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# Nucleosynthesis: Stellar and Solar Abundances and Atomic Data

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## ABSTRACT

Abundance observations indicate the presence of often surprisingly large amounts of neutron capture (*i.e.*, *s*- and *r*-process) elements in old Galactic halo and globular cluster stars. These observations provide insight into the nature of the earliest generations of stars in the Galaxy – the progenitors of the halo stars – responsible for neutron-capture synthesis. Comparisons of abundance trends can be used to understand the chemical evolution of the Galaxy and the nature of heavy element nucleosynthesis. In addition age determinations, based upon long-lived radioactive nuclei abundances, can now be obtained. These stellar abundance determinations depend critically upon atomic data. Improved laboratory transition probabilities have been recently obtained for a number of elements. These new gf values have been used to greatly refine the abundances of neutron-capture elemental abundances in the solar photosphere and in very metal-poor Galactic halo stars. The newly determined stellar abundances are surprisingly consistent with a (relative) Solar System *r*-process pattern, and are also consistent with abundance predictions expected from such neutron-capture nucleosynthesis.

## 1.    Stellar Abundances and New Atomic Data

Abundance studies of heavy elements and isotopes in Galactic halo stars are providing important clues and insights into the nature of, and sites for, nucleosynthesis early in the history of the Galaxy (Sneden & Cowan 2003; Cowan & Thielemann 2004; Cowan & Sneden

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2006). Observations of heavy neutron-capture elements (*i.e.*, those produced in the slow (*s*) or rapid (*r*)-process) in both old (low iron, or metallicity) stars and younger (more metal-rich) stars are also providing clear indications of the nature of the Galactic chemical evolution. In addition the detection of the long-lived radioactive *n*-capture elements, such as thorium and uranium, are allowing direct age determinations for the oldest stars in the Galaxy - thus, providing lower limits on both the age of the Galaxy and the Universe.

All of these abundance determinations and studies depend critically upon atomic data, particularly transition probabilities. During the past few years there have been dramatic improvements in the experimental determinations of these transition probabilities for a number of rare earth elements: these include improved laboratory values for the elements Ce (Palmeri et al. 2000), Nd (Den Hartog et al. 2003), Ho (Lawler et al. 2004), Pt (Den Hartog et al. 2005), and Sm (Lawler et al. 2006). New values for the element Gd have also recently been obtained (Den Hartog et al. 2006), but Gd abundances in the current paper do not reflect these new data. These improved data sets have been employed to determine elemental abundances in three metal-poor Galactic halo stars. In addition new (refined) solar photospheric abundances have been obtained for Nd, Ho and Sm - this was not possible, however, for Pt. We show in Figure 1 the abundances from Ba-Er (normalized at the *r*-process element Eu) in CS 22892-052 (Sneden et al. 2003), BD +17°3248 (Cowan et al. 2002), HD 115444 (Westin et al. 2000) and the Sun (Lodders 2003). We focus in the left panel on abundance determinations for Nd, Sm and Ho in these four stars based upon published atomic data. The abundances for those same three elements, employing the newer laboratory atomic data, is shown in the right panel of this figure. It is clear, that as a result of employing the new atomic data, the star-to-star scatter among the three metal-poor Galactic halo stars is markedly reduced, and there is good agreement between the elemental values in these stars and the solar system *r*-process value (indicated by the horizontal line).

