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Taking Another Look: Light n-Capture Element Abundances in Metal-Poor Halo Stars

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Abstract

Elements are produced in stars through a variety of processes; some are well known, others are still the object of active research. The elements Zirconium (Zr) and Yttrium (Y) are produced via neutron capture (n-capture). These elements reside in the mass range where there is uncertainty about the production mechanism at early time. The rapid n-capture process (r-process) was believed to be responsible for the production, but no study (Burris et al 2000, Gilroy et al 1988 and others) has been able to successfully use the r-process to reproduce the abundance signature for elements in this mass range for metal-poor halo stars. It has been suggested (Snedden and Cowan 2003) that there may be an undiscovered component to the r-process. New abundance calculations for these elements have been conducted for a sample of metal-poor halo stars. Transition probabilities for Zr II from (Malcheva *et al.* 2006) and for YII from (Hannaford *et al.* 1982) were utilized in these calculations as well as new high quality observational data from the Keck telescope. The new laboratory and observational data resulted in improvement in the abundance determinations and uncertainty of the abundances.

Introduction

All naturally occurring elements have astrophysical origins. The lightest of these, Hydrogen, Helium and a fraction of the Universe's Lithium were made within a few minutes after the Big Bang. Beryllium and Boron are created in the interstellar clouds of gas and dust during collisions between cosmic rays and gas nuclei. The other elements were created via various nuclear reactions in stellar interiors. Fusion reactions in stellar core produce elements up to Iron (A=56). However, fusion reactions beyond this point are endothermic; therefore stars cannot continue building heavier elements through fusion processes as there is no external source of additional energy. The process responsible for the creation of most isotopes beyond this Iron peak (Fe-peak) is the neutron-capture (n-capture) process.

There are two "main" processes that involved the capture of neutrons onto Fe-peak seed nuclei: the slow

(s) and the rapid (r) n-capture processes originally identified in 1957 (Burbidge *et al.* 1957, Cameron 1957). The ultimate result of both type of processes is the same, a nucleus captures a neutron and increases its atomic mass. The difference between the two processes is the time scale over which they occur. In the s-process, the time between captures is on the order of thousands of years; while, in contrast, in the r-process many captures will occur in less than a second. The determining factors for process type are temperature and neutron density. All isotopes beyond the Fe-peak, regardless of origin, are much rarer than isotopes below the iron peak. This rarity in some cases carries over to their perceived value on Earth. Gold, Uranium and Platinum are all exclusively produced in the r-process.

The types of isotopes created in each process differ. In the s-process, nuclei never capture enough neutrons to move far from the valley of beta-stability, the region of atomic mass where isotopes of an element are stable to beta decay. When neutron capture yields an unstable nucleus, there is sufficient time for beta decay to occur, leading to a stable nucleus of atomic number one higher than the parent nucleus. This is not so in the case of the r-process, where captures occur in rapid succession, leading to isotopes of large atomic mass that are far from the region of beta-stability. However, as the available neutron flux density decreases, the r-process shuts down, allowing the beta decays to occur unimpeded. These nuclei arrive at the valley of beta-stability with atomic numbers much larger than the original nucleus. If the isotopic breakdown of elements above the iron peak is examined, it can be seen that each process contributes approximately equally to the observed elemental abundances. The conditions required to manufacture s-process isotopes can be reproduced in the laboratory and these have been well studied. However, those necessary for the r-process conditions are too extreme to allow them to be reproduced in the laboratory.

