THE ODD-ISOTOPE FRACTIONS OF BARIUM IN THE STRONGLY R-PROCESS ENHANCED (R-II) STARS∗

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ABSTRACT

We determined the \(f_{\text{odd,Ba}}\) values, 0.46 ± 0.08, 0.51 ± 0.09, 0.50 ± 0.13, 0.48 ± 0.12, which correspond to the r-contribution 100% for four r-II stars, CS 29491-069, HE 1219-0312, HE 2327-5642 and HE 2252-4225, respectively. Our results suggest that almost all of the heavy elements (in the range from Ba to Pb) in r-II stars have a common origin, that is, from a single r-process (the main r-process). We found that the \(f_{\text{odd,Ba}}\) has a intrinsic nature, and should keep constant value of about 0.46 in the main r-process yields, which is responsible for the heavy element enhancement of r-II stars and of our Galaxy chemical enhancement. In addition, except the abundance ratio [Ba/Eu] the \(f_{\text{odd,Ba}}\) is also an important indicator, which can be used to study the relative contributions of the r- and s-process during the chemical evolution history of the Milky Way and the enhancement mechanism in stars with peculiar abundance of heavy elements.

Keywords: stars: abundances — nuclear reactions, nucleosynthesis, abundances — catalogs — stars: Population II

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1. INTRODUCTION

The neutron-capture process produced almost all of the heavy elements ($Z > 30$) in our universe, which was divided into the slow (s-) and rapid (r-) process, respectively (Burbidge et al. 1957). The s-process produces about 82% of solar barium and 6% of solar europium, and the rest are produced by the r-process (Arlandini et al. 1999). Thus, barium is usually regarded as the representative element for the s-process, and europium for the r-process. The s-process occurs in low- to intermediate-mass ($1 - 8 M_{\odot}$) stars during their asymptotic giant branch phase with quietly helium-shell burning (Busso et al. 1999).

Up to now, our knowledge about the r-processes is still poor. The r-process is thought to be associated with explosive conditions such as type-II supernova (a review see Thielemann et al. 2002) and neutron star mergers (Wanajo et al. 2014; Goriely et al. 2015, and a review see Thielemann et al. 2017), while it needs to be further identified. Furthermore, the r-process yields are still not be well estimated with the current models for r-processes. The current solar r-process abundances were obtained by subtract the s-process abundances from the total solar abundances (Arlandini et al. 1999), which is also referred as r-residuals. Beers & Christlieb (2005) defined stars with $[\text{Eu}/\text{Fe}] > 1.0$ and $[\text{Ba}/\text{Eu}] < 0$ as the r-II stars, and more than ten r-II stars have been found to date (see Cui et al. 2013, and references therein), since Sneden et al. (1994) reported the first one, CS 22892-052, with $[\text{Eu}/\text{Fe}] = 1.6$ and $[\text{Ba}/\text{Eu}] = -0.7$. Obviously, study of the r-II stars can greatly improve our knowledge on the r-process especially early in the Milky Way.

In fact, almost all of the r-II stars found up to now show well consistence between their heavier element abundances ($Z \geq 56$) and the scaled solar pure r-process abundances (see Sneden et al. 2008; Cowan et al. 2011, and references therein), while their light neutron-capture elements ($37 \leq Z \leq 47$, i.e., from Rb to Ag) are more deficient than the solar r-process ones (Cowan & Sneden 2006). This implies that different sites and different r-processes are responsible for the solar pure r-process abundances of heavier and lighter neutron-capture elements, respectively. Thus, the main r-process (i.e., the classical r-process) was suggested to mainly explain the solar r-process abundances of heavier neutron-capture elements (Ryan et al. 1996; Sneden et al. 2008), and the “lighter element primary process” (LEPP) (Travaglio et al. 2004) or weak r-process (Ishimaru et al. 2005) was suggested to mainly produce the lighter neutron-capture elements. The good agreements between the heavier element abundances and the scaled solar pure r-process indicate that the solar r-process pattern of heavier elements is robust and universal through large metallicity range in the Galaxy.

Different isotopic abundance mixtures of a neutron-capture element are produced by the r- and the s-processes. For instance, Eu and Ba have two and five stable isotopes, i.e., $^{151}\text{Eu}$, $^{153}\text{Eu}$, and $^{134}\text{Ba}$, $^{136}\text{Ba}$, $^{137}\text{Ba}$, $^{138}\text{Ba}$, respectively. Arlandini et al. (1999) predicted that $f^r_{151} (= N(^{151}\text{Eu})/N(\text{Eu}))$ is about the same value 0.47 in the r-process component of the solar Eu abundance ($f^r_{151}$ hereafter) with their “stellar” and “classical” models, and about 0.54 and 0.59 in the s-process component of the solar Eu abundance ($f^s_{151}$ hereafter), respectively. For Ba, the “stellar” model gave $f^r_{\text{odd,Ba}} \approx 0.46$ and 0.11 in the r- and s-process components of the solar Ba abundance, while the “classical” model gave $f^r_{\text{odd,Ba}} \approx 1.0$ and 0.09, respectively. Obviously, large difference arise from the $f_{\text{odd,Ba}}$ in the r-components of the solar Ba abundance predicted by the “stellar” and “classical” models, respectively. Eu isotopic fractions, $f^r_{151}$, in several r-II stars have been reported by Sneden et al. (2002) for CS 22892-052 (0.5 ± 0.1), HD 115444 (0.5 ± 0.1), BD +17°3248 (0.5 ± 0.1), and Aoki et al. (2003) for CS 31082-001 (0.44 ± 0.1), CS 22892-052 (0.51 ± 0.1), HD 115444 (0.46 ± 0.1). Considering the small interval between the values of $f^r_{151}$ and $f^r_{151}$, about 0.07 dex (“stellar model”) or 0.12 dex (“classical model”), and the relative large errors of $f_{151}$ measured from r-II stars, the $f_{151}$ maybe only used to marginally distinguish the r- and s-process contributions to these stars (also see Figure 13 of Sneden et al. 2008).