## 2. Discussion

Employing the new atomic data, we have updated several of the abundance values from Sneden et al. (2003) for CS 22892-052. We show those values in Figure 2 (top panel) compared to an *s*-only (dashed line) and an *r*-only (solid line) solar system elemental abundance curve. These solar system elemental abundance curves from Simmerer et al. (2004) are the sums of individual isotopic contributions from the *s* and *r*-process and are tabulated in table 1. Using the so called "classical model" approximation in conjunction with measured neutron capture cross-sections, the individual *s*-process contributions are first determined. Subtracting these *s*-process isotopic contributions from the total solar abundances predicts the residual *r*-process contributions. These individual *s*- and *r*-process isotopic solar system abundances (based upon the Si = $10^6$ scale) that are listed in table 1, are derived from the work of Käppeler et al. 1989, Wisshak et al. 1998 and O'Brien et al. 2003, and can be used for future isotopic studies.
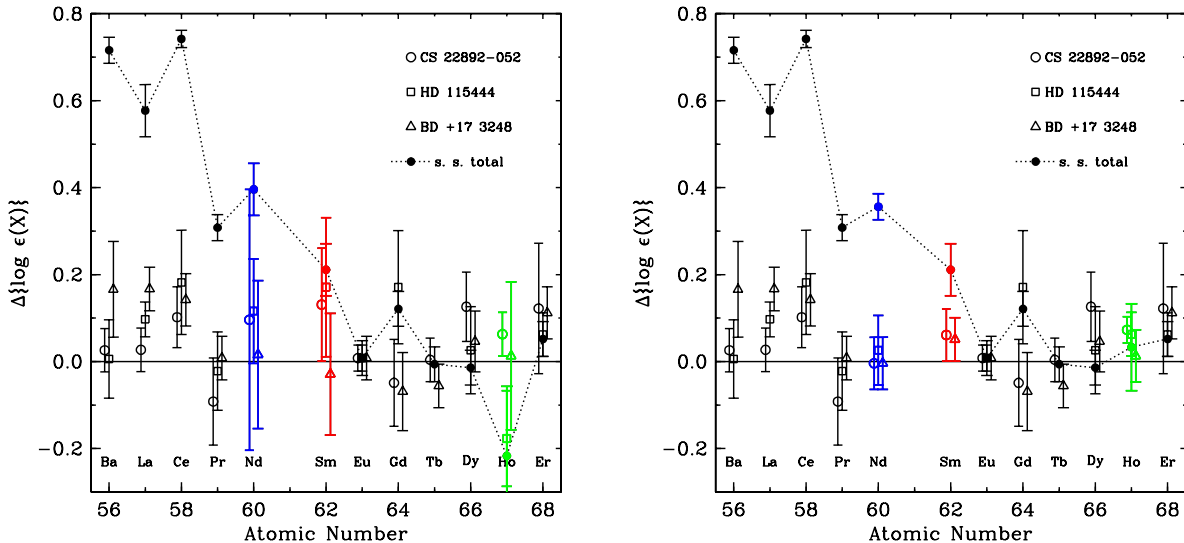
Fig. 1.— (left) Abundance values (scaled at the element Eu) for selected elements in the stars CS 22892-052 (open circles), HD 115444 (squares), BD +17°3248 (triangles) and the Sun (filled circles), based upon previously published atomic data. (right) Newly derived abundance values based upon recent experimental lab data (after Lawler et al. 2006).

It is clear in both the top and bottom panels of Figure 2 that the abundances of the stable elements Ba and above are consistent with the scaled solar system elemental $r$-process distribution. This agreement has been seen in other $r$-process-rich stars and strongly suggests that the $r$-process is robust over the history of the Galaxy. It further demonstrates that early in the history of the Galaxy, all of the $n$-capture elements were synthesized in the $r$-process, and not the $s$-process. Additional comparisons in the figure, however, suggest the lighter elements do not fall on this same curve that fits the heavier $n$-capture elements. The upper limit on Ge, for example, falls far below the scaled solar system $r$-process curve. Recent analyses of this element indicates its abundance is tied to the iron level in metal-poor halo stars (Cowan et al. 2005), and thus suggests Ge synthesis in some type of charged-particle reactions, or other primary process, in massive stars and supernovae in the early Galaxy (see discussion in Cowan & Sneden 2006). We also note that the abundances of the $n$-capture elements from Z = 40–50 in CS 22892-052, in general, fall below the solar $r$-process curve. This has been interpreted as suggesting perhaps a second $r$-process synthesis site in nature (see discussion in Kratz et al. 2006 and Cowan & Sneden 2006). Interestingly, new abundances studies of the star HD 221170 show better agreement with the scaled solar system curve for the elements from Z = 40-50 than CS 22892-052 does (Ivans et al. 2006).

