NEUTRON-CAPTURE ELEMENT TRENDS IN THE HALO

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In a brief review of abundances neutron-capture elements (Z > 30) in metal-poor halo stars, attention is called to their star-to-star scatter, the dominance of *r*-process synthesis at lowest metallicities, the puzzle of the lighter members of this element group, and the possibility of a better *s*-/*s*-process discriminant.

1 Introduction

Most isotopes of elements with atomic numbers Z > 30 are synthesized via neutron capture reactions. These "n-capture" elements are the majority of the periodic table. In the so-called *s*-process, neutron fluxes are small enough to allow β-decays to occur between successive neutron captures, and element buildup proceeds along the valley of β-stability. In the *r*-process, huge but short-lived neutron fluxes overwhelm β-decays, creating very neutron-rich isotopes out to the neutron drip line. Then multiple β-decays drive the nuclei back to the valley of β-stability. The final isotopic mixes will be very different in *r*- and *s*-process synthesis episodes, as will the elemental abundances summed over the isotopes. The *s*-process mainly occurs in the helium shell burning phases of low-intermediate mass AGB stars, while the *r*-process is probably associated with the explosive deaths of high mass stars. Thus, *r*- and *s*-process elemental abundance variations with metallicity should trace the contributions of different mass ranges of stars over the Galaxy's history.

Detailed comparisons of solar system meteoritic abundances of n-capture isotopes (Cameron[1], Käppeler *et al.*[2]) have yielded accurate breakdowns into *r*- and *s*-process parts of each isotope. But stellar spectroscopy generally cannot resolve the finely split isotopic absorption components of atomic transitions, so elemental r- and s-process abundances summed over the isotopes have been computed for solar system material by Burris *et al.*[6], and references therein. No n-capture element with $Z \leq 83$ can be identified solely with the r- or s-process but some have been clearly dominated by a single synthesis mode. For example, Ba and Ce have s-process fractions, and Eu, Gd, and Dy have r-process fractions greater than 80% in solar system material. Such elements are usually labeled as r-process or s-process, regardless of their synthesis history in non-solar Galactic material.

Here we will comment on several aspects of observed n-capture abundance distributions of metal-poor stars: (a) the bulk n-capture abundance levels; (b) the relative s-/r-process dominance among heavier n-capture elements in the lowest metallicity stars, (c) the best spectroscopic indicator of those ratios, and (d) the difficulty in ascribing a nucleosynthetic origin for the lighter n-capture elements. Theoretical interpretation of these observational results will be considered in a companion paper by Cowan *et al.* in this volume.

2 Variations in Bulk n-Capture Abundance Levels

Early large-sample surveys of n-capture elements in metal-poor stars (*e.g.* Luck and Bond[3], Gilroy *et al.*[4]) discovered apparently significant star-to-star scatter in the ratios [n-capture/Fe], where the n-capture elements usually considered were Sr, Y, Zr, Ba, La, Nd, and Eu. But the observational data were usually of modest resolution (R < 30,000) and sometimes low S/N, raising questions about the reality of the n-capture scatter. Recent analyses of much better spectroscopic data have decided the issue unambiguously in favor of σ[n-capture/Fe] > 1 at metallicities [Fe/H] < –2. The reality of these large star-to-star variations can be demonstrated through inspection of spectra of stars with similar atmospheric parameters ($T_{\rm eff}$/log g/[Fe/H]/v_t) but enormous line strength differences of some n-capture elements. For example, compare the spectra of HD 115444 and HD 122563 (Figure 1 of Westin *et al.*[5]; Δ[Fe/H] $\simeq$ –0.2, Δ[Eu/H] $\simeq$ +1.0) and those of HD 6268 and BD +9 2870 (Figure 3 of Burris *et al.*[6]; Δ[Fe/A] $\simeq$ 0.0, Δ[Eu/H] $\simeq$ 0.9). The analyses of these stars and others (*e.g.* McWilliam *et al.*[7]; Ryan *et al.*[8]) quantify these impressions; clearly σ[n-capture/Fe] grows with decreasing [Fe/H]. To date there have been few stars with [Fe/H] $\sim$ –3 (in which n-capture lines are weak) fully analyzed with the highest quality spectra, and in stars with [Fe/H]>-2 many n-capture lines are saturated, so abundances derived from them are less reliable. New VLT data should help at the low metallicity end of the scale; future n-capture surveys at intermediate metallicities would also help.

