MEASUREMENT OF THE EUROPium ISOTOpE RATIO FOR THE EXTREMELY METAL POOR, \( r \)-PROCESS–ENHANCED STAR CS 31082-001

Wako Aoki, Satoshi Honda, Timothy C. Beers, and Christopher Sneden

Received 2002 September 29; accepted 2002 November 22

ABSTRACT

We report the first measurement of the isotope fraction of europium (\(^{151}\)Eu and \(^{153}\)Eu) for the extremely metal poor, \( r \)-process–enhanced star CS 31082-001, based on high-resolution spectra obtained with the Subaru Telescope High Dispersion Spectrograph. We have also obtained new measurements of this ratio for two similar stars with previous europium isotope measurements, CS 22892-052 and HD 115444. The measurements were made using observations of the Eu lines in these spectra that are most significantly affected by isotope shifts and hyperfine splitting. The fractions of \(^{151}\)Eu derived for CS 31082-001, CS 22892-052, and HD 115444 are 0.44, 0.51, and 0.46, respectively, with uncertainties of about ±0.1. CS 31082-001, the first star with a meaningful measurement of U outside of the solar system, is known to exhibit peculiar abundance ratios between the actinide and rare earth elements (e.g., Th/Eu), ratios that are significantly different from those for other stars with large excesses of \( r \)-process elements, such as our two comparison objects. Nevertheless, our analysis indicates that the Eu isotope ratio of CS 31082-001 agrees, within the errors, with those of other \( r \)-process–enhanced objects and with that of solar system material.

Subject headings: Galaxy: abundances — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: individual (CS 31082-001) — stars: Population II

1. INTRODUCTION

The chemical composition of very metal poor ([Fe/H] \( \leq -2.5 \)) stars is expected to be determined by a small number of nucleosynthesis events that preceded the formation of these objects, while that of metal-rich stars like the Sun are the result of the accumulated stellar yields throughout the long history of the Galaxy. In recent years, abundance studies of heavy elements in very metal poor stars have provided quite important constraints on models of the astrophysical neutron-capture processes, both the slow process and the rapid-process. Discoveries of \( r \)-process element-enhanced, very metal poor stars, and their subsequent abundance analyses, have shown that the abundance pattern of neutron-capture elements with \( Z \geq 56 \) agrees very well with the \( r \)-process component abundances in solar system material (e.g., Sneden et al. 1996; Westin et al. 2000). These results suggest that the abundance pattern of the \( r \)-process component in the solar system for \( Z \geq 56 \) is not the result of a mixture of quite different abundance patterns produced by individual processes, but rather that the patterns produced by individual processes are quite similar throughout Galactic history.

By way of contrast, the abundances of light \( r \)-process elements (\( Z < 56 \)) of these objects are known to show a deviation from the \( r \)-process component in the solar system. For instance, Sneden et al. (2000) studied the abundances of neutron-capture elements, including six elements with 40 < Z < 56, of CS 22892-052 in detail and found a clear deviation from the scaled solar system \( r \)-process component, especially for Y, Rh, and Ag. They concluded that different \( r \)-process sites may be responsible for the formation of the lighter (40 < Z < 56) and heavier (Z \( \geq 56 \)) neutron-capture elements. A phenomenological model for these results was proposed by Wasserburg & Qian (2000).

In addition to the above studies of the total abundances of neutron-capture elements, analyses of isotope fractions for individual elements are also quite important for making detailed comparison with predictions from theoretical models for the \( r \)-process. Europium is one of the elements that have comparatively large isotope shifts between the spectral lines of individual components (\(^{151}\)Eu and \(^{153}\)Eu). Sneden et al. (2002) carried out an analysis of the Eu isotope fractions for three \( r \)-process element-enhanced metal-poor stars and showed that the fractions of \(^{151}\)Eu and \(^{153}\)Eu are 0.5, in agreement with that of solar system material. This demonstrates that, even at the isotopic level, there is agreement between the abundance pattern of \( r \)-process elements in very metal poor stars with the \( r \)-process component in the solar system.