In spite of the good overall match between the scaled-solar $r$-process abundances and
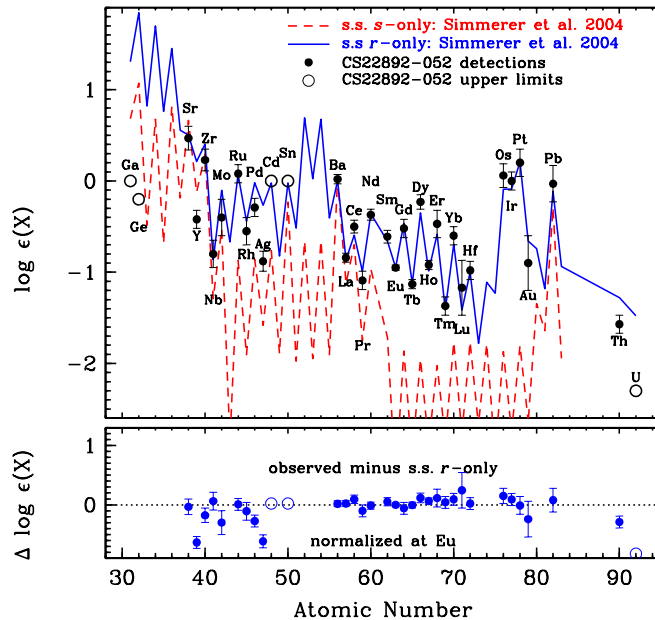
Fig. 2.— (top) Abundance values for CS 22892-052 compared to a scaled solar system *s*-process (dashed line) and *r*-process distribution (solid line, Simmerer et al. 2004). (bottom) Differences between observed abundances in CS 22892-052 and the scaled solar system r-process abundances (after Cowan & Sneden 2006).

those of very metal-poor stars, some small deviations are becoming apparent, as shown in Figures 1 and 2. The increasingly accurate stellar abundance determinations, resulting in large part from the more accurate laboratory atomic data, are helping to constrain, and ultimately could predict, the actual values of the solar system *r*-process abundances. Thus, the current differences might suggest that some of those solar system *r*-process elemental predictions need to be reassessed. Recall that the elemental *r*-process curve is based upon the isotopic *r*-process residuals, resulting from the subtraction of the *s*-process isotopic contributions from the total solar system abundances. Thus, a reanalysis of some of the *s*-process contributions, and new neutron-capture cross sections measurements, might be in order.

## 3.    Conclusions

Abundance observations of metal-poor (very old) Galactic halo stars indicate the presence of *n*-capture elements. New laboratory atomic data is dramatically reducing the stellar abundance uncertainties in these stars and increasingly improving the Solar System abun-

dances. Recently determined abundances, based upon the new laboratory data, indicate that the elemental patterns in the old halo stars are consistent with each other and with a scaled solar system $r$-process abundance distribution – demonstrating that all of these elements (even $s$-process ones like Ba) were synthesized in the $r$-process early in the history of the Galaxy. These more accurate abundance determinations, based upon more precise laboratory atomic data, might be employed to constrain predictions for the solar system $r$-process abundances. In the future additional (and improved) lab data will have implications for a number of synthesis studies, including providing evidence regarding the possibility of two astrophysical $r$-process sites. Such new experimental data will also help in understanding the Galactic chemical evolution of the elements, and could have an impact on chronometric age estimates of the Galaxy and the Universe. New stellar and atomic data in both the UV and IR wavelength regimes may also allow the detection of never before seen elements in these stars, and will aid in new determinations of isotopic abundance mixtures for elements such as Sm.

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Table 1.   *s*- AND *r*-PROCESS ISOTOPIC SOLAR SYSTEM ABUNDANCES

