

# **$r$ -Process Abundance Signatures in Metal-Poor Halo Stars**

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## **Abstract**

Abundance observations indicate the presence of rapid-neutron capture (*i.e.*,  $r$ -process) elements in old Galactic halo and globular cluster stars. Recent observations of the  $r$ -process-enriched star BD+17°3248 include new abundance determinations for the neutron-capture elements Cd I ( $Z=48$ ), Lu II ( $Z = 71$ ) and Os II ( $Z = 76$ ), the first detections of these elements in metal-poor  $r$ -process-enriched halo stars. Combining these and previous observations, we have now detected 32  $n$ -capture elements in BD+17°3248. This is the most of any metal-poor halo star to date. For the most  $r$ -process-rich (*i.e.*  $[\text{Eu}/\text{Fe}] \simeq 1$ ) halo stars, such as CS 22892-052 and BD+17°3248, abundance comparisons show that the heaviest stable  $n$ -capture elements (*i.e.*, Ba and above,  $Z \geq 56$ ) are consistent with a scaled solar system  $r$ -process abundance distribution. The lighter  $n$ -capture element abundances in these stars, however, do not conform to the solar pattern. These comparisons, as well as recent observations of heavy elements in metal-poor globular clusters, suggest the possibility of multiple synthesis mechanisms for the  $n$ -capture elements. The heavy element abundance patterns in most metal-poor halo stars do not resemble that of CS 22892-052, but the presence of heavy elements such as Ba in nearly all metal-poor stars without  $s$ -process enrichment indicates that  $r$ -process enrichment in the early Galaxy is common.

## 1. Introduction

Members of our group have been involved in long-term studies of abundances in Galactic halo stars. These studies have been designed to address a number of important issues, including: the synthesis mechanisms of the heavy, specifically, neutron capture ( $n$ -capture) elements, early in the history of the Galaxy; the identities of the earliest stellar generations, the progenitors of the halo stars; the site or sites for the synthesis of the rapid  $n$ -capture (*i.e.*,  $r$ -process) material throughout the Galaxy; the Galactic Chemical Evolution (GCE) of the elements; and by employing the abundances of the radioactive elements (Th and U) as chronometers, the ages of the oldest stars, and hence the lower limit on the age of the Galaxy and the Universe. (See Truran et al. 2002, Sneden & Cowan 2003, Cowan & Thielemann 2004, and Sneden, Cowan, & Gallino 2008 for discussions of these related and significant topics.)

In the following paper we review some of the results of our studies, starting with new stellar abundance determinations arising from more accurate laboratory atomic data in §II, followed by abundance comparisons of the lighter and heavier  $n$ -capture elements in the  $r$ -process-rich stars in §III, with new species detections in the star BD+17°3248 and the ubiquitous nature of the  $r$ -process throughout the Galaxy described in sections §IV and §V, respectively. We end with our Conclusions in §VI.

## 2. Atomic Data Improvements and Abundance Determinations

Stellar abundance determinations of the  $n$ -capture elements in Galactic halo stars have become increasingly more accurate over the last decade with typical errors now of less than 10% (Sneden, Cowan, & Gallino 2008). Much of that improvement in the precision of the stellar abundances has been due to increasingly more accurate laboratory atomic data. New measurements of the transition probabilities have been published for the rare earth elements (REE) and several others, including: La II (Lawler, Bonvallet, & Sneden 2001a); Ce II (Palmeri et al. 2000; and recently transition probabilities for 921 lines for Ce II, Lawler et al. 2009); Pr II (Ivarsson, Litzén, & Wahlgren 2001); Nd II (transition probabilities for more than 700 Nd II lines, Den Hartog et al. 2003); Sm II (Xu et al. 2003; and recently transition probabilities for more than 900 Sm II lines, Lawler et al. 2006); Eu I, II, and III (Lawler et al. 2001c; Den Hartog, Wickliffe, & Lawler 2002); Gd II (Den Hartog et al. 2006); Tb II (Den Hartog, Fedchak, & Lawler 2001; Lawler et al. 2001b); Dy I and II (Wickliffe, Lawler, & Nave 2000); Ho II (Lawler et al. 2004); Er II (transition probabilities for 418 lines of Er II, Lawler et al. 2008); Tm I and II (Anderson, Den Hartog, & Lawler 1996; Wickliffe & Lawler 1997); Lu I, II, and III (Den Hartog et al. 1998; Quinet et al. 1999, Fedchak et al. 2000); Hf II (Lawler et al. 2007); Os I and II (Ivarsson et al. 2003, 2004; Quinet et al. 2006); Ir I and II (Ivarsson et al. 2003, 2004; Xu et al. 2007); Pt I (Den Hartog et al. 2005); Au I and

II (Fivet et al. 2006; Biémont et al. 2007); Pb I (Biémont et al. 2000); Th II (Nilsson et al. 2002a); U II (Nilsson et al. 2002b); and finally in new, more precise solar and stellar abundances of Pr, Dy, Tm, Yb, and Lu (Sneden et al. 2009).