On the other hand, the extremely \( r \)-process element-enhanced, very metal poor ([Fe/H] = −2.9) star CS 31082-001, first reported by Cayrel et al. (2001), exhibits a somewhat different abundance pattern, as compared with otherwise similar stars. The abundances of heavy (Z \( \geq 72 \)) neutron-capture elements in this star are higher than what would be predicted from the abundances of elements with 56 \( \leq Z \leq 70 \), when the scaled solar system \( r \)-process component pattern is extended to the third \( r \)-process peak (Hill et al. 2002). This suggests that the site and/or conditions under which \( r \)-process nucleosynthesis of (at least) the heavy neutron-capture elements occurs are not unique but have some star-to-star variation. The theoretical implications of CS 31082-001 have been considered in detail by Qian & Wasserburg (2001), Wanajo et al. (2002), and Schatz et al. (2002).
The agreement of the abundance pattern of CS 31082-001 with that of the solar system r-process component only appears to be valid in the range $56 \leq Z \leq 70$. One open question at this stage is whether the isotope ratios, such as $^{151}$Eu/$^{153}$Eu, agree with those of other r-process element-enhanced stars, as well as with that of the solar system material. 

In this paper, we report the isotope fractions of Eu derived for three stars, CS 31082-001, CS 22892-052, and HD 115444, based on high-resolution spectra obtained with the Subaru Telescope and the High Dispersion Spectrograph (HDS; Noguchi et al. 2002). The latter two objects have already been studied by Sneden et al. (2002), but for comparison purposes we have carried out an independent analysis using new spectra with higher resolution than were previously available.

### 2. OBSERVATIONS AND MEASUREMENTS

Observations were carried out with the HDS of the 8.2 m Subaru Telescope. The detector is a mosaic of two 4k $\times$ 2k EEV CCDs with 13.5 $\mu$m pixels. Besides CS 31082-001, we observed two other r-process element-enhanced, metal-poor stars, CS 22892-052 (Sneden et al. 1996) and HD 115444 (Westin et al. 2000). These two objects have already been studied by Sneden et al. (2002) and are quite useful for comparison purposes. Details of the observations are provided in Table 1. While the spectra of CS 22892-052 and HD 115444 were taken with a resolving power $R = 90,000$, CS 31082-001 was observed with somewhat lower resolution, $R = 60,000$, due to poor weather conditions. Nevertheless, this resolving power is still sufficient for the present analysis. The S/N ratios per 0.012 A $\times$ pixel at 4100 A are 110, 65, and 300 for CS 31082-001, CS 22892-052, and HD 115444, respectively. Data reduction was performed in the standard way within the IRAF environment, following procedures described by Aoki et al. (2002).

For future studies on the possible binarity of these objects, which will be investigated on the basis of observed radial velocity variations, Table 1 also provides (heliocentric) radial velocities measured for our spectra. The radial velocities were measured using clean Fe II lines. The radial velocity of CS 22892-052 obtained in our present work is $+13.2$ km s$^{-1}$ and shows no significant changes from the results of Preston & Sneden (2001), who suggested a small variation of the radial velocity (with a period of 120 days) for this object. CS 31082-001 was observed in 2001 July and October. The results of the two measurements agree very well, and no variation of the radial velocity was found with respect to the results of Hill et al. (2002). Although there is no clear evidence for binarity of these objects from the above measurements, further long-term monitoring of their velocities is required to obtain any definitive conclusions. We note that our abundance analysis for CS 31082-001 is based only on the 2001 October spectrum, because the quality of the data is superior to that obtained in 2001 July.

### 3. ANALYSIS OF EUROPium ISOTOpE RATIOS AND RESULTS

The Eu isotope ratios were measured by fitting the observed spectra of Eu lines with synthetic spectra calculated using model atmospheres (Kurucz 1993), including the effect of the isotope shifts. We adopted atmospheric parameters for our objects (effective temperature, $T_{eff}$; surface gravity, log $g$; microturbulent velocity, $v_{micro}$; and metallicity, as represented by the iron abundance, [Fe/H]) that are similar to those in previous work: $T_{eff}$ (K) / log $g$ / $v_{micro}$ (km s$^{-1}$) / [Fe/H] = 4800/1.5/1.8/−3.0 for CS 31082-001 (Cayrel et al. 2001), 4750/1.3/2.3/−3.0 for CS 22892-052 (Sneden et al. 1996), and 4650/1.5/2.1/−3.0 for HD 115444 (Westin et al. 2000). It is worth stressing that, in contrast to studies of elemental abundances, the analyses of isotope ratios are generally quite insensitive to the adopted atmospheric parameters.