The environment required to produce each of these processes has long been of interest to astrophysicists. Because the s-process can be created in the laboratory, the conditions for it to operate can be unambiguously identified and located in nature (Snedden and Cowan 2003, Cowan and Thielemann 2004, Kappeler *et al.*

1989). The conditions needed are also generated in the shell-burning phase of Asymptotic Giant Branch (AGB) low to intermediate mass stars (Busso et al. 1999). These stars have lifetimes measured in billions of years. This is significant because n-capture elements created by stars via either process cannot be observed directly. To determine the abundances of elements produced within a star's interior it must evolve, die, and expel the material back into the interstellar medium (ISM). Then this material must be swept up during the formation of the next generation of stars where the elements can be detected as a part of the new star's atmosphere. Thus any s-process elements that are observed must have come from stars that lived on the order of billions of years prior to the formation of the star under observation. The s-process contribution to the abundances has been determined to have two components: main and weak. Each is responsible for the production of different mass ranges of isotopes and requires slightly different mechanisms within the AGB star. These phenomena have been studied and discussed by many authors (Kappeler et al. 1989, Gallino et al. 1998, Raiteri et al. 1993 and others).

Unfortunately, the situation is not so clear for the r-process. Several possible systems that could create the required conditions have been proposed (Burris et al. 2000, Sneden and Cowan 2003, Freiburghaus et al. 1999, Woosley et al. 1994). The most popular among these is the core collapse supernova (type II) originating from the death of stars that exceed 8 solar masses. These stars would live and die on timescales on the order of millions of years, matching the time scales required for r-process contributions (Woosley et al. 1994, Thompson 2003). Another proposed source is merging binary neutron stars, however, the frequency of such events is not believed to be high enough to account for the observed elemental abundances (Freiburghaus et al. 1999, Freiburghaus, et al. 1999, Meyer 1989). Of additional concern, none of the computer simulations of such mechanisms have been successful in reproducing the abundance signature observed in Solar System meteorites or in stellar spectra.

The complexities of the r-process are just beginning to be understood. The abundances of n-capture elements with $Z \geq 56$ agree well with r-process distribution obtained from the solar system material. Many examples support this result, including the results from some 50 metal-poor halo field giants (Burris et al 2000, Gilroy et al 1988, McWilliam et al 1995, Sneden et al 1996). As older halo objects, these stars formed prior to heavy enrichment from s-process sources. The r-process signature should dominate and

good agreement is found for elements from Barium upward. However, a problem arises when the Solar System distribution is applied to the lighter n-capture elements as indicated in Burris et al. 2000. Strontium, Yttrium and Zirconium are the elements from this range for which observational data is available. No subsequent studies (Burris et al 2000, Travaglio et al, 2004, Cowan et al 2005) have been able to achieve reasonable agreement between the observed abundances of these elements and any combination of known s- and r-process components. It has recently been suggested by other authors that r-process is not a single component process as has been believed (Travaglio et al. 2004, Cowan et al. 2005, Sneden and Cowan 2003, Cowan and Thielemann 2004). These authors agree that the key to unlocking the mystery of this second r-process or light element process lies with further study of these lighter mass elements.

Methods

Our objective was to make new calculations for light n-capture elemental abundances in a group of metal-poor, and thus presumably old, Galactic halo stars. The trends in abundances of these elements over time have important implications for the understanding of the final stages of stellar evolution and of the chemical evolution history of the Milky Way Galaxy. A limited number of objects have lifetimes compatible with the time frame for the earliest contribution to the r-process elements. However failure of existing models to reproduce the element abundance signature over the entire range of atomic mass indicates that the site of the r-process is not known, and there may be two components to the r-process. These two processes operate in different environments and over different time scales. By choosing to examine specific elements, we were able to study the constraints on the type of objects and the parameters required for this potential second component.

The spectra utilized in this study are the same ones used by (Cowan et al. 2005). It is visible-region high-resolution spectra obtained from the Keck I HIRES instrument.

The spectra are taken over a wavelength range of 3150Å to 4600Å with a resolving power of $R \approx 45,000$. The signal to noise ratio of the spectra increased with wavelength for these cool halo stars, ranging from 30 to 200.