Comparing to Eu, the large interval ($\sim 0.35$ dex) between the values of $f^r_{\text{odd,Ba}}$ and $f^s_{\text{odd,Ba}}$ may support to get reliable conclusions. The Ba isotope fraction was first reported by Magain & Zhao (1993) to study the r-process contribution to the Ba abundance in the metal-poor ([Fe/H] = −2.4) subgiant HD 140283, their result is subsequently examined by a series of works (Magain 1995; Collet et al. 2009; Lambert & Allende Prieto 2002; Gallagher et al. 2010, 2012, 2015). However, contrary conclusions have been obtained with different $f_{\text{odd,Ba}}$ values determined by the above works. The main reasons are the low barium abundance, $[\text{Ba}/\text{Fe}] = -0.87$ (also weak Ba lines) in HD 140283. In addition, we note that the non-local thermodynamical equilibrium (NLTE hereafter) would probably lead to the unreasonably large difference of Ba abundances. Therefore, the different conclusions are due to different NLTE effects. For Ba, we therefore use $f^r_{\text{odd,Ba}}$ only to distinguish the Ba contribution.

Note that $f^r_{\text{odd,Ba}} = [N(^{135}\text{Ba}) + N(^{137}\text{Ba})]/N(\text{Ba})$, where r represents $f_{\text{odd,Ba}}$ in the r-process component of the solar Ba abundance, s represents $f_{\text{odd,Ba}}$ in the s-process component of the solar Ba abundance.
effects have not been considered during analyses of Ba isotope fractions in the above works, which may also lead to some uncertainties on this issue. Furthermore, Mashonkina et al. (1999); Short & Hauschildt (2006) have confirmed that the profile of the BaII resonance line λ4554 (used to measure f_{odd,Ba}) suffers strong NLTE effects for metal-poor stars. Mashonkina & Zhao (2006) have determined the Ba odd-isotope fractions for 25 disk stars, and found that the thick disk stars show larger f_{odd,Ba} values than these of the thin disk stars, and their f_{odd,Ba} values decrease with increasing metallicities. Ba isotope fractions in r-II stars were first reported by Meng et al. (2016), who found that the f_{odd,Ba} values in CS 31082-001 is consistent with the solar pure r-process component.

In order to give an unambiguous verdict on the origin of heavy elements in r-II stars and giving critical constraint on theoretical models for the r-process, on the isotopic level, it should also be important to determine the isotopic fractions of other heavy elements especially Ba (surrogate of the s-process) except Eu for a large samples of r-II stars. In this paper, we report the Ba odd-isotope fractions for four stars with strongly r-process enhancement, CS 29491-069, HE 1219-0312, HE 2327-5642 and HE 2252-4225, and this is also the first report on isotopic fractions of their heavy elements. The paper is structured as follows. After presenting the observational data in Sect. 2, we describe model atmospheres and stellar parameters determination in Sect. 3, and the results are showed in Sect. 4. The origin of heavy elements for r-II stars is analyzed in Sect. 5, and the characters of f_{odd,Ba} in r-II stars are described in Sect. 6, while our conclusions are presented in Sect. 7.

2. OBSERVATIONS AND DATA REDUCTION

For convenience, we list astrometry and photometry informations of the four r-II stars CS29491-069, HE 1219-0312, HE 2327-5642 and HE 2252-4225 in Table 1. The photometry result was taken from Beers et al. (2007). All the high resolution, high signal-to-noise spectra of these stars were observed with the VLT spectrograph UVES. CS 29491-069 and HE 1219-0312 were observed with resolutions of ~ 60 000 and ~ 70 000 in 2004 and 2005 by Hayek et al. (2009), respectively. The observations of CS 29491-069 and HE 1219-0312 were spanned ~ 1.5 and ~ 14 months, in which the total integration times are 1 h and 15 h for the spectra including the BaII resonance line at 4554 Å, while 1 h and 16 h of exposures for the region with BaII lines at 5853 and 6496 Å, respectively (detailed see Hayek et al. 2009, in their Table 2). The S/N of the final combined spectra are 70 and 50 around 4554 Å, 110 and 111 around 5853 and 6496 Å for CS 29491-069 and HE 1219-0312, respectively.

High-quality spectra of HE 2327-5642 and HE 2252-4225 were obtained during May-November 2005 with R ∼ 60 000 and R ∼ 50 000, respectively. For HE 2327-5642, the total integration time are 10 h and 4 h for the spectra at 4554 Å and 5853 Å, 6496 Å, respectively. The S/N of the resulting spectra are larger than 50 around 4554 Å, and 100 around 5853, 6496 Å, respectively (detailed see Mashonkina et al. 2010, in their Table 2). For HE 2252-4225, the total integration time are 10 h and 9 h for the spectra at 4554 Å and 5853 Å, 6496 Å, respectively. The S/N of the resulting spectra are larger than 70 around 4554 Å, and 60 around 5853 and 6496 Å, respectively (detailed see Mashonkina et al. 2014, in their Table 2). The raw data of the above four r-II stars were downloaded from the European Southern Observatory (ESO) archive.

The spectra were reduced with an IDL software package, which was designed originally for the FOCES spectrograph (Pfeiffer et al. 1998), and has been modified to work for UVES spectrograph. Cosmic rays and bad pixels were removed by careful comparisons of different exposures from the same objects. The instrumental response and background scatter light were also considered during the data reducing. It is worth noting that we have not found the proper lamp exposures with the same settings for the red region taken by the CD#3 equipped on the red arm of the UVES spectrograph for almost all of the sample stars except HE 2252-4225, while we have found them for the blue region for CS 29491-069, HE 1219-0312, and HE 2252-4225 except HE 2327-5642. Thus, the pipeline-reduced spectra have been adopted for the red spectra region (> 500 nm) for CS 29491-069, HE 1219-0312, and HE 2327-5642, which also was adopted for the blue region (< 500 nm) for HE 2327-5642.