The effects of isotope shifts and hyperfine splitting in Eu lines have been discussed by Lawler et al. (2001). The line list produced by Sneden et al. (2002), based on Lawler et al. (2001), was applied in the present work. Sneden et al. (2002) analyzed the Eu II lines at 3819, 3907, 4129, and 4205 A. Unfortunately, the 3907 A line was not covered in our CS 31082-001 spectrum because of the gap between the two CCDs of HDS. Instead, we analyzed the weaker Eu II line at 4435 A for CS 31082-001 and CS 22892-052. As shown in the following analysis, this line is actually quite useful for the measurement of the isotope ratios in these extremely Eu-enhanced stars, because the lines at 3819, 4129, and 4205 A are sufficiently strong so that they compromise the accuracy of the derived isotope fractions, as well as the total abundance. We note that the 4435 A line in HD 115444 is too weak; hence, it was not used in the analysis of this object. The Eu II 4522 A line has an appropriate strength for isotopic and abundance analyses but was not used because of severe blending with other elemental lines.

The instrumental profile of HDS, for spectra with resolving power higher than $R \sim 90,000$, can be well approximated by a Gaussian shape, but this does not pertain to spectra obtained with lower resolving powers (Noguchi et al. 2002). Accordingly, we have employed Gaussian profiles

### Table 1: Program Stars and Observations

| Star          | Wavelength Range (Å) | Exposure$^a$ | Observation (JD) | Radial Velocity (km s$^{-1}$) |
|---------------|----------------------|-------------|-----------------|--------------------------------|
| CS 31082-001  | 3080–3900, 3960–4780 | 200 (5)     | 2001 Oct 26 (2,452,208.9) | $+13.92 \pm 0.28$ |
|               | 3540–4350, 4440–5250 | 20 (1)      | 2001 Jul 30 (2,452,121.1) | $+13.91 \pm 0.30$ |
| CS 22892-052  | 3540–4350, 4440–5250 | 120 (3)     | 2001 Jul 23 (2,452,114.0) | $+13.16 \pm 0.36$ |
| HD 115444     | 3540–4350, 4440–5250 | 30 (2)      | 2000 Jul 5 (2,451,730.8)  | $-27.12 \pm 0.34$ |
|               | 3080–3900, 3960–4780 | 30 (2)      | 2001 16 Apr (2,452,016.0) | $-27.11 \pm 0.28$ |

$^a$ Total exposure time (minutes) and number of exposures.
for the instrumental line broadening for calculation of the synthetic spectra of CS 22892-052 and HD 115444, which were observed with $R = 90,000$. For the analysis of CS 31082-001, which was observed with $R = 60,000$, we measured the instrumental profile from the Th emission lines obtained for the wavelength calibration and applied the resulting profile to the spectrum synthesis calculations.

The macroturbulence for the individual stellar atmospheres was estimated by fitting clean Fe i lines with synthetic spectra for each object, assuming Gaussian profiles. This approximation should be valid, since the axial rotation of these (very old) red giants is expected to be quite small.

In order to estimate the quality of the fit between observed and synthetic spectra, we calculated the values of reduced $\chi^2$, defined as

$$\chi^2 = \frac{1}{\nu - 1} \sum_i (O_i - C_i)^2 / \sigma_i^2,$$

where $(O_i - C_i)$ is the difference between the observed and synthetic spectra at the $i$th spectrum point (e.g., Smith et al. 2001). The quantity $\sigma_i$ is defined as $\sigma_i = [S/N \times (f_i)^{1/2}]^{-1}$, where $S/N$ is the signal-to-noise ratio of the continuum level and $f_i$ indicates the normalized flux at the $i$th point ($0 \leq f_i \leq 1$ for absorption profiles). In the above equation, $\nu$ is the number of degrees of freedom in the fit and is approximately the number of data points to which the fit is applied (20–30 pixels). Then $\chi^2$ is represented as

$$\chi^2 \sim \left( \frac{(O_i - C_i)^2}{\sigma_i^2} \right).$$

By dividing $O - C$ by $\sigma$, the dependence of the data quality on the depth of the absorption is accounted for. In this definition, $\chi^2$ is expected to be unity in the best-fit case for data of a given $S/N$ because the $\chi^2$ value, taking the $S/N$ ratio at the line into consideration, cancels out the line-to-line and object-to-object differences in data quality. In the following presentation, however, we show the result for a fixed value of $S/N$ in order to compare directly the goodness of the fit between individual lines. We fix the $S/N$ to be 100, which roughly represents the $S/N$ ratio of the CS 31082-001 spectrum.