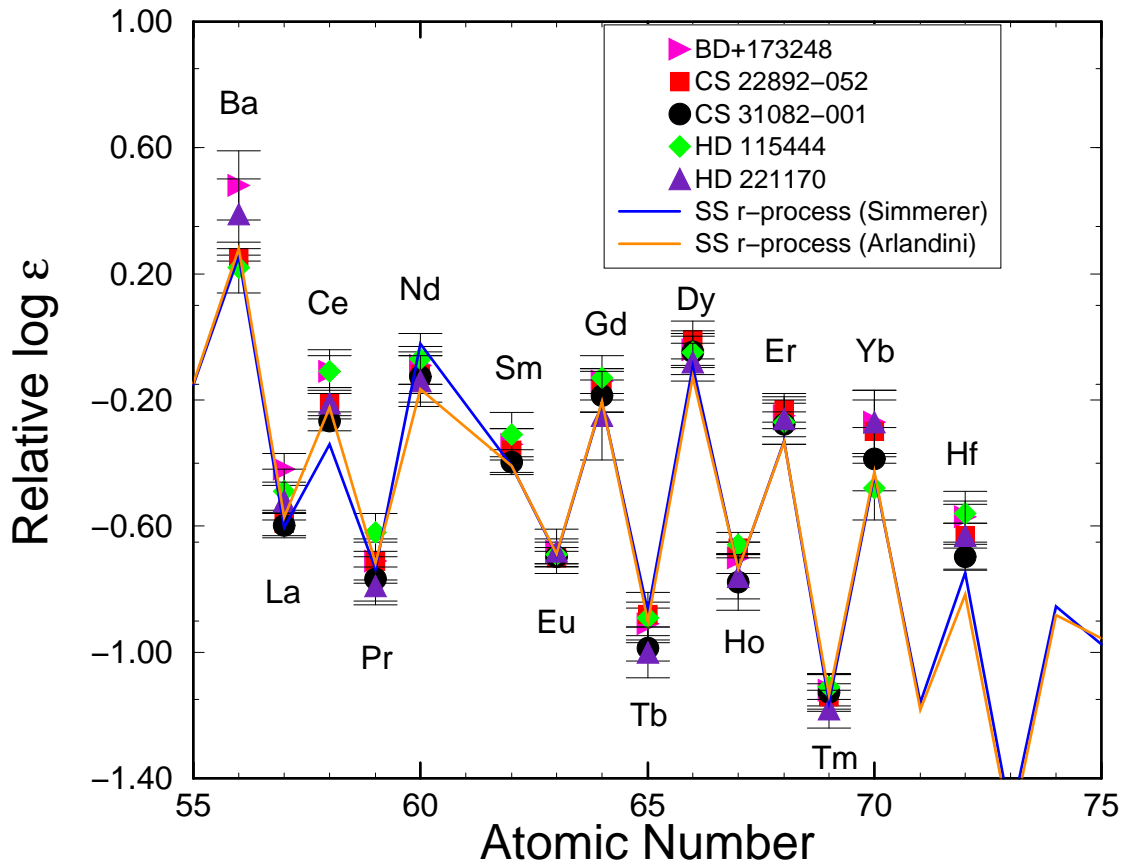
These new atomic data have been employed to redetermine the solar and stellar abundances. We show in Figure 1 (from Sneden et al. 2009) the relative REE, and Hf, abundances in five *r*-process rich stars: BD+17°3248, CS 22892-052, CS 31082-001, HD 115444 and HD 221170, where the abundance distributions have been scaled to the element Eu for these comparisons. Also shown in Figure 1 are two Solar System *r*-process-only abundance predictions from Arlandini et al. (1999) (based upon a stellar model calculation) and Simmerer et al. (2004) (based upon the “classical” *r*-process residual method) that are also matched to the Eu abundances. What is clear from the figure is that all of the REE abundances—as well as Hf, which is a heavier interpeak element—are in the same relative proportions from star-to-star and with respect to the solar *r*-process abundances. This agreement between the heavier *n*-capture elements and the Solar System *r*-process abundance distribution has been noted in the past (see, *e.g.*, Sneden et al. 2003), but the overall agreement has become much more precise, and convincing, as a result of the new atomic laboratory data.

### 3. Abundance Comparisons

We can also compare more comprehensive—not just the REE—elemental abundance determinations for the *r*-process-rich halo stars. This is potentially a more rewarding enterprise, as it can illuminate the complex nucleosynthetic origin of the lightest *n*-capture elements, and can provide new ways of looking at the age of the Galactic halo.

#### 3.1. Heavy *n*-capture Elements

We show in Figure 2 abundance comparisons with extensive elemental data for 10 *r*-process-rich stars (from the top): filled (red) circles, CS 22892-052 (Sneden et al. 2003; Sneden et al. 2009); filled (green) squares, HD 115444 (Westin et al. 2000; Sneden et al. 2009; Hansen & Primas 2011); filled (purple) diamonds, BD+17°3248 (Cowan et al. 2002; Roederer et al. 2010b); (black) stars, CS 31082-001 (Hill et al. 2002; Plez et al. 2004); solid (turquoise) left-pointing triangles, HD 221170 (Ivans et al. 2006; Sneden et al. 2009); solid (orange) right-pointing triangles, HE 1523-0901 (Frebel et al. 2007); (green) crosses, CS 22953-003 (Francois et al. 2007); open (maroon) squares, HE 2327-5642 (Mashonkina et al. 2010); open (brown) circles, CS 29491-069 (Hayek et al. 2009); and open (magenta) triangles, HE 1219-0312 (Hayek et al. 2009). The abundances of all the stars except CS 22892-052 have been vertically displaced downwards for display purposes. In each case the solid lines are (scaled) solar system *r*-process only predictions from Simmerer et al. (2004) that have been matched to the Eu abundances.

