed ratio in HD140283 (Ref. [25]).

the pure solar-system s-process value ($s, \odot \simeq 75$).

3 Conclusions

With our "classical r-process model" we can reproduce isotopic and elemental $N_{r,\odot}$ abundances quite well. This allows us to derive stringent constraints on n_n-conditions which reproduce the above "observables", i.e. elemental abundances including r-chronometers as well as recent isotopic abundance ratios. However, astronomers ought to be careful with straightforward "interpretations". Sometimes, there is no unambiguous distinction between solar s- and r-process abundances, as in limited n_n-ranges specific r-components may show an s-like pattern. Therefore, it is extremely important to perform more high-resolution optical spectroscopy of various elements in UMP halo stars. Furthermore, a systematic study of the metallicity dependence of element or isotope abundance ratios, as shown above, may determine the onset of s-process nucleosynthesis in medium-mass AGB stars which evolve slower than the first-generation, high-mass progenitors of supernovae, the most probable sites of the r-process in the early Galaxy. And, last but not least, improved r-abundance calculations within realistic astrophysical scenarios are required to replace the present parametrized models.

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