We show examples of the observed and synthetic spectra in Figures 1 and 2 for the Eu ii 4129 and 4435 Å lines, respectively. We first assumed the fraction of $^{151}$Eu to be 0.5 and derived the total Eu abundance for each line. Then we fitted the synthetic spectra to the observed ones for the longer wavelength (redder) part of the spectral line, which is insensitive to the assumed isotope ratio, by shifting the observed spectra. The shifts we applied are smaller than 0.01 Å. These are reasonable, as the uncertainties of the wavelength calibration of the spectra and the absolute wavelength of the Eu lines are likely to be in error at this level. We then calculated the $\chi^2$ for the red portion of the line to determine the wavelength shifts. We estimated the uncertainties of the wavelength determination by taking a value where $\chi^2$ is twice larger than the best-fit case.

We next proceeded to the determination of the Eu isotope fractions, as well as the total Eu abundances. We searched for the isotope fractions that resulted in the smallest $\chi^2$ for a given Eu abundance. This analysis was carried out by changing the Eu abundance in steps of 0.01 dex and adopting the Eu abundances and isotope fractions that gave the best $\chi^2$. We estimated the uncertainty of the derived Eu abundances by considering the range in abundance over which the $\chi^2$ is twice as large as the best-fit case. The errors in the isotope fractions due to the uncertainty of the total abundance of Eu were estimated from the range of the isotope fractions that were allowed within the adopted abundance uncertainty. As an example of this procedure, Figure 3 shows the values of $\chi^2$, as a function of $^{151}$Eu/$^{153}$Eu, for the Eu ii 4129 Å line.

Table 2 lists the derived isotope fractions and the Eu abundances determined by the above analysis for each line. The $\chi^2$ value and the fitting error ($\sigma_{\text{fit}}$) are also given. The fitting errors given here were simply estimated as being those obtained when the $\chi^2$ was assumed to be twice larger than the best-fit case at the adopted Eu abundance. We also
estimated the errors due to the uncertainties of the adopted Eu abundance, the macroturbulent velocity, the continuum level, and the wavelength calibration of the spectrum and the position of the Eu line (see below). The total error ($\sigma_{\text{total}}$) was estimated by adding, in quadrature, these errors to $\sigma_{\text{fit}}$ and is also given in Table 2.

### Table 2

| Star               | Line (Å) | fr(151Eu) | log(e(Eu)) | $\chi^2$ | $\sigma_{\text{fit}}$ | $\sigma_{\text{total}}$ |
|--------------------|----------|-----------|------------|----------|----------------------|-------------------------|
| HD 115444 ..........| 3819     | 0.42      | –1.87      | 0.59     | 0.07                 | 0.11                    |
|                    | 4129     | 0.48      | –1.80      | 0.49     | 0.09                 | 0.12                    |
|                    | 4205     | 0.49      | –1.76      | 0.10     | 0.04                 | 0.08                    |
| CS 22892-052 ...... | 4129     | 0.50      | –1.01      | 0.19     | 0.11                 | 0.15                    |
|                    | 4205     | 0.47      | –0.95      | 1.50     | 0.07                 | 0.09                    |
|                    | 4435     | 0.57      | –0.90      | 3.07     | 0.12                 | 0.13                    |
| CS 31082-001 ...... | 4129     | 0.43      | –0.62      | 2.22     | 0.06                 | 0.10                    |
|                    | 4205     | 0.36      | –0.62      | 2.50     | 0.05                 | 0.09                    |
|                    | 4435     | 0.52      | –0.62      | 2.51     | 0.10                 | 0.11                    |

was estimated by adding, in quadrature, these errors to $\sigma_{\text{fit}}$ and is also given in Table 2.

### 3.1. HD 115444

The values of $\chi^2$ obtained from the fits of the three Eu lines in HD 115444 are much smaller than those obtained for the other two stars, as expected from the considerably higher S/N ratio of the spectrum of this object. The small values of $\chi^2$, and the agreement of the $^{151}\text{Eu}$ fractions derived from the three lines considered, indicate that the Eu isotope fraction derived for HD 115444 is quite reliable. The average of the $^{151}\text{Eu}$ fraction from the three lines is $\text{fr}(^{151}\text{Eu}) = 0.46$.