3. MODEL ATMOSPHERES AND STELLAR PARAMETERS

We redetermined the stellar parameters of the four r-II sample stars in this work in order to reduce the uncertainties of the final results, although they can be found in literatures (Hayek et al. 2009; Mashonkina et al. 2010, 2014). The opacity sampling (OS) model atmosphere MAFAGS-OS9 was adopted in the following analysis processes of the stellar parameters, the Ba abundance and the Ba isotopic fraction. This model was developed by Grupp (2004) and updated by Grupp et al. (2009), which is based on one-dimensional plane-parallel

2 http://archive.eso.org/cms.html
(LTE) model. In the new version, the new iron atomic data computed by Kurucz (2009) was incorporated.

We derived the stellar parameters of the four r-II stars via the spectroscopic approach, namely, the effective temperature $T_{\text{eff}}$ was determined by requiring the equilibrium between the excitation and iron abundance from FeI lines, and the surface gravity $\log g$ was derived from the ionization equilibrium of FeI and FeII. The microturbulence velocity $V_{\text{mic}}$ was estimated by requiring [Fe/H] derived from the FeI lines to be independent of their equivalent widths, and the equivalent widths are listed in Table 3. An iterative procedure was adopted to measure stellar parameters, where the initial parameters were taken from the latest literatures, e.g., Hayek et al. (2009) for CS 29491-069 and HE 1219-0312, Mashonkina et al. (2010) for HE 2327-5642 and Mashonkina et al. (2014) for HE 2252-4225. The initial effective temperatures were all derived by fitting the Balmer-line profiles of both H$\alpha$ and H$\beta$ using the manually rectified spectra, while the initial surface gravities were determined through the ionization equilibrium of FeI and FeII. There are 21 FeI and 5 FeII lines included in our analysis, which were listed in Table 3 with their atomic parameters and the references of the adopted $g$-$f$-values. The van der Waals broadening of the iron lines is accounted for using the most accurate data available as provided by Anstee & O’Mara (1995); Barklem & O’Mara (1997); Barklem et al. (1998, 2000); Barklem & Aspelund-Johansson (2005). The final stellar parameters are given in Table 2. During this process, the NLTE line formation for FeI and FeII have been considered, where the iron model atom was adopted from Mashonkina et al. (2011). Based on multiple iterative processes, the typical uncertainties of $T_{\text{eff}}$, log $g$, [Fe/H] and $V_{\text{mic}}$ are estimated to be $\pm 80$ K, $\pm 0.20$ dex, $\pm 0.08$ dex and $\pm 0.1$ km s$^{-1}$, respectively.

For comparing, the stellar parameters for the sample stars from the literature are also presented in Table 2. There are good consistence between our stellar parameters and those from literatures, except the effective temperature $T_{\text{eff}}$ for CS 29491-069. The newly determined $T_{\text{eff}}$ value is 5200 K, which is 100 K lower than that derived by Hayek et al. (2009). However, considering the uncertainties of $T_{\text{eff}}$ for CS 29491-069 $\pm 80$ K estimated by this work, and $\pm 100$ K by Hayek et al. (2009), our $T_{\text{eff}}$ is still consistent with that from Hayek et al. (2009) in some degree. The good consistence between the stellar parameters determined by this work and those from literatures (Hayek et al. 2009; Mashonkina et al. 2010, 2014) may be mainly due to the considering of NLTE effects for FeI and FeII lines in their determining processes.

4. RESULTS
4.1. Methods

Ba has five stable isotopes, i.e., $^{134}$Ba, $^{135}$Ba, $^{136}$Ba, $^{137}$Ba, $^{138}$Ba, where $^{134}$Ba and $^{136}$Ba, are s-only nucleus due to the shielding by $^{134}$Xe and $^{136}$Xe on the r-process path, the others are produced by both the r- and s-process nucleosynthesis. Therefore, the Ba odd-isotope fractions can help us to estimate the r- and s-process contributions to the heavy elements in a star, e.g., larger $f_{\text{odd,Ba}}$ values corresponding to larger r-process contributions.

In order to study the nature of the neutron-capture processes in r-II stars, following the approach adopted by Mashonkina & Zhao (2006) and Meng et al. (2016) we determined the fractions of the odd Ba isotopes $f_{\text{odd,Ba}}$ for CS 29491-069, HE 1219-0312 HE 2252-4225 and HE 2327-5642. This method is firstly to derive the stellar total Ba abundances from lines insensitive to HFS or isotope shifts, and two subordinate lines of BaII at 5853 and 6496 Å were adopted here. The average Ba abundances derived from the above two lines were adopted as the final total Ba results. Subsequently, the $f_{\text{odd,Ba}}$ values was determined through fitting the line profile of the BaII resonance line at 4554 Å. This line is sensitive to the Ba odd-isotope fractions. During this process, the stellar total Ba abundance was fixed, and the $f_{\text{odd,Ba}}$ values changed freely.