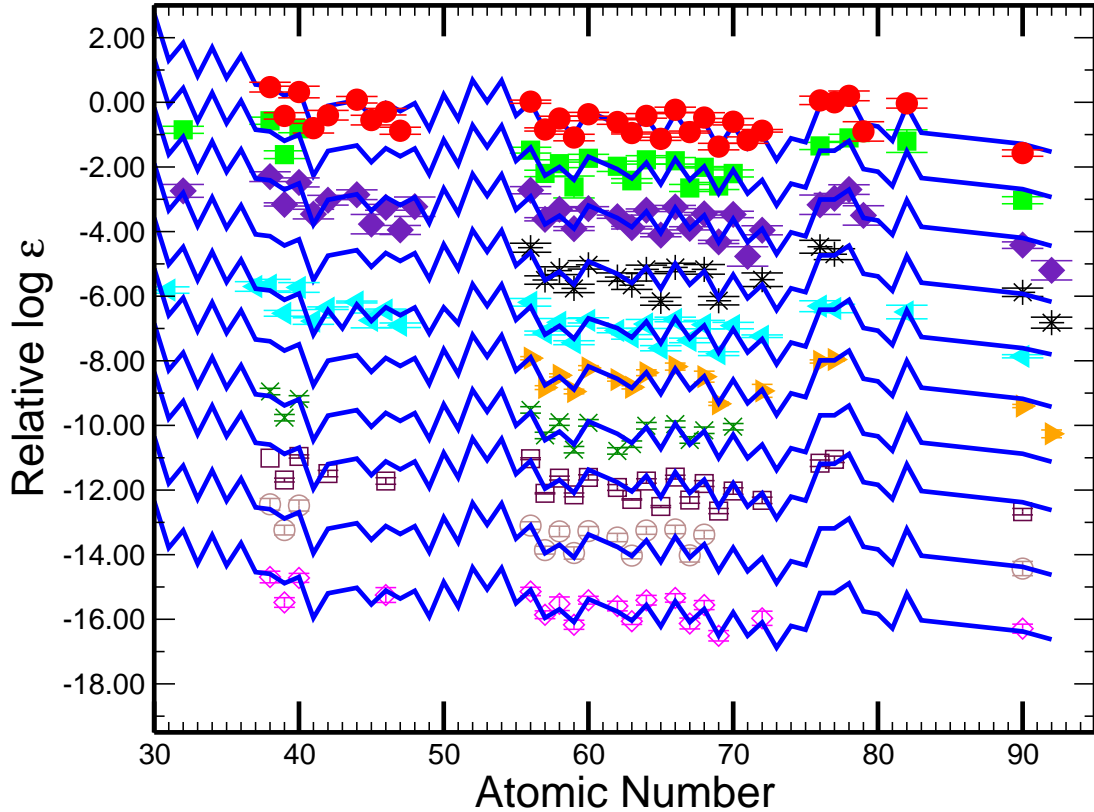


**Figure 1.**— Recent abundance determinations in five  $r$ -process rich stars, based upon new atomic lab data, compared with two solar system  $r$ -process only predictions. The abundances in each star have been normalized to the element Eu. After Sneden et al. (2009). Reproduced by permission of the AAS.

The figure indicates that for the ten stars plotted, the abundances of *all* of the heavier stable  $n$ -capture elements (*i.e.*, Ba and above) are consistent with the relative solar system  $r$ -process abundance distribution (see also Sneden et al. 2009). Earlier work had demonstrated this agreement for several  $r$ -process rich stars (where  $[\text{Eu}/\text{Fe}] \simeq 1$ ), including CS 22892-052, and the addition of still more such  $r$ -process-rich stars supports that conclusion.

### 3.2. Light $n$ -capture Elements

While the heavier  $n$ -capture elements appear to be consistent with the scaled solar system  $r$ -process curve, the lighter  $n$ -capture elements ( $Z < 56$ ) seem to fall below that same solar curve. One problem in analyzing this region of interest is that there have been relatively few stellar observations of these lighter  $n$ -capture elements until now. With the limited amount of data it is not yet clear if the pattern is the same from



**Figure 2.**— Abundance comparisons between 10 *r*-process rich stars and the Solar System *r*-process values. See text for references. Adapted from Sneden et al. (2011).

star-to-star for the lighter *n*-capture elements in these *r*-process rich stars.

There has been extensive work on trying to understand the synthesis of these elements. Observations of 4 metal-poor *r*-enriched stars by Crawford et al. (1998) suggested that Ag ( $Z = 47$ ) was produced in rough proportion to the heavy elements in stars with  $-2.2 < [\text{Fe}/\text{H}] < -1.2$ . Wasserburg, Busso, & Gallino (1996) and McWilliam (1998) pointed out that multiple sources of heavy elements (other than the *s*-process) were required to account for the observed abundances in the solar system and extremely metal-poor stars, respectively. Travaglio et al. (2004) quantized this effect, noting that Sr-Zr Solar System abundances could not be totally accounted for from traditional sources, such as the *r*-process, the (main) *s*-process and the weak *s*-process. They suggested that the remaining (missing) abundances—8% for Sr to 18%

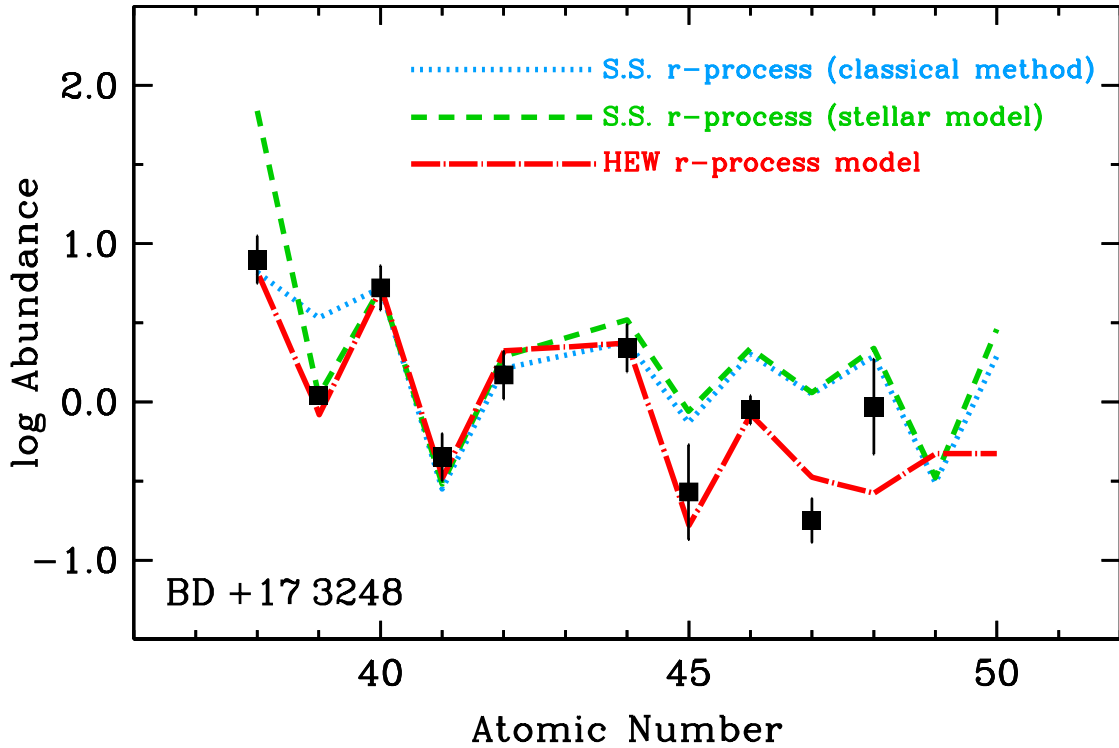
for Y and Zr—came from a light element primary process (LEPP). Travaglio et al. also noted, “The discrepancy in the  $r$ -fraction of Sr-Y-Zr between the  $r$ -residuals method and the CS 22892-052 abundances becomes even larger for elements from Ru to Cd: the weak  $s$ -process does not contribute to elements from Ru to Cd. As noted [previously], this discrepancy suggests an even more complex multisource nucleosynthetic origin for elements like Ru, Rh, Pd, Ag, and Cd.”