We estimated the errors in our derived isotope fractions due to uncertainties in (1) macroturbulent velocity ($\Delta v_{\text{macro}}$), (2) wavelength calibration and line position ($\Delta \lambda$), (3) continuum level of the spectrum ($\Delta (\text{cont})$), and (4) Eu abundance adopted [$\Delta \log e(Eu)$]. The uncertainty of the Eu abundance, as well as the wavelength calibration (or absolute line position), have been estimated as noted above and are $\Delta \log e(Eu) = 0.02$ dex and $\Delta \lambda = 0.002$ Å, respectively. We assumed uncertainties for the macroturbulent velocity and the continuum level to be $\Delta v_{\text{macro}} = 1$ km s$^{-1}$ and $\Delta (\text{cont}) = 1\%$, respectively, for this star. These assumptions are probably conservative for a spectrum with S/N = 200 ~ 300. The errors due to these uncertainties are $\Delta \text{fr}(^{151}\text{Eu}) = -0.07$, $-0.03$, and $-0.02$ for $\Delta v_{\text{macro}} = +1.0$ km s$^{-1}$, $\Delta \lambda = +0.002$ Å, and $\Delta (\text{cont}) = +0.01$, respectively. The sense of the change in the derived $^{151}\text{Eu}$ fraction with respect to the change of the total Eu abundance is dependent on the line under consideration. The uncertainties in fr($^{151}\text{Eu}$) are about 0.02 for $\Delta \log e(Eu) = \pm 0.02$ dex.

### 3.2. CS 22892-052

A similar analysis was applied to the spectrum of CS 22892-052. The lower S/N of the spectrum of this object, as compared with that of HD 115444, results in the larger values of $\chi^2$ and the larger fitting errors. In addition, there is a difficulty in the analysis of the Eu $\pi 4435$ Å line. This line is quite strong—the central part of the absorption line is almost saturated. As a result, although the line depth is insensitive to the increase of the total Eu abundance, the line width increases along with the Eu abundance because of the growth of weak components in the bluer part of the line to which weak $^{151}\text{Eu}$ lines primarily contribute. This behavior is similar to that for the increase of the fraction of $^{151}\text{Eu}$ for a given Eu abundance. As a result, the effects of the changes

![Fig. 2.—Same as Fig. 1, but for the Eu $\pi 4435$ Å line](image)

![Fig. 3.—Reduced $\chi^2$ as a function of the fraction of $^{151}\text{Eu}$ determined by the 4129 Å line. The asterisks, open circles, and filled circles indicate the derived results for HD 115444, CS 22892-052, and CS 31082-001, respectively. The values of HD 115444 and of CS 22892-052 are multiplied by 2 and $\frac{1}{2}$, respectively, for clarity.](image)
of the total Eu abundance and the fraction of $^{151}$Eu are degenerate. We attempted to estimate the uncertainty of the $^{151}$Eu due to that of the Eu abundance by the same manner as other lines and found quite large uncertainties: $\Delta f(r^{151}\text{Eu}) = 0.15$ and $\Delta \log(\text{Eu}) = 0.10$ dex. For this reason, we decided to exclude this line for determination of the isotope ratio and adopted the average of the values determined from the other three lines, $f(r^{151}\text{Eu}) = 0.51$, as the final result. We note that the uncertainty of the derived $^{151}$Eu fraction due to the uncertainty in the total Eu abundance obtained from the Eu ν 4129 A line is rather large (0.09). This is partly due to the strength of this line, as in the case of the 3819 A line, but the poor quality of the fit to this line also contributes. The uncertainties arising from other factors are small ($\leq 0.04$), even though a larger error in the continuum determination [$\Delta(\text{cont}) = 0.02$] was assumed for this object, taking the low S/N ratio of the spectrum into consideration.