The spectral synthesis program MOOG, developed by Chris Sneden (Sneden 1973) of the University of Texas, was used to obtain abundances of the elements in each star. The program generates 4 possible fits to the observed spectral line based on model atmosphere,

Taking Another Look: Light n-Capture Element Abundances in Metal-Poor Halo Stars

metallicity and spectral line atomic data supplied by the user. The model atmospheres for the stars were the same ones used by (Simmerer *et al.* 2004) which used a Kurucz model with no convective overshoot. A full discussion of the atmosphere parameters can be found in (Simmerer *et al.* 2004). The metallicity values for these stars were also adopted from the Simmerer survey. The atomic data was taken from the Kurucz line lists. The new oscillator strengths for Zr, as published in Malcheva *et al.* 2006, were used in lieu of the older data from Biemont *et al.* 1981. The Malcheva data supplies data for many wavelengths of astrophysical interest that had not been previously measured. The fit that most closely matches the observed spectra is then selected by the user to determine the abundance of the element. Because of the narrow wavelength parameters in the MOOG program and the spacing of the lines of interest (~10-20 Å), each line was synthesized individually and the abundances for each element were averaged from the results of individual lines. Figure 1a. is an example of a synthesis for Y 3600Å and 1b. is an example of Zr 3714Å for HD 204543.

Results

For the 6 program stars, a total of 4 singly-ionized Zr (Zr II) and 6 singly-ionized Y (Y II) lines were analyzed. The wavelengths of these lines are given in Table 1 along with the oscillator strength used to

perform the synthesis. The average calculated abundance for each element (A) is presented in Table 2 along with the standard deviation for each element. The abundance results utilize the spectroscopic notation of $\log \epsilon (A)$ where the number abundance (N_A) of the element is compared to the number abundance of Hydrogen (N_H). The spectroscopic notation for this format is

$$\log \epsilon (A) = \log_{10}(N_A/N_H) + 12.0.$$

Also presented in Table 2 are the most recent results for these elements from other authors where available. The results from this analysis are in general agreement with previous work, with the lone exception of HD 135148. The reported results from Burris et al 2000 are likely erroneous, as inferior quality spectra were used and no statistical analysis was done on the abundance results. This discrepancy is not considered as a significant issue for this survey. We do find differences for the Zr abundance for HD 128279. Since both our survey and the Johnson et al. 2002 survey used similar quality observational data, we attribute this difference to the new values for $\log g_f$ increasing the number of lines we were able to use in our abundance analysis. The variations seen in the abundance of Y for HD 74462 can be attributed to the superior quality observational data used in this survey. In both cases we were able to improve the uncertainty in the abundance values.

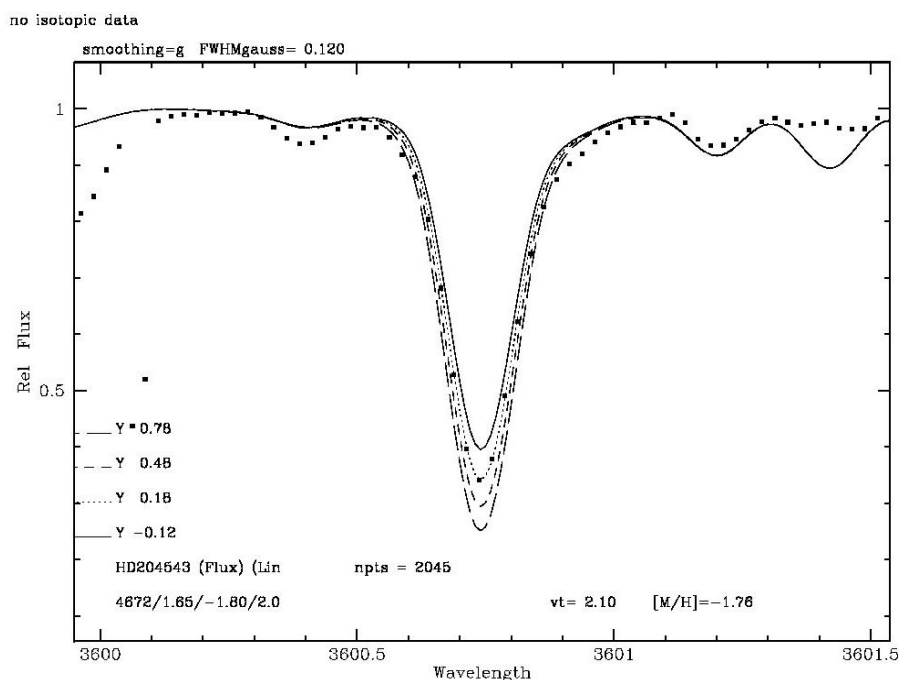


Figure 1a. An example of a spectral synthesis for the YII 3600Å line from HD 204543. The data was best fit for Y=0.18.