Montes et al. (2007) extended studies of the LEPP and suggested that a range of  $n$ -capture elements, perhaps even including heavier elements such as Ba, might have a contribution from this primary process. (Since, however, Ba in  $r$ -process rich stars is consistent with the solar  $r$ -process abundances, such contributions for these heavier elements must be quite small.) They noted, in particular, that this LEPP might have been important in synthesizing the abundances in the  $r$ -process poor star HD 122563.

Further insight into the (complicated) origin of the lighter  $n$ -capture elements is provided by the detections of Ge ( $Z = 32$ ) in a few stars. Cowan et al. (2005) noted a correlation of Ge with the iron abundances in the halo stars with  $-3.0 \lesssim [\text{Fe}/\text{H}] \lesssim -1.5$ , suggesting that the Ge is being produced along with the Fe-group elements at these low metallicities. To produce the protons needed to satisfy such a correlation, a new neutrino (*i.e.*,  $\nu$ -p) process that might occur in supernovae was suggested (Fröhlich et al. 2006). We note that for higher (*i.e.*, at solar) metallicities, Ge is considered a neutron-capture element, synthesized in the  $r$ -process (52%) and the  $s$ -process (48%) (Simmerer et al. 2004; Sneden et al. 2008). Thus, there should be a change in the slope of the Ge abundances from low metallicities to higher metallicities, a behavior that has not yet been observed.

We show in Figure 3 several  $r$ -process predictions for the lighter  $n$ -capture element abundances compared with observations of those elements in BD+17°3248 from Roederer et al. (2010b). The two Solar System  $r$ -process models (“classical” and “stellar model”) reproduce some of these elements but begin to diverge from the observed abundances at Rh ( $Z = 45$ ). Also shown in Figure 3 are predictions from a High Entropy Wind (HEW) model, that might be typical in a core-collapse (or Type II) supernova (Farouqi et al. 2009; K.-L. Kratz, private communication.) This model gives a better fit to the abundances, but does not reproduce the observed odd-even effects in Ag ( $Z = 47$ ) and Cd ( $Z = 48$ ) in this star (resembling a trend discovered in other  $r$ -enriched stars by Johnson & Bolte 2002). Recent work by Hansen & Primas (2011) to study Pd ( $Z = 46$ ) and Ag abundances in stars with  $-3.2 \lesssim [\text{Fe}/\text{H}] \lesssim -0.6$  confirms the divergence between observations and simulation predictions.

These comparisons between calculations and observations do in fact argue for a combination of processes to reproduce the observed stellar abundances of some of these light  $n$ -capture elements. This combination of processes might include (contributions from) the main  $r$ -process, the LEPP, the  $\nu$ -p process, charged-particle reactions accompanied by  $\beta$ -delayed fission and the weak  $r$ -process (*e.g.*, Kratz et al. 2007). (See, *e.g.*, Farouqi et al. 2009, 2010, Roederer et al. 2010a,b, and Arcones & Montes 2011 for further discussion.) It may also be that during the synthesis the main  $r$ -process and



**Figure 3.**— *r*-process abundance predictions for light *n*-capture elements compared with observations of BD+17°3248 from Roederer et al. (2010b). See text for further details.

the LEPP are separate processes, and that the abundance patterns in all metal-poor stars could be reproduced by mixing their yields (Montes et al. 2007). Alternatively, it may be that the *r*-process and the LEPP can be produced in the same events, but sometimes only the lower neutron density components are present (Kratz et al. 2007; Farouqi et al. 2009). It has also been suggested that the heavier and lighter *n*-capture elements are synthesized in separate sites (see *e.g.*, Qian & Wasserburg 2008).

New observations of heavy elements in metal-poor globular cluster stars reaffirm the abundance patterns seen in field stars. In the globular cluster M92, Roederer & Sneden (2011) found that the observed star-to-star dispersion in Y ( $Z = 39$ ) and Zr ( $Z = 40$ ) is the same as for the Fe-group elements (*i.e.*, consistent with observational uncertainty only). Yet, the Ba (Sneden, Pilachowski, & Kraft 2000), La, Eu, and Ho abundances exhibit significantly larger star-to-star dispersion that cannot be attributed to observational uncertainty alone. Furthermore, the Ba and heavier elements were produced by *r*-process nucleosynthesis without any *s*-process contributions. This indicates that, as in the field stars, these two groups of elements could not have formed entirely in the same nucleosynthetic process in M92.

## 4. New Species Detections

Roederer et al. (2010b) reanalyzed near-UV spectra obtained with HST/STIS of the star BD+17°3248. (See also Cowan et al. 2002, 2005 for earlier HST observations of BD+17°3248.) We show in Figure 4 (from Roederer et al. 2010b) spectral regions around Os II and Cd I lines in the stars BD+17°3248, HD 122563 and HD 115444. There is a clear detection of Os II in both BD+17°3248 and HD 115444 but not in HD 122563. The star HD 115444 is similar in metallicity and atmospheric parameters to HD 122563 (see Westin et al. 2000), but much more *r*-process rich:  $[\text{Eu}/\text{Fe}] = 0.7$  versus  $-0.5$ , respectively. In the lower panel of Figure 4 we see the presence of Cd I in BD+17°3248 and HD 115444, as well as a weak detection in HD 122563. Synthetic fits to these spectra in BD+17°3248 and HD 122563 indicate the presence of Cd I and Lu II lines in both stars, as well as the detection (and upper limit of) Os II in the same two stars, respectively. This work was the first to detect Cd I, Lu II, and Os II in metal-poor halo stars.