| Element | Z | Isotope | N[s] | N[r] | Element | Z | Isotope | N[s] | N[r] |
|---|---|---|---|---|---|---|---|---|---|
| Ga | 31 | 69 | 11.137 | 11.600 | Pd | 46 | 104 | 0.165 | 0.000 |
|  |  | 71 | 10.413 | 4.700 |  |  | 105 | 0.040 | 0.269 |
| Ge | 32 | 70 | 15.000 | 0.000 |  |  | 106 | 0.186 | 0.193 |
|  |  | 72 | 18.323 | 14.000 |  |  | 108 | 0.226 | 0.145 |
|  |  | 73 | 3.531 | 5.670 |  |  | 110 | 0.000 | 0.163 |
|  |  | 74 | 15.733 | 27.300 | Ag | 47 | 107 | 0.058 | 0.239 |
|  |  | 76 | 0.000 | 9.200 |  |  | 109 | 0.059 | 0.196 |
| As | 33 | 75 | 1.456 | 5.330 | Cd | 48 | 110 | 0.178 | 0.000 |
| Se | 34 | 76 | 4.656 | 0.000 |  |  | 111 | 0.042 | 0.165 |
|  |  | 77 | 1.679 | 3.040 |  |  | 112 | 0.198 | 0.196 |
|  |  | 78 | 7.402 | 7.210 |  |  | 113 | 0.060 | 0.139 |
|  |  | 80 | 7.446 | 24.300 |  |  | 114 | 0.287 | 0.140 |
|  |  | 82 | 0.000 | 5.710 |  |  | 116 | 0.000 | 0.121 |
| Br | 35 | 79 | 0.450 | 0.000 | In | 49 | 115 | 0.057 | 0.121 |
|  |  | 81 | 0.479 | 4.640 | Sn | 50 | 116 | 0.511 | 0.000 |
| Kr | 36 | 80 | 1.021 | 0.000 |  |  | 117 | 0.146 | 0.128 |
|  |  | 82 | 6.207 | 0.000 |  |  | 118 | 0.706 | 0.137 |
|  |  | 83 | 1.989 | 3.750 |  |  | 119 | 0.155 | 0.065 |
|  |  | 84 | 10.575 | 18.000 |  |  | 120 | 1.099 | 0.078 |
|  |  | 86 | 9.481 | 0.930 |  |  | 122 | 0.000 | 0.154 |
| Rb | 37 | 85 | 0.690 | 2.790 |  |  | 124 | 0.000 | 0.199 |
|  |  | 87 | 2.214 | 0.100 | Sb | 51 | 121 | 0.047 | 0.113 |
| Sr | 38 | 86 | 2.111 | 0.000 |  |  | 123 | 0.000 | 0.132 |
|  |  | 87 | 1.443 | 0.000 | Te | 52 | 122 | 0.133 | 0.000 |
|  |  | 88 | 16.986 | 2.550 |  |  | 123 | 0.047 | 0.000 |
| Y | 39 | 89 | 3.344 | 1.310 |  |  | 124 | 0.248 | 0.000 |
| Zr | 40 | 90 | 4.529 | 0.990 |  |  | 125 | 0.088 | 0.267 |
|  |  | 91 | 1.158 | 0.040 |  |  | 126 | 0.450 | 0.525 |
|  |  | 92 | 1.289 | 0.540 |  |  | 128 | 0.000 | 1.526 |
|  |  | 94 | 1.687 | 0.170 |  |  | 130 | 0.000 | 1.634 |
|  |  | 96 | 0.000 | 0.300 | I | 53 | 127 | 0.050 | 0.851 |
| Nb | 41 | 95 | 0.229 | 0.110 | Xe | 54 | 128 | 0.126 | 0.000 |
| Mo | 42 | 95 | 0.189 | 0.213 |  |  | 129 | 0.066 | 1.240 |
|  |  | 96 | 0.475 | 0.000 |  |  | 130 | 0.199 | 0.000 |
|  |  | 97 | 0.156 | 0.087 |  |  | 131 | 0.087 | 0.954 |
|  |  | 98 | 0.514 | 0.093 |  |  | 132 | 0.498 | 0.800 |
|  |  | 100 | 0.000 | 0.242 |  |  | 134 | 0.000 | 0.449 |
| Tc | 43 | 99 | 0.006 | 0.172 |  |  | 136 | 0.000 | 0.373 |
| Ru | 44 | 99 | 0.049 | 0.000 | Cs | 55 | 133 | 0.056 | 0.315 |
|  |  | 100 | 0.242 | 0.000 | Ba | 56 | 134 | 0.178 | 0.000 |
|  |  | 101 | 0.050 | 0.266 |  |  | 135 | 0.068 | 0.298 |
|  |  | 102 | 0.261 | 0.327 |  |  | 136 | 0.500 | 0.000 |
|  |  | 104 | 0.000 | 0.348 |  |  | 137 | 0.372 | 0.283 |
| Rh | 45 | 103 | 0.055 | 0.289 |  |  | 138 | 3.546 | 0.225 |
| La | 57 | 139 | 0.337 | 0.110 | Lu | 71 | 175 | 0.006 | 0.031 |
| Ce | 58 | 140 | 0.894 | 0.089 |  |  | 176 | 0.002 | 0.000 |
|  |  | 142 | 0.000 | 0.115 | Hf | 72 | 176 | 0.008 | 0.000 |
| Pr | 59 | 141 | 0.079 | 0.082 |  |  | 177 | 0.005 | 0.024 |
| Nd | 60 | 142 | 0.227 | 0.000 |  |  | 178 | 0.021 | 0.022 |
|  |  | 143 | 0.037 | 0.065 |  |  | 179 | 0.007 | 0.015 |
|  |  | 144 | 0.105 | 0.094 |  |  | 180 | 0.035 | 0.020 |
|  |  | 145 | 0.020 | 0.049 | Ta | 73 | 181 | 0.009 | 0.013 |