| Quantity | CS 29491 − 069 | HE 1219-0312 | HE 2327-5642 | HE 2252-4225 |
|----------|----------------|--------------|--------------|--------------|
| RA (2000.0) | 22:31:02.1 | 12:21:34.1 | 23:30:37.2 | 22:54:58.6 |
| dec (2000.0) | -32:38:36 | -03:28:40 | -56:26:14 | -42:09:19 |
| $V$ [mag] | 13.075 ± 0.002 | 15.940 ± 0.007 | 13.881 ± 0.003 | 14.878 ± 0.003 |
| $B − V$ | 0.600 ± 0.004 | 0.641 ± 0.027 | 0.709 ± 0.005 | 0.822 ± 0.005 |
| $V − R$ | 0.421 ± 0.003 | 0.455 ± 0.011 | 0.456 ± 0.004 | 0.499 ± 0.005 |
| $V − I$ | 0.900 ± 0.004 | 0.897 ± 0.009 | 0.933 ± 0.005 | 1.023 ± 0.006 |
Table 2. Comparison of stellar parameters with other studies

| Name          | $T_{\text{eff}}$ (K) | $\log g$ (dex) | $[\text{Fe/H}]$ | $V_{\text{mic}}$ (km s$^{-1}$) | References$^a$ |
|---------------|-----------------------|----------------|------------------|---------------------------|----------------|
| CS 29491-069  | 5200                  | 2.80           | $-2.58$          | 1.8                       | This work      |
|               | 5300                  | 2.80           | $-2.51$          | $-1.6$                    | HAY09          |
| HE 1219-0312  | 5060                  | 2.30           | $-2.94$          | 1.7                       | This work      |
|               | 5060                  | 2.30           | $-2.96$          | 1.6                       | HAY09          |
| HE 2327-5642  | 5000                  | 2.34           | $-2.87$          | 1.6                       | This work      |
|               | 5050                  | 2.34           | $-2.78$          | 1.8                       | MAS10          |
| HE 2252-4225  | 4750                  | 1.65           | $-2.67$          | 1.7                       | This work      |
|               | 4710                  | 1.65           | $-2.63$          | 1.7                       | MAS14          |

$^a$ HAY09: Hayek et al. (2009), MAS10: Mashonkina et al. (2010), MAS14: Mashonkina et al. (2014).

until the best fitting result obtained, and simultaneously the final $f_{\text{odd,Ba}}$ value was obtained. In this work, the adopted Ba atomic model is same as that adopted by Mashonkina et al. (1999) and Mashonkina & Zhao (2006). The IDL/Fortran SIU software package of Reetz (1991) was used to compute the synthetic line profiles.

Table 3. Line data for Fe I and Fe II lines used to determine the stellar parameters, and equivalent widths of neutral iron lines for sample stars (EW$_1$: CS 29491-069, EW$_2$: HE 1219-0312, EW$_3$: HE 2327-5642, EW$_4$: HE 2252-4225)$^a$.

| $\lambda$(Å) | $\chi_{\text{ex}}$(eV) | $\log gf$  | $\log C_6$ | EW$_1$ | EW$_2$ | EW$_3$ | EW$_4$ | Reference |
|-------------|-------------------|------------|-------------|--------|--------|--------|--------|-----------|
| Fe I        |                   |            |             |        |        |        |        |           |
| 4427.310    | 0.05              | -2.92      | -31.86      | 80.3   | 67.7   | 83.0   | 105.1  | OB91      |
| 4920.505    | 2.83              | 0.07       | -30.51      | 70.8   | 51.4   | 59.0   | 84.4   | OB91      |
| 4994.129    | 0.91              | -2.96      | -31.71      | 33.2   | 24.9   | 29.0   | 60.8   | BA91      |
| 5166.282    | 0.00              | -4.20      | -31.93      | 35.6   | 24.1   | 30.3   | 65.8   | BL79      |
| 5198.717    | 2.22              | -2.14      | -31.32      | 13.8   | ...    | 11.6   | ...    | BL82a     |
| 5216.274    | 1.61              | -2.15      | -31.52      | 42.7   | 29.8   | 33.5   | ...    | FU88      |
| 5232.940    | 2.94              | -0.06      | -30.54      | 59.4   | 48.5   | 54.1   | ...    | OB91      |
| 5247.056    | 0.09              | -4.95      | -31.92      | ...    | ...    | ...    | 14.5    | BL79      |
| 5281.791    | 3.04              | -0.83      | -30.53      | ...    | 17.1   | ...    | ...    | OB91      |
| 5324.180    | 3.21              | -0.10      | -30.42      | 43.3   | 27.7   | 33.5   | 55.1   | BA91      |
| 5367.470    | 4.41              | 0.44       | -30.20      | 14.2   | ...    | ...    | ...    | OB91      |
| 5383.369    | 4.31              | 0.64       | -30.37      | 22.9   | 19.2   | ...    | ...    | OB91      |
| 5393.173    | 3.24              | -0.72      | -30.42      | 20.2   | 12.6   | ...    | ...    | BA91      |
| 5434.530    | 1.01              | -2.12      | -31.74      | 77.9   | 64.8   | 77.8   | 105.5  | FU88      |
| 5586.760    | 3.37              | -0.10      | -30.38      | 34.7   | 22.9   | 24.6   | 48.0   | BA91      |
| 6065.490    | 2.61              | -1.53      | -31.41      | 20.4   | ...    | 11.7   | 26.5   | BL82b     |

Table 3 continued
The reduced $\chi^2$, $\chi^2_r$\(^3\) was computed to find the best fit to the observed spectra from a set of synthetic ones. Same as that in Meng et al. (2016), there are three free parameters: the wavelength shift, a continuum level shift to match the synthetic continuum, and macroturbulence when determining the $f_{\text{std}, \text{Ba}}$ values, which are required to make the comparison between the synthetic and observed spectra. A careful renormalisation for the observed spectra was done first to fix the continuum level over a window of each Ba II resonance line at 4554 Å. In our fitting, the line profiles of $\lambda$4554 Å include 22, 25, 23, and 27 pixels for CS 29491-069, HE 1219-0312, HE 2327-5642 and HE 2252-4225, respectively. Thus the minimum value is expected for $\chi^2_r$ to get the best fit results. Smith et al. (1998) had pointed out that any non-Gaussian extended wings of the instrumental profile are weak, which could be ignored during the line-profile fitting. The instrumental broadening was thus determined from a Th-Ar lamp spectrum by a Gaussian fit, which was observed with the same instrumentation setup when the object exposures. The rotation broadening is also involved in our synthetic profiles. Smith et al. (1998) had shown that $v \sin i$ is less than 3 km s\(^{-1}\) for old stars, where $v$ is the surface equatorial rotational velocity. In this work, we adopted $v \sin i = 1.5$ km s\(^{-1}\) as the projected rotational velocity for our sample stars.