D. Burris, E. Jones, and J. Lusk

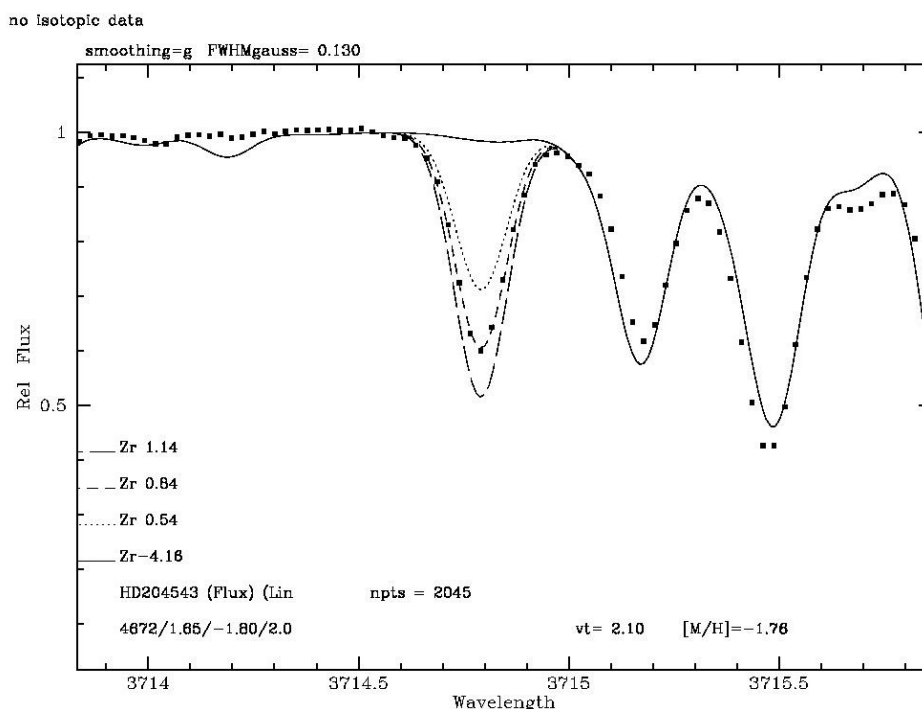


Figure 1b. An example of a spectral synthesis for the Zr II 3714Å line from HD 204543. The data was best fit for Zr=0.84.

Table 1. Program Wavelengths and Associated log gf values

Zr		Y	
λ (Å)	log gf (Malcheva <i>et al.</i> 2006)	λ (Å)	log gf (Hannaford <i>et al.</i> 1982)
3499	-0.81	3600	0.28
3505	-0.36	3611	0.01
3714	-0.93	3710	0.46
4050	-1.00	3747	-0.91
		3950	-0.49
		4398	-1.00

Table 2. New Abundance Values and Standard Deviation of Results compared to Previous Authors

Star	Zr	σ	Previous Results log ϵ/σ	Y	σ	Previous Results
BD +17 3248	0.62	0.14	0.76/0.14 (Cowan <i>et al.</i> 2002)	0.08	0.05	0.04/0.05 (Cowan <i>et al.</i> 2002)
HD 74462	0.92	0.15	1.06/not done (Burris <i>et al.</i> 2000)	0.03	0.07	0.54/not done (Burris <i>et al.</i> 2000)
HD 122563	-0.30	0.16	-0.28/0.25 (Montes <i>et al.</i> 2007)	-1.04	0.12	-0.93/0.20 (Montes <i>et al.</i> 2007)
HD 128279	0.21	0.02	-0.09/0.14 (Johnson <i>et al.</i> 2002)	-0.68	0.08	-0.72/0.15 (Johnson <i>et al.</i> 2002)
HD 135148	0.51	0.09	1.2/not done (Burris <i>et al.</i> 2000)	-0.18	0.08	1.22/not done (Burris <i>et al.</i> 2000)
HD 204543	0.85	0.11	0.97/not done (Burris <i>et al.</i> 2000)	0.12	0.08	0.28/not done (Burris <i>et al.</i> 2000)