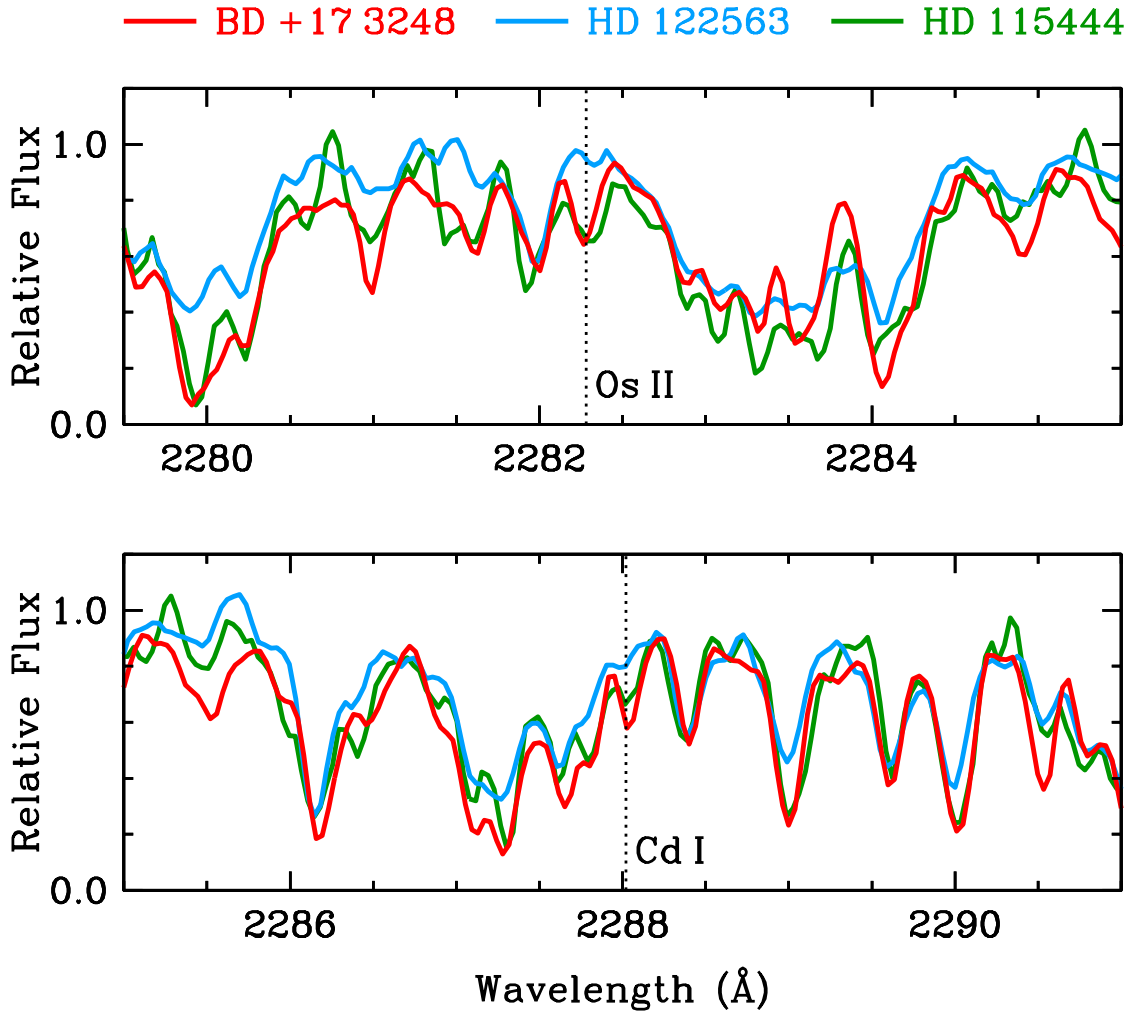
In addition to these new detections, Roederer et al. (2010b) employed Keck/HIRES spectra to derive new abundances of Mo I, Ru I and Rh I in this star. Combining these abundance determinations led to the detection of a total of 32 *n*-capture species—the most of any metal-poor halo star. (Previously, CS 22892-052 had the most such detections.) Further, we note that the total detections in BD+17°3248 did not count the element Ge. And while Ge may be synthesized in proton-rich processes early in the history of the Galaxy, it is classified as a *n*-capture element in Solar System material (see Simmerer et al. 2004 and Cowan et al. 2005). We illustrate this total abundance distribution in Figure 5 compared with the two Solar System *r*-process curves from Simmerer et al. (2004) and Arlandini et al. (1999). We again see the close agreement between the heavier *n*-capture elements and (both of) the predictions for the Solar System *r*-process curve, as well as the deviation between the abundances of the lighter *n*-capture elements and that same curve.

## 5. The *r*-process Throughout the Galaxy

The results of Roederer et al. (2010b) also confirm earlier work indicating significant differences in the abundances between *r*-process rich stars, such as BD+17°3248, and *r*-process poor stars, such as HD 122563. This difference is shown clearly in Figure 6. The abundance distribution for BD+17°3248 (shown in the top panel) is relatively flat—compare the abundance of Sr with Ba—and is consistent with the scaled Solar System *r*-process abundances for the heavy *n*-capture elements. In contrast the lower panel of this figure indicates that the abundances in the *r*-process poor HD 122563 fall off dramatically with increasing atomic number—again compare the abundance of Sr with Ba.

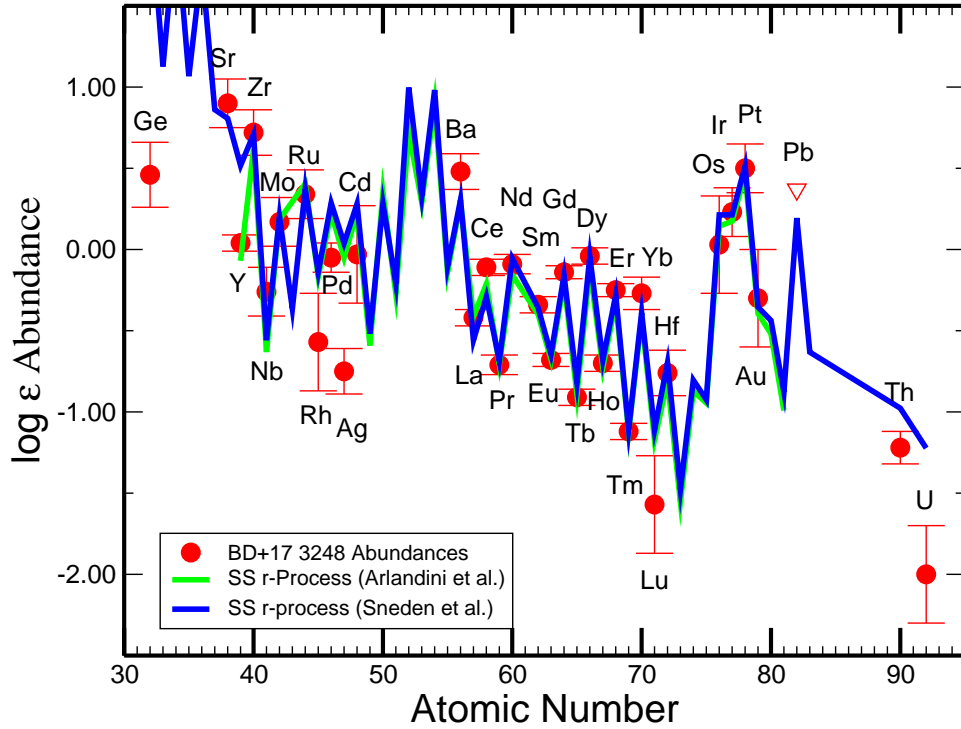
It is clear from much work (*e.g.*, Honda et al. 2006, 2007) that the abundances even





