Stellar and nuclear-physics constraints on two r-process components in the early Galaxy

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Recent astrophysical results indicate the existence of (at least) two types of the rapid neutron-capture nucleosynthesis (r-process). The evidence is based on a variety of observations in different fields:

(a) The study of extinct radionuclides present in the early Solar System [1,2].
(b) Isotope abundance anomalies observed in presolar diamonds [3,4].
(c) The strongest – because less model-dependent – indication for more than one type of r-process, however, may come from the observation of heavy neutron-capture element abundances in very metal-poor halo stars [5–8] as well as in the globular cluster M15 [9].

On the one hand, metallicity-scaled abundances of elements in the Pt peak and down to Ba (Z=56) in all halo stars so far investigated are in remarkable agreement with the solar r-process pattern \(N_{r,\odot}\), while on the other hand the abundances of “low-Z” neutron-capture elements (\(^{39}\text{Y}\) to \(^{48}\text{Cd}\)) in CS 22892-052 are lower than solar [8]. An interesting feature of the abundances of these elements is their pronounced odd-even-Z staggering, which reflects nuclear-structure properties of the progenitor isotopes involved. All odd-Z elements from \(^{39}\text{Y}\) to \(^{47}\text{Ag}\) are clearly under-abundant compared to the solar pattern, whereas the even-Z elements (\(^{40}\text{Zr} - ^{48}\text{Cd}\)) are closer to solar (see Fig. 1).

Taking advantage of our site-independent waiting-point approach to fit the \(N_{r,\odot}\) pattern, we now can test under which stellar conditions the possible two r-processes, presumably separated by the A\(\approx\)130 \(N_{r,\odot}\) peak, have to run. When assuming that the abundances are a living record of the first (few) generation(s) of Galactic nucleosynthesis [10], the observed pattern beyond Z\(\approx\)40 up to \(^{90}\text{Th}\) should most likely be produced by only one (or a few) r-process event(s) in a unique stellar site, e.g. supernovae of type II (SNII). This scenario (the “main” r-process) then produces the “low-Z” elements under-abundant compared to solar, and reaches the full solar values presumably around \(^{52}\text{Te}\). For CS22892-052 both, the general trend as well as the detailed structure of the “low-Z” abundances (\(40\leq Z\leq 48\)) are nicely reproduced in our fit with the ETFSI-Q atomic masses (see Fig. 1). At the same time, the good overall reproduction of the “high-Z” elements (beyond \(^{56}\text{Ba}\)) is maintained [11]. Starting our calculations from an Fe-group seed would require neutron densities of \(n_n\geq10^{23} \text{ cm}^{-3}\) at freeze-out (\(T_9=1.35\)). It should be mentioned in this context, that our approach would imply a roughly constant abundance ratio between the “low-Z” and “high-Z” elements. This has recently been confirmed in the case of HD115444, where our
Figure 1. Comparison between observed (filled squares) and calculated (solid line) elemental r-abundances from the ultra-metal-poor halo star CS 22892-052. The abundance distribution from $Z \approx 40$ to $^{90}\text{Th}$ is denoted as the “main” r-process in the text. The scaled solar-system distribution is shown as dashed curve with filled circles. The $N_{r,\odot} - N_{r,\text{main}}$ “residuals” at “low-Z” require contributions from a second (“weak”) r-process; see Fig. 2.

The “weak” component as identified here must be of secondary origin, as is clearly shown by its absence in the old metal-poor halo stars [8]. In contrast, the presence there of the main component with a pattern virtually identical to that of the solar system r-process in the mass range above $A \approx 130-140$ attests to its primary and robust nature. Another outcome of our calculations is that the “weak” component as devised to produce the low-mass r-process nuclides in solar-system proportions that are “missing” from the “main” component does not make a significant contribution to the $A \approx 130$ abundance peak, in agreement with calculations from Truran and Cowan [13]. Our result thus does not support the conclusion of Qian et al. [2] of separate r-process sources being responsible for the observed abundance level in the early solar system of extinct radionuclides $^{129}\text{I}$ and $^{182}\text{Hf}$. In this context, we note that in all models [2,10,11] the actinides are coproduced with the nuclides in the Hf range, but that the observed limit on the abundance in the early solar system of $^{247}\text{Cm}$ ($^{247}\text{Cm}/^{235}\text{U}<4 \times 10^{-3}$; [14]) is barely compatible with expectations based on the same approach as used for $^{182}\text{Hf}$. An improved measurement
Figure 2. Comparison between abundance “residuals” \((N_{r,\odot} - N_{\text{halo}} = N_{r,\text{resid}})\); filled diamonds) and calculated (full curve) elemental r-abundances from the ultra-metal-poor halo star CS 22892-052. This abundance distribution for “low-Z” elements is denoted as the “weak” r-process in the text. The scaled solar-system distribution is shown as dashed curve with filled circles, the observed halo-values are displayed as filled squares.

of this abundance ratio may be an important step to address the question whether or not for \(^{182}\text{Hf}\) a special process [15] is required.

REFERENCES

7. J.A. Johnson et al., contribution to this conference.