4.2. Stellar Total Ba Abundances
For the sample r-II stars, Ba abundances were obtained through fitting the line profiles of Ba II $\lambda\lambda$5853 and 6496, respectively. The NLTE effects were also considered. Table 4 shows the line data of Ba II lines $\lambda\lambda$5853, 6496 and 4554, respectively. The equivalent widths and Ba abundance from individual line for our sample stars were also presented in Table 4. The final Ba abundances were provided in Table 5, and the LTE Ba abundances were also included for comparing.

From Table 5, we can see that for most of sample stars our NLTE Ba abundances are slightly higher than the LTE ones from literatures except HE 2252-4225, which is lower than its LTE abundance about 0.13 dex. This can be naturally explained by the NLTE effects on different kind of Ba II lines.
Figure 1. Left panel (from up to down): the best statistical fit synthetic profile obtained with $f_{\text{odd}, \text{Ba}} = 0.46, 0.51, 0.50, 0.48$ and NLTE line shapes for the observed (filled circles) Ba II resonance line of $\lambda 4554$ in CS 29491-069, HE 1219-0312, HE 2327-5642 and HE 2252-4225, respectively. The residual plots are shown below of each subfigure, respectively. For comparison, the lines with $f_{\text{odd}, \text{Ba}} = 0.30 (0.46 - 2\sigma)$, 0.33 (0.51 - 2$\sigma$), 0.37 (0.50 - $\sigma$), 0.36 (0.48 - $\sigma$) and the corresponding residuals have been plotted (dash-dot line) in each subfigures. The value for $V_{\text{mac}}$ has been optimised to one that minimises $\chi^2$, and the value for [Ba/Fe] remains the same for each star. Right panel (from up to down): we show the $\chi^2$ fit for the $\lambda 4554$ line, every star shows where the minimum of the fit lies. The vertical dotted lines indicate the solar $f_{\text{odd,Ba}}^0$ (left) and $f_{\text{odd,Ba}}'$ (right) calculated from Arlandini et al. (1999), respectively.
Table 4. Line data, equivalent widths (EW, unit: mÅ), and NLTE barium abundances of individual Ba II lines for the sample stars.

| $\lambda$ (Å) | $\chi_{exc}$ (eV) | log $gf$ | EW [Ba/Fe] | EW [Ba/Fe] | EW [Ba/Fe] | EW [Ba/Fe] |
|---------------|-----------------|---------|------------|------------|------------|------------|
|               |                 |         | CS 29491-069 | HE 1219-0312 | HE 2327-5642 | HE 2252-4225 |
| 5853.668      | 0.604           | -1.000  | 20.7       | 0.27       | 37.9       | 0.74       | 25.1       | 0.37       | 44.9       | 0.17       |
| 6496.897      | 0.604           | -0.377  | 58.1       | 0.25       | 75.8       | 0.69       | 62.1       | 0.31       | 91.4       | 0.14       |
| 4554.029      | 0.000           | 0.170   | 124.1      | –          | 136.9      | –          | 127.2      | –          | 151.8      | –          |

Table 5. NLTE Ba abundances and Ba odd-isotope fractions for the sample stars, respectively.

| Name           | [Ba/Fe]$^L$ | [Ba/Fe] | $\sigma$(total) | $f_{odd,Ba}$ | $\Delta$ |
|----------------|------------|---------|-----------------|---------------|----------|
| CS 29491-069   | 0.24       | 0.26    | 0.13            | 0.46          | 0.08     |
| HE 1219-0312   | 0.65       | 0.72    | 0.10            | 0.51          | 0.09     |
| HE 2327-5642   | 0.31       | 0.34    | 0.05            | 0.50          | 0.13     |
| HE 2252-4225   | 0.29       | 0.16    | 0.08            | 0.48          | 0.12     |

$L$ LTE abundance
used the subordinate Ba II lines of \( \lambda 5853, \lambda 6141 \) and \( \lambda 6496 \) determining the LTE Ba abundance for HE 2252-4225. Although the subordinate lines are almost free of HFS effects, it is found that large negative NLTE abundance corrections for these lines, \( \Delta \text{NLTE} = -0.02, -0.17 \) and \(-0.23 \text{dex} \), respectively. In fact, our NLTE Ba abundance \( [\text{Ba}/\text{Fe}] = 0.16 \pm 0.08 \) is consistent with the NLTE result \( [\text{Ba}/\text{Fe}] = 0.14 \pm 0.04 \) obtained by Mashonkina et al. (2014). The NLTE effects on the resonance Ba II line of \( \lambda 4554 \) is strong, resulting a positive NLTE abundance correction, \( \Delta \text{NLTE} = +0.2 \) (Asplund 2005). For CS 29491-069, HE 1219-0312 and HE 2327-5642, both the resonance Ba II line of \( \lambda 4554 \) and the subordinate lines such as Ba II \( \lambda 5853, \lambda 6496 \) etc. were used to determine their LTE Ba abundances by Hayek et al. (2009); Mashonkina et al. (2010). NLTE largely reduced the difference in LTE abundances between different Ba II lines, resulting the slightly higher Ba abundances for CS 29491-069, HE 1219-0312 and HE 2327-5642.