**Figure 4.**— HST (near-UV) spectral regions containing Os II and Cd I lines in BD+17°3248, HD 122563, and HD 115444 from Roederer et al. (2010b). Reproduced by permission of the AAS.

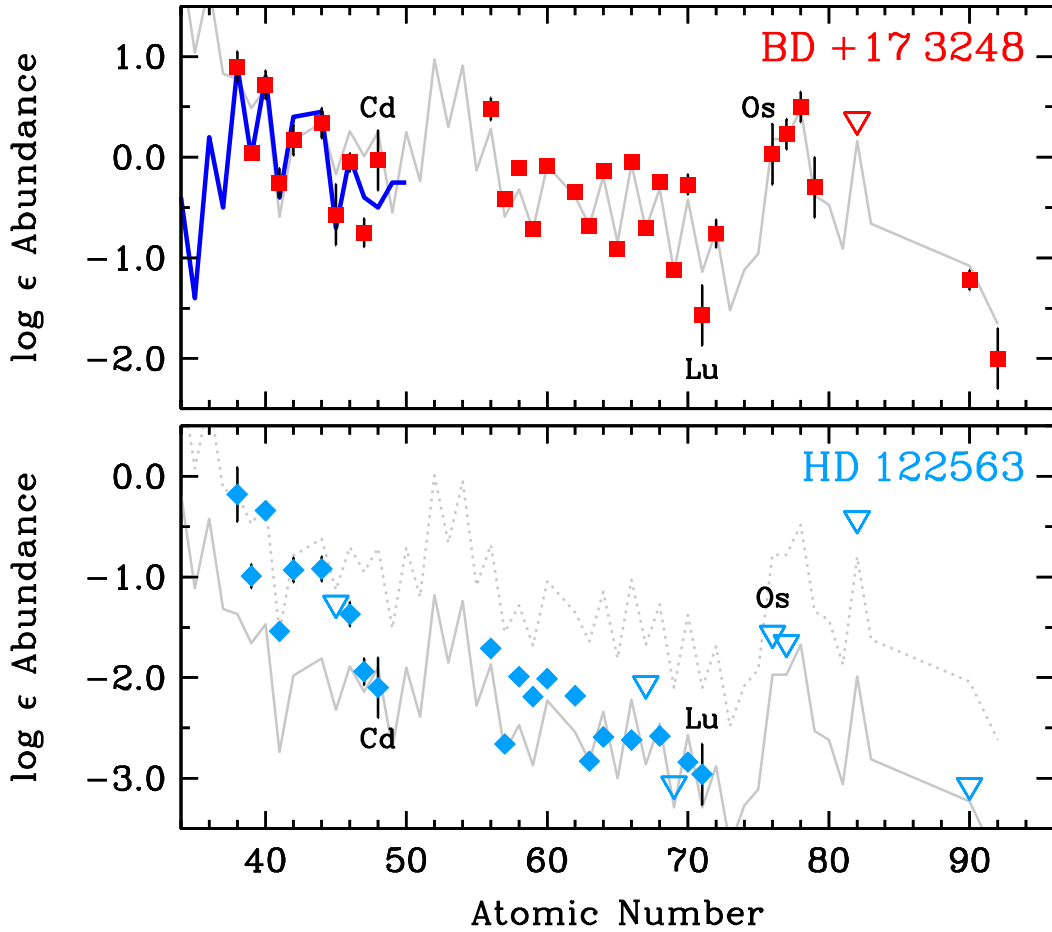
in a star such as HD 122563 do come from the *r*-process—the source for the *s*-process, low- or intermediate-mass stars on the AGB with longer evolutionary timescales, have not had sufficient time to evolve prior to the formation of this metal-poor halo star (cf. Truran 1981). Instead, one can think of the abundance distribution in HD 122563, illustrated in Figure 6, as the result of an “incomplete *r*-process”—there were not sufficient numbers of neutrons to form all of the heavier *n*-capture elements, particularly the “third-peak” elements of Os, Ir, and Pt. In the classical “waiting point approximation” the lighter *n*-capture elements are synthesized from lower neutron number density ( $n_n$ ) fluxes, typically  $10^{20}$ – $10^{24}$ , with the heavier *n*-capture elements (and the total *r*-process abundance distribution) requiring values of  $n_n = 10^{23}$ – $10^{28}$   $\text{cm}^{-3}$  (see Figures 5 and 6 of Kratz et al. 2007). Physically in this “incomplete” or “weak *r*-process,” the neutron flux was too low to push the *r*-process “path” far enough away



**Figure 5.**— The total observed abundance distribution in BD+17°3248. There are a total of 32—not including Ge—detections of  $n$ -capture elements, the most in any metal-poor halo star. This distribution is compared with the two Solar System  $r$ -process curves from Simmerer et al. (2004) and Arlandini et al. (1999).

from the valley of  $\beta$ -stability to reach the higher mass numbers after  $\alpha$  and  $\beta$ -decays back to stable nuclides. Instead the lower neutron number densities result in the  $r$ -process path being too close to the valley of stability leading to a diminution in the abundances of the heavier  $n$ -capture elements. The lighter  $n$ -capture elements, such as Sr, in this star may have formed as a result of this incomplete or weak  $r$ -process, or the LEPP, or combinations as described previously for the  $r$ -process rich stars.