3 Dominance of the r-Process at Lowest Metallicities

Perhaps the first indication of non-solar abundance ratios of n-capture elements in halo stars was the Wallerstein *et al.*[9] assertion that the bright very metal poor ([Fe/H] $\simeq$ –2.7) giant HD 122563 has very small amounts of these elements compared to Fe. Re-analysis of their data by Pagel[10], and further studies of in succeeding decades have shown that Ba is much more deficient than Eu in HD 122563: [Ba/Eu] $\simeq$ –0.7. But attention to s-/r-process abundance mixes was really first brought by Spite and Spite[11], who found persistent deficiencies of Ba with respect to Eu in their sample of 11 halo stars. These abundances (as well as those of Y) suggested to Truran[12] that "...the observed trends follow in a natural and straightforward manner from the assumption that the Y and Ba in the most extreme metal-poor stars represent products of r-process nucleosynthesis." Since then the supporting data have improved but the basic conclusion has not. The observational attack has been on two fronts: (a) determination a few key abundance ratios in many stars, and (b) mapping the detailed abundance pattern in a few n-capture-rich stars.

Metal-poor stars with [n-capture/Fe] $\gg$ 0 have ideal spectra for studying the entire range of n-capture elements, because the ubiquitous Fe-peak element transitions weaken substantially relative to those of n-capture elements, allowing rarely-detected elements (*e.g.* Tb, Ho, Hf) to be detected. Two prominent examples are CS 22892-052 (Sneden *et al.*[13]) and HD 115444 (Westin *et al.*[5]). These stars have n-capture abundance patterns for elements with Z $\geq$ 56 that are near-perfect matches to a scaled solar r-process abundance distribution. The presence of s-process synthesis cannot be detected. These stars' abundances suggest that regardless of the site(s) that are responsible for the r-process nuclei, they release their products into the ISM in a remarkably uniform pattern.[a]

Most observers simply estimate s-/r-process influence from a few abundance ratios of elements whose syntheses are dominated by one or the other mechanism in the solar system. In Figure 1 we show likely candidate elements, through comparison of their solar number densities $\log_{10}\epsilon$. Clearly there should be a major abundance shift between elements Ba$\leftrightarrow$Ce with respect to Eu$\leftrightarrow$Tm if the synthesis shifts from the solar (combined s- and r-) mix to a pure r-process. In practice, this has come down to derivations of [Ba/Eu] ratios, since these two elements have the strongest transitions in most routinely accessible spectral regions. Nearly all large-sample n-capture abundance studies of low metallicity stars have correlated [Ba/Eu] with [Fe/H],

[a] S-process-rich stars do exist at very low metallicities, such as the "CH stars" discussed by Norris *et al.*[14] and McWilliam *et al.*[7], but these appear to be in the minority.

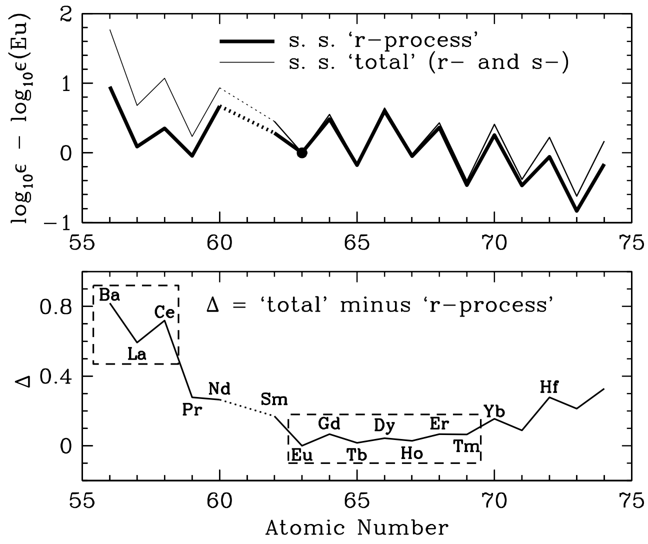

Figure 1. Top panel: total solar-system abundances and r-process parts only of n-capture elements in the range $56 \leq$ Z ≤ 74, normalized to the Eu abundance. Bottom panel: the subtraction of the two curves from the top panel. Ratios of any element within the upper left dashed box to any element within the lower middle dashed box should in principle be useful indicators of the s-/r-process ratios in n-capture material.

and a consensus has arisen that <[Ba/Eu]> ~ 0 for $-2 \leq$ [Fe/H] ≤ 0, and then the mean ratio declines to ~ -0.9 as [Fe/H] ~ -3. Little is known about <[Ba/Eu]> at even lower metallicities because the Eu transitions usually become extremely weak; it would be useful to detect this element even in a few stars with [Fe/H] < -3.