Taking Another Look: Light n-Capture Element Abundances in Metal-Poor Halo Stars

To test for variations in the abundance, we recalculated the abundance value for Zr and Y while changing the temperatures in the model atmosphere. The range of temperatures varied from 4000K to 6000K, to encompass temperatures that are outside typical values for evolved giant stars. These temperature variations produced no apparent differences in the abundance synthesis. Other factors that will need to be explored are variations in metallicity, oscillator strength of the transitions and any effects from micro-turbulent velocity. The abundance dependence of these parameters will be explored in future work.

Discussion

To observe the abundance trends of the individual elements over the history of the galaxy, the [n-capture element/Fe] abundance ratios vs. iron metallicity [Fe/H] are plotted. The standard spectroscopic notation for comparison of element A to element B is given by

$$[A/B] = \log_{10}(N_A/N_B)_{\text{star}} - \log_{10}(N_A/N_B)_{\text{Solar}}$$

In the heavier n-capture elements, the variation in the abundance values that exists at low metallicity disappears as metallicity increases. This scatter is interpreted as the effect of local nucleosynthesis events enriching the interstellar medium (ISM) nearby that has not had sufficient time to become homogenized. As time passes, there is a smooth distribution of the

elements as the ISM becomes well mixed. The mixing time can be determined by looking at where scatter in the abundance ratio decreases. Also, the reduction in scatter can be an indicator of more common sources for production of the n-capture elements are contributing to the elemental abundances. The turn-on time of these events will eliminate certain objects, such as low mass stars, as potential early contributors to the r-process.

The abundances of Y and Zr are plotted versus s-process element Ba to observe any correlations. By comparison of these ratios, any inherent errors brought about by choices of atmospheric model parameters cancel out. During the early history of the Galaxy, Ba is produced via the r-process. Correlation between abundances of the two elements is indicative of a common source of production. If no correlation is seen, it will strengthen the likelihood of a “missing” light element process as suggested by some authors (Travaglio *et al.* 2004). Results indicate that the behavior of Y and Zr is not consistent with the abundance trends of Ba indicating that these elements might not be produced by the same process (Gilroy *et al.* 1988, Burris *et al.* 2000). The plot of [Y/Fe] vs. [Zr/Fe] compares abundances of Y and Zr for any correlation. If there is any commonality within this subgroup it indicates Y and Zr are produced in the same process. Figure 2 shows a strong correlation between the abundances of Y and Zr in these metal-poor stars.

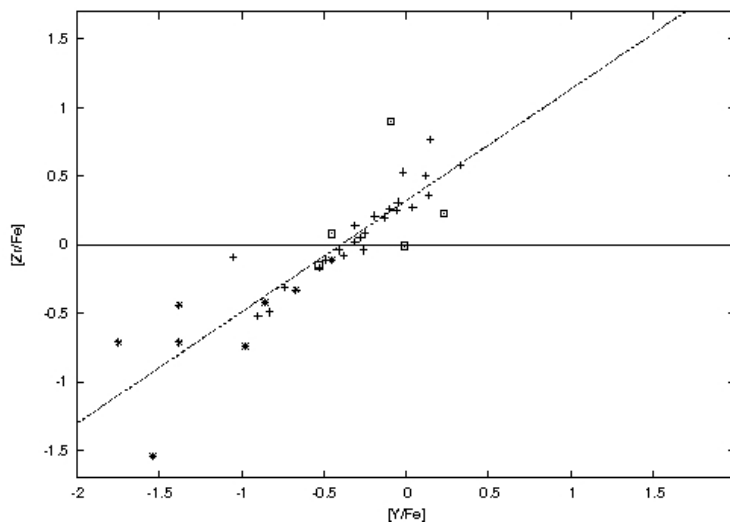


Figure 2. A comparison of the abundance of Zr to Y in a sample of metal-poor halo stars. Squares are from this work, plus signs from Francois *et al.* 2007, asterisk are upper limits from Francois *et al.* 2007.