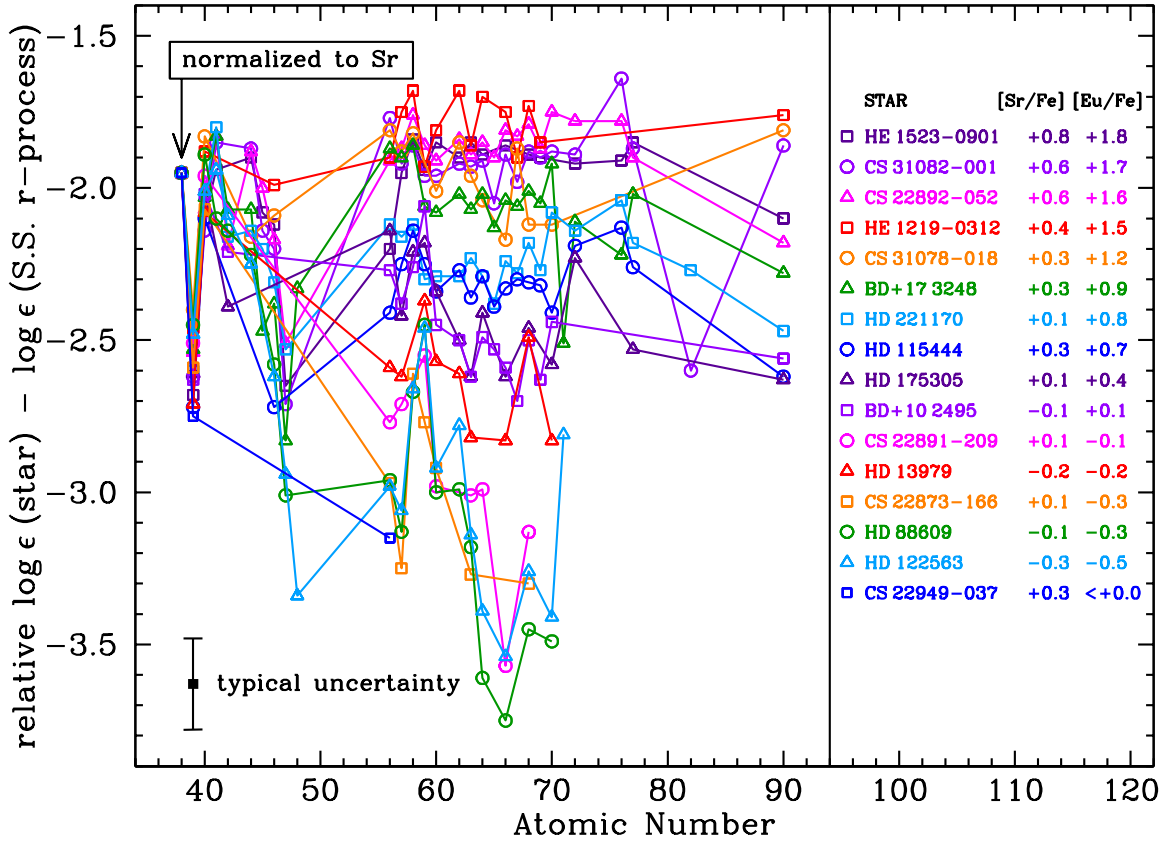
This analysis was extended to a larger sample by Roederer et al. (2010a) and is illustrated in Figure 7. We show the differences between the abundance distributions of 16 metal-poor stars, normalized to Sr, compared with the Solar System  $r$ -process distribution (Sneden, Cowan, & Gallino 2008). The stars are plotted in order of descending values of  $[\text{Eu}/\text{Fe}]$ , a measure of their  $r$ -process richness. Thus, we see near the top CS 22892-052 with a value of  $[\text{Eu}/\text{Fe}] = 1.6$  and near the bottom, HD 122563 with  $[\text{Eu}/\text{Fe}] = -0.5$ . The figure illustrates the relative flatness of the distributions



**Figure 6.**— Abundance distributions in BD+17°3248 and HD 122563 with detections indicated by filled symbols and upper limits by downward-pointing open triangles. The new measurements of Os, Cd, and Lu illustrated in Figure 4 are labeled. In the top panel (BD+17°3248) the bold curve is an HEW calculation from Farouqi et al. (2009) normalized to Sr, while the solid line is the Solar System *r*-process curve (Sneden, Cowan, & Gallino 2008) normalized to Eu. In the bottom panel (HD 122563) the solar curve is normalized both to Eu (solid line) and Sr (dotted line). Abundances were obtained from Cowan et al. (2002, 2005), Honda et al. (2006), Roederer et al. (2009, 2010b), and Sneden et al. (2009). Figure from Roederer et al. (2010b). Reproduced by permission of the AAS.

of the most *r*-process-rich stars ( $[Eu/Fe] \simeq 1$ ) with respect to the solar curves, while the *r*-process poor stars have abundances that fall off sharply with increasing atomic number. It is also clear from Figure 7 that there are a range of abundance distributions falling between these two extreme examples. (We note that Figure 7 should not be taken as an unbiased distribution of stars at low metallicity.)

We emphasize four important points here. First, not all of the metal-poor stars have the same abundance pattern as CS 22892-052, only those that are *r*-process rich. Second, while the distributions are different between the *r*-process rich and poor stars there is no indication of *s*-process synthesis for these elements. Thus, all of the elements in these stars were synthesized in the *r*-process, at least for the heavier *n*-capture



