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 \cite{1,2}.
(b) Isotope abundance anomalies observed in presolar diamonds \cite{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 \cite{5–8} as well as in the globular cluster M15 \cite{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 ($^{39}$Y to $^{48}$Cd) in CS 22892-052 are lower than solar \cite{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 $^{39}$Y to $^{47}$Ag are clearly under-abundant compared to solar, whereas the even-Z elements ($^{40}$Zr - $^{48}$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 \cite{10}, the observed pattern beyond Z$\approx$40 up to 90 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 $^{52}$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 $^{56}$Ba) is maintained \cite{11}. Starting our calculations from an Fe-group seed would require neutron densities of $n_n\geq10^{23}$ 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 $Z \simeq 40$ to $90$ 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. 

Consequently, the abundance "residuals" ($N_{r,\odot} - N_{r,\text{main}} = N_{r,\text{resid}}$) at low $Z$ will require a separate "weak" r-process component of yet unknown stellar site. When assuming seed compositions from $^{14}$Si to $^{24}$Cr or $^{28}$Ni in solar-system fractions, our calculations can reproduce the $N_{r,\text{weak}}$ pattern in CS22892-052 with neutron densities of $n_n \leq 10^{20}$ cm$^{-3}$ and process durations $\tau \simeq 500$–1000 ms (see Fig. 2). These stellar conditions might be provided in explosive shell-burning scenarios (see, e.g. \cite{12,13}).

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 \cite{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 $A \simeq 130$–140 attests to its primary and robust nature. Another outcome of our calculations is that the "weak" component does not make a significant contribution to the $A \simeq 130$ abundance peak, in agreement with calculations from Truran and Cowan \cite{13}. Our result thus does not support the conclusion of Qian et al. \cite{2} of separate r-process sources being responsible for the observed abundance level in the early solar system of extinct radionuclides $^{129}$I and $^{182}$Hf. In this context, we note that in all models \cite{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 $^{247}$Cm ($^{247}$Cm/$^{235}$U$<4 \times 10^{-3}$; \cite{14}) is barely compatible with expectations based on the same approach as used for $^{182}$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 \cite{15} is required.

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