Burris *et al.*[6] have estimated the s-process component of Ba in their sample of halo stars by first assuming that Eu is a 100% r-process product and that the r-process part of Ba is fixed by the solar system r-process Ba/Eu ratio. They then subtract the inferred $\mathrm{Ba_{r-process}}$ from $\mathrm{Ba_{total}}$. The result (see their Figure 7) suggests a complete absence of the s-process for [Fe/H] ≤ -2.8, and a stochastic rise to a full (solar-system) s-/r-process ratio by [Fe/H] ~ -2.

Ratios of [Ba/Eu] are subject to large uncertainties, because the four commonly employed Ba II lines are often very strong even in metal-poor stars, and because these lines suffer isotopic and hyperfine structure (hfs) splitting, so Ba abundances are very dependent on assumed microturbulent velocity and isotopic abundance fractions. Of the alternate s-process abundance indicators,

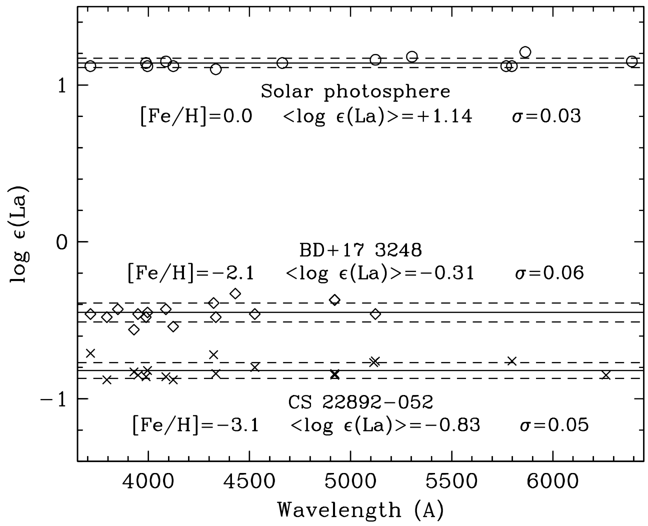

Figure 2. La abundances in the Sun and two metal-poor giants as functions of wavelength. The solid and dashed lines are drawn at the mean and mean$\pm\sigma$ abundances for each star.

Ce has only weak lines, rendering it almost useless unless [n-capture/Fe] $\gg 0$. But La has many weak and strong lines, and has only one stable isotope, ^{139}La. The atomic data for La has been not the best, but Lawler *et al.*[15]have determined new accurate gf's and hfs components for La II. In Figure 2 we show results of the application of these lab data to the spectra of the Sun and two metal-poor but n-capture-rich stars. The line-to-line scatter is satisfactorily low and a reasonable mean abundance for all these stars is obtained. In preliminary tests we have derived La/Eu abundance ratios for these and a few other stars, finding excellent accord with the predicted pure r-process ratio at the lowest [Fe/H] values, and gradual rise to solar system values at higher metallicities. We believe that La/Eu ratios can be more accurately determined than Ba/Eu ratios, and it is possible that La/Eu may become the standard s-/r-process indicator in future spectroscopic investigations of metal-poor stars.

4 The Lighter n-Capture Elements

Brief notice must be given of n-capture elements in the range $31 \leq \mathrm{Z} \leq 55$. Until recently, the elements Rb, Sr, Y, and Zr represented the observational situation of the entire group. These elements are known to present a puzzle. Their overall abundance levels correlate poorly with heavier (Z $\geq$ 56) n-capture elements (see references cited previously). Neither a pure solar system r-process, or pure s-process (or indeed any linear combination) provides a satisfactory match to their observed abundances (Cowan *et al.*[16]). New near-UV spectra for some metal-poor stars are rapidly providing abundance data for other elements in this atomic number range such as Ag (Crawford *et al.*[17]), and Sneden *et al.*[13] report first detections of five new light n-capture elements in CS 22892-052. But their derived abundances do not shed further insight on the matter, and still there is no reasonable fit to scaled solar-system abundance patterns. The study of these elements should be actively pursued in the future.

Acknowledgments

We thank all of the colleagues who have collaborated with us on various studies of n-capture elements in halo stars. This research has received support from NSF grants AST-9987162 to C.S. and AST-9986974 to J.J.C., from DOE contract B341495 to J.W.T., and from the Space Telescope Science Institute grant GO-8342.

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