4.3. Ba Odd-Isotope Fractions

The \( f_{\text{odd,Ba}} \) values for CS 29491-069, HE 1219-0312, HE 2327-5642, and HE 2252-4225 were derived through fitting the profiles of Ba II resonance line \( \lambda 4554 \), and listed in Table 5. The Ba atomic model from Mashonkina et al. (1999) were adopted, and the hyperfine structure components of Ba II 4554 can be found in Mashonkina & Zhao (2006). Figure 1 shows the determination processes for these stars, and our calculations of the synthetic profile are based on the NLTE line formations for the Ba II resonance line of \( \lambda 4554 \).

Following Meng et al. (2016), the macroturbulence values were still allowed to be free during the analysis processes. Our synthetic spectra were convolved with the profile broadening by macroturbulence \( V_{\text{mac}} \), the instrumental profile \( \Gamma \) and the rotational velocity \( v \sin i \). The projected rotational velocity \( v \sin i = 1.5 \text{ km s}^{-1} \) was adopted for all sample stars. Through a Gaussian fit to the Th-Ar lamp spectrum, we obtained the instrumental broadening values, \( \Gamma = 3.1, 3.0, 3.6 \text{ km s}^{-1} \) for CS 29491-069, HE 1219-0312, HE 2252-4225 except HE 2327-5642, as no proper lamp spectrum found for HE 2327-5642. Then the macroturbulence values of the Ba II line at 4554 Å were found to be \( V_{\text{mac}} = 2.5, 2.2, 4.5 \text{ km s}^{-1} \) for CS 29491-069, HE 1219-0312, and HE 2252-4225, respectively. As these three parameters, \( V_{\text{mac}}, \Gamma \) and \( v \sin i \) are convolved together when calculating the synthetic spectra using the SIU software, we can not determine the \( V_{\text{mac}} \) value for HE 2327-5642 due to no proper lamp spectra obtained. For HE 2327-5642, we obtain a Gaussian value \( 4.2 \text{ km s}^{-1} \) (i.e., \( \sqrt{V_{\text{mac}}^2 + \Gamma^2} \)). Finally, the \( \chi^2 \) fits also require small wavelength shift, \( \Delta \lambda = -8, 12, -17, \) and \(-9 \text{ mÅ} \), respectively. Figure 1 shows the best statistical fit to the \( \lambda 4554 \) line and residual (synthetic – observed profile) in the left panel from up to down for CS 29491-069, HE 1219-0312, HE 2327-5642, and HE 2252-4225, respectively. The synthetic profiles for Ba II line of \( \lambda 4554 \) with \( 2\sigma \) for CS 29491-069 and HE 1219-0312, or \( 1\sigma \) for HE 2327-5642 and HE 2252-4225 lower than their final \( f_{\text{odd,Ba}} \) value were also been presented for comparison. From the residual plots for the Ba II line of \( \lambda 4554 \), we can see that the fits of the synthetic lines with \( 2\sigma \) or \( 1\sigma \) deviation from their final \( f_{\text{odd,Ba}} \) values are poor.

In the right panel of Figure 1, we show the \( \chi^2 \) versus \( f_{\text{odd,Ba}} \). The \( \chi^2 \) minimum 0.272, 0.639, 0.736, and 0.151 can be respectively obtained at \( f_{\text{odd,Ba}} = 0.46, 0.51, 0.50, 0.48 \) for CS 29491-069, HE 1219-0312, HE 2327-5642, and HE 2252-4225, where the gradient of the \( \chi^2 \) curve is zero. We note that all of the four r-II stars are enhancement with Ba, \( [\text{Ba}/\text{Fe}] = 0.26, 0.72, 0.34, 0.16 \), and their Ba II resonance line of \( \lambda 4554 \) are strong enough, \( EW = 124.1, 136.9, 127.2, 151.8 \text{ mÅ} \) (see Table 4), to get reliable \( f_{\text{odd,Ba}} \) values.

4.4. Uncertainty of the Ba-odd-isotope Fraction

Random errors in \( f_{\text{odd,Ba}} \) are resulted from the errors in Ba abundance and the stellar parameters, i.e., \( T_{\text{eff}}, \log g \) and \( V_{\text{mic}} \), while the uncertainty of the Ba II \( \lambda 4554 \) atomic parameters, i.e., \( \log gf \) and \( C_6 \), causing their systematical errors. Following Meng et al. (2016), we estimated the total errors of \( f_{\text{odd,Ba}} \) values as \( \pm 0.08 \) for CS 29491-069, \( \pm 0.09 \) for HE 1219-0312, \( \pm 0.13 \) for HE 2327-5642, and \( \pm 0.12 \) for HE 2252-4225, respectively. Here, various sources of uncertainties influencing the derived \( f_{\text{odd,Ba}} \) values were included, which were listed in Table 6. Although we can not determine the \( V_{\text{mac}} \) value for HE 2327-5642 without proper lamp spectra obtained, a same uncertainty value \(-0.2 \) of the \( V_{\text{mac}} \) was adopted to compare with other sample stars when estimating its total errors in \( f_{\text{odd,Ba}} \).