3.3. CS 31082-001

The Eu ν lines in the spectrum of CS 31082-001 are even stronger than those in the spectrum of CS 22892-052 because of the larger excesses of the r-process elements, which are boosted by about 0.4 dex relative to this star (Hill et al. 2002). We excluded the 3819 A line from the analysis for this star, as we did in the analysis of CS 22892-052. The other two lines, at 4129 and 4205 A, are also quite strong. The uncertainties of $f(r^{151}\text{Eu})$ due to that of the total Eu abundance are 0.07; the most important factors in the total errors. In this sense, the isotope ratio derived from the Eu ν 4435 A line is the most reliable, because the line strength is appropriate for the analysis of the total abundance and isotope fractions, even though the fitting error for this line is larger than for other lines. The uncertainties arising from other factors are minor.

4. DISCUSSION AND CONCLUDING REMARKS

Figure 4 shows the results for our derived $^{151}$Eu fractions based on each line considered; the error bars indicate the uncertainty ($\sigma_{\text{total}}$). The average of the results from individual lines are 0.46, 0.51, and 0.44 for HD 115444, CS 22892-052, and CS 31082-001, respectively. The calculation, weighted by $\sigma^{-1}$, alters the results by less than 0.01. The results for HD 115444 and CS 22892-052 show excellent agreement with those by Sneden et al. (2002), who derived $f(r^{151}\text{Eu}) = 0.5 \pm 0.1$ for these objects.

The dotted line in Figure 4 indicates the $^{151}$Eu fraction in solar system material [$f(r^{151}\text{Eu}) = 0.478$; Anders & Grevesse 1989]. Since 95% of the Eu in solar system material is expected to originate from the r-process (Arlandini et al. 1999), this ratio well represents that of the r-process component in the solar system. The $^{151}$Eu fractions in our three objects, including CS 31082-001, are consistent with the solar system value.

One clear difference between the abundance pattern of CS 22892-052 and that of CS 31082-001 is the abundance ratios between the actinide and the rare earth elements produced by r-process nucleosynthesis (e.g., the Th/Eu ratio; Hill et al. 2002). This difference is speculated to arise from the variety in the ratios of the neutron-to-seed nuclei in the r-process site that contributed to the abundances of heavy elements in these objects. Theoretical studies of r-process nucleosynthesis have shown that the neutron to seed-nuclei ratio is strongly dependent on the entropy-per-baryon ratio and the electron fraction ($Y_e$) in the nucleosynthesis site, as well as on the dynamic timescale of the event (e.g., Hoffman, Woosley, & Qian 1997; Otsuki et al. 2000; Wanajo et al. 2002). These quantities are, however, quite difficult to estimate from theoretical studies; hence, numerical simulations of the r-process often treat them as free parameters.

In contrast to the above, the abundance ratios of the nuclei produced by the r-process surrounding Eu are expected to be insensitive to these parameters, because the nucleosynthesis paths in this mass range (i.e., $A \sim 150$) are quite similar in the r-process models that predict the production of actinide nuclei, even though the abundances of the actinides show a significantly large dispersion (e.g., Otsuki, Mathews, & Kajino 2002; Wanajo et al. 2002). This prediction is supported by the similarity in the abundance patterns of the elements with $56 \leq Z \leq 70$ found in extremely metal poor stars, as mentioned in § 1. The result of the present study, that similar $^{151}$Eu/$^{152}$Eu ratios are found even in the r-process element-enhanced, extremely metal poor stars with quite different Th/Eu ratios, is naturally explained by the above theoretical expectation. In conclusion, our analysis of the isotope shifts appearing in a few Eu absorption lines shows that the Eu isotope fractions in very metal poor, r-process–enhanced stars exhibit the value expected from standard nucleosynthesis models and that they are independent of the global abundance patterns from light to heavy r-process elements.