Table 1—Continued

| Element | Z | Isotope | N[s] | N[r] | Element | Z | Isotope | N[s] | N[r] |
|---------|----|---------|-------|-------|---------|----|---------|-------|-------|
|         |    | 146     | 0.091 | 0.053 | W       | 74 | 182     | 0.024 | 0.012 |
|         |    | 148     | 0.004 | 0.044 |         |    | 183     | 0.013 | 0.007 |
|         |    | 150     | 0.000 | 0.047 |         |    | 184     | 0.029 | 0.013 |
| Sm      | 62 | 147     | 0.003 | 0.031 |         |    | 186     | 0.006 | 0.031 |
|         |    | 148     | 0.038 | 0.000 | Re      | 75 | 185     | 0.004 | 0.014 |
|         |    | 149     | 0.005 | 0.031 |         |    | 187     | 0.001 | 0.033 |
|         |    | 150     | 0.022 | 0.000 | Os      | 76 | 186     | 0.012 | 0.000 |
|         |    | 152     | 0.018 | 0.053 |         |    | 187     | 0.006 | 0.000 |
|         |    | 154     | 0.000 | 0.059 |         |    | 188     | 0.016 | 0.079 |
| Eu      | 63 | 151     | 0.000 | 0.042 |         |    | 189     | 0.004 | 0.111 |
|         |    | 153     | 0.002 | 0.048 |         |    | 190     | 0.021 | 0.168 |
| Gd      | 64 | 152     | 0.001 | 0.000 |         |    | 192     | 0.001 | 0.293 |
|         |    | 154     | 0.009 | 0.000 | Ir      | 77 | 191     | 0.005 | 0.241 |
|         |    | 155     | 0.003 | 0.045 |         |    | 193     | 0.003 | 0.408 |
|         |    | 156     | 0.015 | 0.055 | Pt      | 78 | 192     | 0.010 | 0.000 |
|         |    | 157     | 0.007 | 0.046 |         |    | 194     | 0.020 | 0.431 |
|         |    | 158     | 0.027 | 0.058 |         |    | 195     | 0.006 | 0.457 |
|         |    | 160     | 0.000 | 0.072 |         |    | 196     | 0.035 | 0.312 |
| Tb      | 65 | 159     | 0.004 | 0.060 |         |    | 198     | 0.000 | 0.099 |
| Dy      | 66 | 160     | 0.009 | 0.000 | Au      | 79 | 197     | 0.010 | 0.176 |
|         |    | 161     | 0.004 | 0.075 | Hg      | 80 | 198     | 0.035 | 0.000 |
|         |    | 162     | 0.016 | 0.101 |         |    | 199     | 0.016 | 0.043 |
|         |    | 163     | 0.002 | 0.093 |         |    | 200     | 0.051 | 0.030 |
|         |    | 164     | 0.018 | 0.091 |         |    | 201     | 0.020 | 0.027 |
| Ho      | 67 | 165     | 0.006 | 0.083 |         |    | 202     | 0.079 | 0.026 |
| Er      | 68 | 164     | 0.004 | 0.000 |         |    | 204     | 0.000 | 0.020 |
|         |    | 166     | 0.012 | 0.072 | Tl      | 81 | 203     | 0.042 | 0.012 |
|         |    | 167     | 0.005 | 0.053 |         |    | 205     | 0.060 | 0.041 |
|         |    | 168     | 0.020 | 0.047 | Pb      | 82 | 204     | 0.057 | 0.000 |
|         |    | 170     | 0.001 | 0.037 |         |    | 206     | 0.326 | 0.223 |
| Tm      | 69 | 169     | 0.006 | 0.031 |         |    | 207     | 0.313 | 0.280 |
| Yb      | 70 | 170     | 0.006 | 0.000 |         |    | 208     | 1.587 | 0.118 |
|         |    | 171     | 0.004 | 0.029 | Bi      | 83 | 209     | 0.051 | 0.093 |
|         |    | 172     | 0.018 | 0.036 | Th      | 90 | 232     | 0.000 | 0.042 |
|         |    | 173     | 0.008 | 0.031 | U       | 92 | 235     | 0.000 | 0.006 |
|         |    | 174     | 0.040 | 0.037 |         |    | 238     | 0.000 | 0.020 |
|         |    | 176     | 0.000 | 0.030 |         |    |         |       |       |