5. ORIGIN OF HEAVY ELEMENTS FOR R-II STARS

The fraction of the odd Ba isotopes, \( f_{\text{odd,Ba}} \), in our sample stars versus a: \([\text{Eu}/\text{Fe}]\), b: \([\text{Ba}/\text{Fe}]\), c: \([\text{Ba}/\text{Eu}]\), and d: \([\text{Fe}/\text{H}]\) are shown in Figure 2. As comparison, the \( f_{\text{odd,Ba}} \) value of CS 31082-001 derived by Meng et al. (2016) was also included. In Figure 2a, the adopted LTE values of \([\text{Eu}/\text{Fe}]\) are \( 0.96 \pm 0.10 \) for CS 29491-069 (Hayek et al. 2009), \( 1.38 \pm 0.10 \) for HE 1219-0312 (Hayek et al. 2009), \( 0.98 \pm 0.11 \) for HE 2327-5642 (Mashonkina et al. 2010), and \( 0.81 \pm 0.08 \) for
Table 6. Effects on the values of $f_{\text{odd,Ba}}$ resulting from uncertainties of atomic data and stellar parameters.

| Input parameter | Input CS 29491 | HE 1219 | Input HE 2327 | Input HE 2252 |
|-----------------|----------------|---------|----------------|----------------|
| $\log C_6(5d - 6p)$ | +0.1 | -0.01 | +0.1 | +0.04 | +0.1 | -0.08 | +0.1 | -0.07 |
| $[\text{Fe/H}]$ | -0.08 | +0.03 | -0.08 | +0.06 | -0.08 | +0.06 | -0.08 | +0.01 |
| $T_{\text{eff}}$ | +80 | +0.05 | +80 | +0.02 | +80 | +0.04 | +80 | +0.02 |
| $\log g$ | -0.20 | -0.01 | -0.20 | -0.02 | -0.15 | -0.04 | -0.15 | +0.01 |
| $V_{\text{mic}}$ | -0.10 | +0.05 | -0.10 | -0.01 | -0.10 | +0.01 | -0.10 | -0.01 |
| log $g_f(4554)$ | -0.1 | +0.02 | -0.1 | +0.04 | -0.1 | +0.04 | -0.1 | +0.06 |
| log $C_6(4554)$ | +0.1 | +0.01 | +0.1 | -0.01 | +0.1 | +0.04 | +0.1 | -0.07 |
| $V_{\text{mac}}$ | -0.2 | +0.01 | -0.2 | -0.01 | -0.2 | +0.01 | -0.2 | +0.01 |
| $\Delta(\text{total})$ | ±0.08 | ±0.09 | ±0.13 | ±0.12 |

Figure 2. The fraction of the odd Ba isotopes, $f_{\text{odd,Ba}}$, versus a: $[\text{Eu/Fe}]$ (LTE), b: $[\text{Ba/Fe}]$ (NLTE), c: $[\text{Ba/Eu}]$, and d: $[\text{Fe/H}]$ (NLTE except CS 31082-001). Filled upsidedown triangle represents CS 29491-069, filled triangle for HE 1219-0312, filled square for HE 2252-4225, and filled circle for HE 2327-5642, respectively. The $f_{\text{odd,Ba}}$ value of CS 31082-001 (asterisk) derived by Meng et al. (2016) was also presented out for comparing. Uncertainties are shown by short vertical lines. Dotted horizontal lines indicate the $f_{\text{odd,Ba}}$ values, 0.18 for the solar system, 0.46 for the pure r-process, and 0.11 for the pure s-process in the solar barium abundance predicted by Arlandini et al. (1999). The Eu abundance of CS 29491-069 and HE 1219-0312 adopted from Hayek et al. (2009), from Mashonkina et al. (2010) for HE 2327-5642, and from Mashonkina et al. (2014) for HE 2252-4225.
HE 2252-4225 (Mashonkina et al. 2014). In addition, Mashonkina et al. (2014) also provided a NLTE [Eu/Fe] 0.91 ± 0.09 for HE 2252-4225.

It is noted that the adopted [Eu/Fe] values for CS 29491-069, HE 2327-5642, and HE 2252-4225 are all slightly lower than 1.0 (one of the two criteria suggested for r-II stars by Beers & Christlieb 2005). Mashonkina et al. (2010) found a clear distinction in abundance ratios [Sr/Eu] between the r-II and r-I (0.3 ≤ [Eu/Fe] < 1.0 and [Ba/Eu] < 0, see Beers & Christlieb 2005) stars. The r-II stars show a low [Sr/Eu] value, that is, ~ −0.92 ± 0.13, however, the r-I stars have 0.36 dex higher [Sr/Eu] values, i.e., ~ −0.56 ± 0.13. Therefore, Mashonkina et al. (2010) proposed to use [Sr/Eu] < −0.8 as the third criterion to identify the r-II stars. The LTE values of [Sr/Eu] for our sample stars were calculated from literatures, which are −0.81 ± 0.21 for CS 29491-069, −1.03 ± 0.21 for HE 1219-0312 (Hayek et al. 2009), −1.13 ± 0.14 for HE 2327-5642 (Mashonkina et al. 2010), −0.94 ± 0.02 (LTE) and −1.0 ± 0.06 (NLTE) for HE 2252-4225 (Mashonkina et al. 2014). Thus, these stars should be divided into the r-II group. HE 1219-0312 and CS 31082-001 (Eu/Fe) = 1.63 ± 0.11 are usually regarded as the benchmark r-II stars (Mashonkina et al. 2014).

The r-II stars have very similar abundance patterns for the elements in the range from Ba to Pb, thus a common origin in the r-process for the heavy elements (56 ≤ Z ≤ 82) has been suggested for these stars (see Sneden et al. 2008; Cowan et al. 2011; Mashonkina et al. 2014). From Figure 2, we can see that all of the $f_{\text{odd,Ba}}$ values, 0.46 ± 0.08, 0.51 ± 0.09, 0.50 ± 0.13, 0.48 ± 0.12, 0.43 ± 0.09 for CS 29491-069, HE 1219-0312, HE 2327-5642, HE 2252-4225, and CS 31082-001, are consistent with the value 0.46 of $f_{\text{odd,Ba}}$ well within the error bars, which supports the “stellar model” predicted result of Arlandini et al. (1999). Using the formula, r-process(%) = ($f_{\text{odd,Ba}} - 0.11$)/0.0035 (see Gallagher et al. 2010; Meng et al. 2016), the r-process contributions can be calculated as 100 ± 22.9% for CS 29491-069, 114.3 ± 25.7% for HE 1219-0312, 111.4 ± 37.1% for HE 2327-5642, and 91.4 ± 25.7% for HE 2252-4225, respectively. As the value of the r-process contribution larger than 100% is not physical, we adopted 100% for both HE 1219-0312 and HE 2327-5642. The r-process contribution is 91.4 ± 25.7% for CS 31082-001 adopted from Meng et al. (2016). This indicates that the r-process produced almost all of the Ba element in these r-II stars. It is noted that the Ba element usually is regarded as the representative element of s-process, thus we can infer that almost all of the heavy elements (at least beyond Ba and up to Pb) in these r-II stars are synthesized by a single nucleosynthesis process, that is, the main r-process. Based on the fact that all of $f_{\text{odd,Ba}}$ values for our five r-II sample stars are close to the solar pure r-process value 0.46, we can speculate that this may be also same for other r-II stars. It can be seen that the conclusion for the origin of neutron-capture elements obtained from their abundance pattern is also supported on the isotopic level.