---

7 Although the $^{151}$Eu fraction of the s-process component has not been constrained by observations, Arlandini et al. (1999) predicted it to be 0.54, similar to that of the r-process component (0.47), based on their stellar model. For this reason, the contribution of the s-process nucleosynthesis is not estimated from the Eu isotopes. However, it should be negligible in the very metal poor stars studied here, particularly for Eu.
Analyses of isotope fractions for other neutron-capture elements will provide quite strong constraints on modeling of the \( r \)-process nucleosynthesis. Ba and Pb are known to show rather large isotope shifts in their absorption lines. Although the analysis for these isotopes will prove more difficult than that of Eu, their isotope ratios should be sensitive to related nuclear reactions. Eu isotopes, which are (by comparison) rather easily measured from high-resolution spectra of suitable quality, are not sensitive to these processes. We would like to note, however, that small differences might be expected if detailed nucleosynthesis processes are included. For instance, processes that occur after freezeout of the neutron-capture elements are expected to affect the fine structure of the abundance patterns of individual nuclei (e.g., Qian et al. 1997). These effects will appear more clearly through examination of abundances at the isotopic level, although they are likely to be smoothed out at the elemental level. The typical error in modern determinations of elemental abundances is \( 0.1-0.2 \) dex (\( \sim 25\%-50\% \)). It thus follows that, unavoidably, some dispersion (\( \lesssim 25\% \)) may exist even in the derived abundance patterns of the neutron-capture elements with \( 56 \leq Z \leq 70 \) in \( r \)-process element-enhanced, metal-poor stars. We stress that derived isotope ratios of \( r \)-process elements, such as Eu, are almost completely free from these uncertainties, even though they are more difficult to determine and higher quality spectra are required. The difference in the mean \(^{151}\)Eu fractions between the stars CS 22892-052 and CS 31082-001 is \( \Delta f\left(^{151}\right)\text{Eu} = 0.07 \), smaller than the uncertainty of the analysis for individual lines. However, the fact that the derived \(^{151}\)Eu fractions obtained from the three Eu lines used in the analysis of CS 31082-001 are all lower than those obtained for CS 22892-052 may perhaps indicate a small difference of the \(^{151}\)Eu fractions between the two stars. Further observational study of the Eu isotopes, based on higher quality spectra, for these, and other \( r \)-process–enhanced, extremely metal poor stars, is strongly desired.

W. A. and S. H. are grateful for valuable discussions with T. Kajino, K. Otsuki, S. Wanajo, K. Sumiyoshi, and M. Terasawa on the modeling of \( r \)-process nucleosynthesis and interpretation of our observational results. T. C. B. acknowledges partial support of this work from grants AST 00-98508 and AST 00-98549, awarded by the US National Science Foundation.

REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Aoki, W., et al. 2002, PASJ, 54, 427
Arlandini, C., Käppeler, F., Wisshak, K., Gallino, R., Lugaro, M., Busso, M., & Straniero, O. 1999, ApJ, 525, 886
Cavrel, R., et al. 2001, Nature, 409, 691
Hill, V., et al. 2002, A&A, 387, 560
Hoffman, R. D., Woosley, S. E., & Qian, Y.-Z. 1997, ApJ, 482, 951
Kurucz, R. L., 1993, CD-ROM 13, ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid (Cambridge: SAO)
Lawler, J. E., Wickliffe, M. E., Den Hartog, E. A., & Sneden, C. 2001, ApJ, 563, 1075
Noguchi, K., et al. 2002, PASJ, 54, 855
Otsuki, K., Mathews, G. J., & Kajino, T. 2002, ApJ, submitted
Otsuki, K., Tagishi, H., Kajino, T., & Wanajo, S. 2000, ApJ, 533, 424
Preston, G. W., & Sneden, C. 2001, AJ, 122, 1545
Qian, Y.-Z., Haxton, W. C., Langanke, K., & Vogel, P. 1997, Phys. Rev. C, 55, 1532
Qian, Y.-Z., & Wasserburg, G. J. 2001, ApJ, 552, L55
Schatz, H., Toonen, R., Pfeiffer, B., Beers, T. C., Cowan, J. J., Hill, V., & Kratz, K.-L. 2002, ApJ, 579, 626
Smith, V. V., Vargas-Ferro, O., Lambert, D. L., & Olgin, J. G. 2001, AJ, 121, 453
Sneden, C., Cowan, J. J., Ivans, I. I., Fuller, G. M., Burles, S., Beers, T. C., & Lawler, J. E. 2000, ApJ, 533, L139
Sneden, C., Cowan, J. J., Lawler, J. E., Burles, S., Beers, T. C., & Fuller, G. M. 2002, ApJ, 566, L25
Sneden, C., McWilliam, A., Preston, G. W., Cowan, J. J., Burris, D., & Armcosky, B. J. 1996, ApJ, 467, 819
Wanajo, S., Itoh, N., Ishimaru, Y., Nozawa, S., & Beers, T. C. 2002, ApJ, 577, 853
Wasserburg, G. J., & Qian, Y.-Z. 2000, ApJ, 529, L21
Westin, J., Sneden, C., Gustafsson, B., & Cowan, J. J. 2000, ApJ, 530, 783