**Figure 7.**— Differences between Solar System  $r$ -process abundances and stellar abundances for 16 metal-poor stars, normalized to Sr. The stars are listed in order of descending [Eu/Fe], and that value and [Sr/Fe] are listed in the box to the right in the figure. A value for a typical uncertainty is illustrated in the lower left. Note the difference in the abundance pattern between the  $r$ -process rich star CS 22892-052 and that of HD 122563, with the other stars falling between those extremes. Abundance references are as follows: S.S.  $r$ -process abundances (Snedden, Cowan, & Gallino 2008); HE 1523-0901 (Frebel et al. 2007 and A. Frebel, 2009, private communication); CS 31082-001 (Hill et al. 2002; Plez et al. 2004; Sneden et al. 2009); CS 22892-052 (Snedden et al. 2003; Sneden et al. 2009); HE 1219-0312 (Hayek et al. 2009; Roederer et al. 2009); UMi-COS 82 (Aoki et al. 2007); CS 31078-018 (Lai et al. 2008); CS 30306-132 (Honda et al. 2004); BD+17 3248 (Cowan et al. 2002; Sneden et al. 2009; Roederer et al. 2010b); HD 221170 (Ivans et al. 2006; Sneden et al. 2009); HD 115444 (Westin et al. 2000; Roederer et al. 2009; Sneden et al. 2009); HD 175305 (Roederer et al. 2010c); BD+29 2356 (Roederer et al. 2010c); BD+10 2495 (Roederer et al. 2010c); CS 22891-209 (Francois et al. 2007); HD 128279 (Roederer et al. 2010c); HD 13979 (I. Roederer et al., in preparation); CS 29518-051 (Francois et al. 2007); CS 22873-166 (Francois et al. 2007); HD 88609 (Honda et al. 2007); CS 29491-053 (Francois et al. 2007); HD 122563 (Honda et al. 2006; Roederer et al. 2010b); and CS 22949-037 (Depagne et al. 2002). Figure from Roederer et al. (2010a). Reproduced by permission of the AAS.

elements, and  $r$ -process material was common in the early Galaxy. Third, the approximate downward displacement from the top to the bottom of the Figure 7 (a measure of the decreasing [Eu/Sr] ratio) roughly scales as the [Eu/Fe] ratio, listed in the right-hand panel. This can be understood as follows: since the abundance patterns are normalized to Sr, and if Sr is roughly proportional to Fe in these stars (with a moderate degree of

scatter—cf. Figure 7 of Roederer et al. 2010a), then *of course* the [Eu/Sr] ratio roughly follows [Eu/Fe]. (See also Aoki et al. 2005.) Finally, we note that Ba has been detected in all of these stars and the vast majority of low-metallicity field and globular cluster stars studied to date. Only in a few Local Group dwarf galaxies do Ba upper limits hint that Ba (and, by inference, all heavier elements) may be extremely deficient or absent (Fulbright et al. 2004; Koch et al. 2008; Frebel, Kirby, & Simon 2010).

## 6. Conclusions

Extensive studies have demonstrated the presence of *n*-capture elements in the atmospheres of metal-poor halo and globular cluster stars. New detections of the *n*-capture elements Cd I ( $Z = 48$ ), Lu II ( $Z = 71$ ) and Os II ( $Z = 76$ ), derived from HST/STIS spectra, have been made in several metal-poor halo stars. These were the first detections of these species in such stars. Supplementing these observations with Keck data and new measurements of Mo I, Ru I and Rh I, we reported the detections of 32 *n*-capture elements in BD+17°3248. This is currently the most detections of these elements in any metal-poor halo star, supplanting the previous “champion” CS 22892-052.

Comparisons among the most *r*-process-rich stars ( $[\text{Eu}/\text{Fe}] \simeq 1$ ) demonstrate that the heavier stable elements (from Ba and above) are remarkably consistent from star-to-star and consistent with the (scaled) solar system *r*-process distribution. Detailed comparisons of the REE (along with Hf) among a well-studied group of *r*-process-rich stars, employing new experimental atomic data, strongly supports this finding. The newly determined, and lab-based, stellar abundances are more precise and show very little scatter from star-to-star and with respect to the Solar System *r*-process abundances. This suggests that the *r*-process produced these elements early in the history of the Galaxy and that the same type(s) of process was responsible for the synthesis of the *r*-process elements at the time of the formation of the Solar System.

While the heavier elements appear to have formed from the main *r*-process and are apparently consistent with the solar *r*-process abundances, the lighter *n*-capture element abundances in these stars do not conform to the solar pattern. There have been little data in these stars until recently, but now with the new detections of Cd and increasing Pd and Ag detections, some patterns are becoming clear. First, the main *r*-process alone is not responsible for the synthesis of these lighter *n*-capture elements. Instead, other processes, alone or in combination, may have responsible for such formation. These processes include a so-called “weak” *r*-process (with lower values of  $n_n$ ), the LEPP, the  $\nu$ -p process, or charged particle reactions in the HEW of a core-collapse supernova. It is also not clear whether different processes are responsible for different mass regions with one for Ge, a different one for Sr-Zr and still another for Pd, Ag, and Cd. It is also not clear whether these processes operate separately from each other or in the same site, or whether different mass ranges of the *n*-capture elements

are synthesized in different sites. Clearly, much more work needs to be undertaken to understand the formation of these lighter  $n$ -capture elements.

The stellar abundance signatures of the heaviest of these elements, i.e., Ba and above, are consistent with the rapid neutron capture process,  $r$ -process, but not the  $s$ -process in these old stars. Similar conclusions are found for stars in the ancient globular clusters with comparable abundance spreads in the  $r$ -process elements (see, *e.g.*, Gratton, Sneden, & Carretta 2004, Sobeck et al. 2011, Roederer 2011, and Roederer & Sneden 2011). There is also a clear distinction between the abundance patterns of the  $r$ -process rich stars such as CS 22892-052 and the  $r$ -process poor stars like HD 122563. The latter seem to have an element pattern that was formed as a result of a “weak” or “incomplete”  $r$ -process. Most of the old, metal-poor halo stars have abundance distributions that fall between the extremes of CS 22892-052 and HD 122563. However, the very presence of  $n$ -capture elements in the spectra of these stars argues for  $r$ -process events being a common occurrence early in the history of the Galaxy.

Finally, we note the need for additional stellar observations, particularly of the UV regions of the spectra *only* accessible using STIS or COS aboard HST. These observations require high signal-to-noise ratios and high resolution to identify faint lines in crowded spectral regions. Also we will require more laboratory atomic data for elements that have not been well studied to improve the precision of the stellar and solar abundances. Additional experimental nuclear data, not yet available, for the heaviest neutron-rich nuclei that participate in the  $r$ -process, will be critical to these studies. Until that time new, more physically based, theoretical prescriptions for nuclear masses, half-lives, etc. for these  $r$ -process nuclei will be necessary. New theoretical models of supernova explosions and detailed synthesis scenarios, such as might occur in the HEW, will be very important to help to identify the site or sites for the  $r$ -process, a search that has been ongoing since 1957.

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