D. Burris, E. Jones, and J. Lusk

A recent publication by (Francois *et al.* 2007) has given an unusual result for stars that are the most depleted in the n-capture elements. These stars appear to be depleted in Ba (as we expect), since Ba is primarily created in the s-process and thus is deficient early in the Galaxy's history when the r-process is responsible for its production. However, the same stars appear to be much more deficient in Sr providing further indications that Sr and Ba are not produced by the same process (Figure 3a). This provides further impetus to solve the riddle of this low mass regime, since clearly the same process is not responsible for the

production of both Sr and Ba as was previously believed. We have included our results along with the data used in the Francois paper to determine if Y and Zr exhibit the anomalous behavior shown by Sr. The relationships of Y (Figure 3b) and Zr (Figure 3c) to Ba do not exhibit the same level of scatter in the observations described for Sr in the Francois paper. Therefore, we will next turn to the study of these depleted stars to search for elements not considered, such as Germanium, in the Francois paper to see if this unusual trend holds throughout the low mass n-capture range.

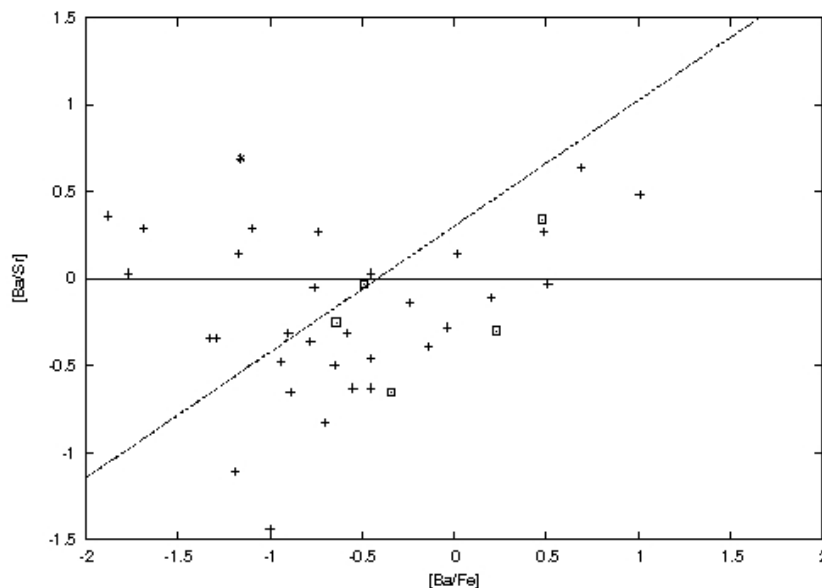


Figure 3a. A comparison of [Ba/Sr] to [Ba/Fe] after Francois *et al.* 2007. Symbols are those used in previous figure. Sr data for this work's stars are from literature.

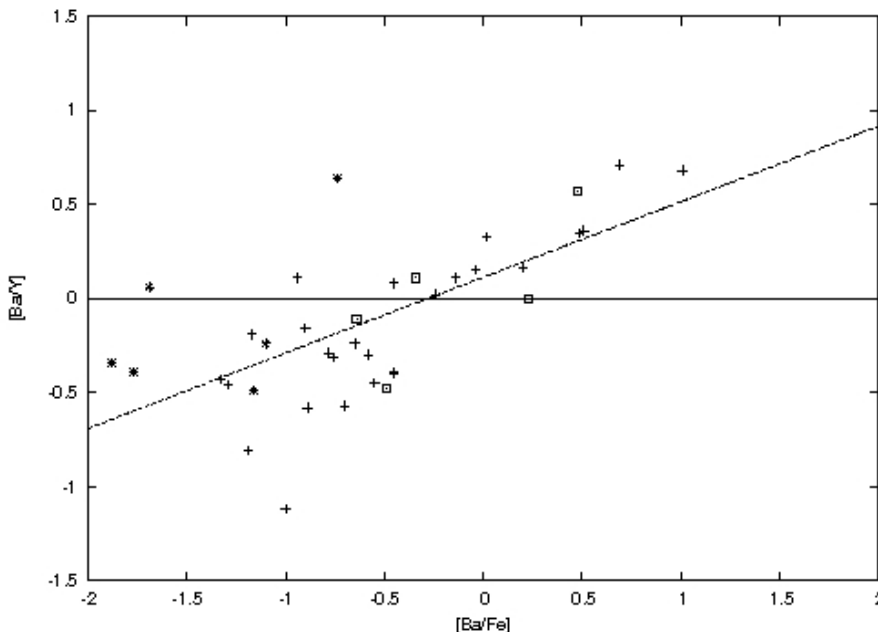


Figure 3b. A comparison of [Ba/Y] to [Ba/Fe]. Symbols are those used in Figure 2.

Taking Another Look: Light n-Capture Element Abundances in Metal-Poor Halo Stars

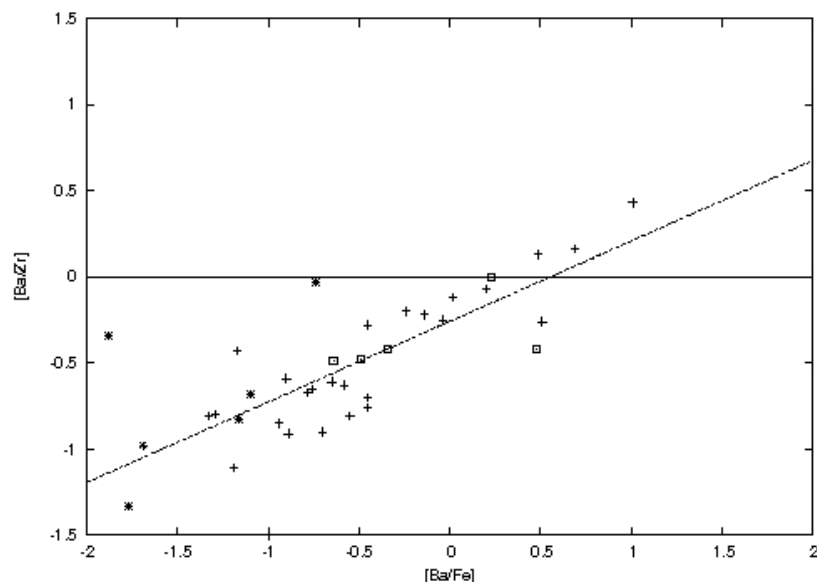


Figure 3c. A comparison of $[Ba/Zr]$ to $[Ba/Fe]$. Symbols are those used in Figure 2.

Conclusions

We have performed new abundance calculations for the elements Y and Zr in 6 metal-poor halo giants using high quality spectra and in the case of Zr new atomic data. Our results are consistent with previous authors' analysis of these stars but with improved values for the uncertainty due to new laboratory data and better quality observational data.

Comparison of the abundances of lighter n-capture elements to those of the heavier s-process element Ba shows that there is no correlation between the production of the light elements to the heavy elements. This indicates that there seem to be two distinct processes operating early in the history of the Galaxy. The main r-process is responsible for production of the elements from Ba onward in atomic number while some as yet unknown process is responsible for the production of the lighter n-capture elements.

By comparing the abundance of the two light elements to one another, a distinct correlation can be seen. This indicates that these elements are produced in the same way, even if the mechanism is not known. The s-process, r-process or any combination of the two cannot reproduce the abundance signatures of these light elements. Therefore the production mechanism is a unique and undiscovered process that must have at least operated early in the history of the Galaxy.

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D. Burris, E. Jones, and J. Lusk

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