6. CHARACTERS OF $f_{\text{odd,Ba}}$ IN R-II STARS

From Figure 2, we can see that the $f_{\text{odd,Ba}}$ values of the r-II stars are very good agreement with that of the solar pure r-process $f_{\text{odd,Ba}}$, although they suffer large scatters, about 0.9 dex and 1.0 dex, in the abundance ratios [Eu/Fe] (Figure 2a) and [Ba/Fe] (Figure 2b), respectively. This means that the main r-process responsible for the Eu and Ba abundance of the r-II stars has an intrinsic $f_{\text{odd,Ba}}$ value, about 0.46, which is very close to the mean value about 0.48 ± 0.01 of $f_{\text{odd,Ba}}$ in our r-II sample stars, and the environment for the main r-process is quite robust. In other words, the $f_{\text{odd,Ba}}$ value obtained from the solar abundance by residual method is reliable. This also indicates that the different enhancement level of Eu and Ba, including other relative heavy elements in the r-II stars may be due to the dilution effects.

Figure 2c shows that $f_{\text{odd,Ba}}$ versus [Ba/Eu] for r-II stars. From this figure, we can see that these r-II stars have a small scatter about 0.08 dex among $f_{\text{odd,Ba}}$ values, and the scatter of about 0.20 dex among [Ba/Eu] ratios, which even reach to about 0.30 dex in nine r-II stars collected by Mashonkina et al. (2010). Furthermore, the mean $f_{\text{odd,Ba}}$ value is 0.48 ± 0.01, which is almost equal to the solar pure r-process value 0.46. As Ba and Eu are the representative elements for the s- and r-process, respectively, the abundance ratio [Ba/Eu] is regarded as an important indicator to understand the relative importance of the r- and s-process, throughout the Galaxy history or in a star with peculiar abundances of neutron-capture elements well. For r-II stars, Mashonkina et al. (2010) gave a mean value of log(Ba/Eu) = 1.05 ± 0.10 calculated from nine r-II stars, which corresponds [Ba/Eu] = −0.61 ± 0.10. This value is about 0.1 dex larger than the solar pure r-process value log(Ba/Eu) = 0.93, which corresponds [Ba/Eu]$^{\odot}$ = −0.73 (Arlandini et al. 1999). This can be explained as that a small number of s-nuclei existed in the matter out of which the r-II stars formed (Mashonkina et al. 2010). For r-II stars, the mean $f_{\text{odd,Ba}}$ seems to show a better agreement with that of the solar pure r-process value $f_{\text{odd,Ba}}$, while the difference is slightly large between the mean abun-
dance ratio [Ba/Eu] and the solar pure r-process value [Ba/Eu]_s. This indicates that f_{odd,Ba} is also an important indicator to study the relative contributions of the r- and s-process, which can provide more detailed nucleosynthesis information on the isotopic level than [Ba/Eu] on the abundance level.

In addition, the r-contribution is 105.7 ± 2.9% calculated from the mean f_{odd,Ba} 0.48 ± 0.01 using the formula referred in Section 5. The physical value 100% for the r-contribution to r-II stars should be adopted, which means that almost all of their heavy elements from Ba to Pb were produced by the r-process. We plot f_{odd,Ba} versus [Fe/H] for r-II stars in Figure 2d, and found no trend of f_{odd,Ba} with the metallicity. This also supports that the f_{odd,Ba} value, i.e., 0.46, calculated from the solar r-residul is the typical value with great possibility for the r-process responsible for the production of heavy elements beyond Ba and up to Pb in r-II stars, and it is universal and stable throughout the whole Galaxy history.

7. CONCLUSIONS

In this work, we determined the f_{odd,Ba} values, 0.46 ± 0.08, 0.51 ± 0.09, 0.50 ± 0.13, 0.48 ± 0.12 for four r-II stars, CS 29491-069, HE 1219-0312, HE 2327-5642 and HE 2252-4225, based on the high resolution and high signal-to-noise spectra, which are downloaded from ESO archive. Using the formula, r-process(%) = (f_{odd,Ba} − 0.11)/0.0035, the r-contributions to these r-II stars are calculated as 100±22.9% for CS 29491-069, 114.3±25.7% for HE 1219-0312, 111.4±37.1% for HE 2327-5642, and 91.4±25.7% for HE 2252-4225, respectively. As the value of the r-contributions larger than 100% is not physical, we adopted 100% for both HE 1219-0312 and HE 2327-5642. We confirmed that almost all of the heavy elements (from Ba to Pb) in r-II stars have a common origin, that is, from a single r-process (the main r-process), and the r-process environment should be quite robust.

We found that the different enhancement level of Eu and Ba, including other relative heavy elements in the r-II stars should be mainly due to the dilution effects by the clouds before they formed, as their f_{odd,Ba} shows a intrinsic nature and has no trends with [Eu/Fe] and [Ba/Fe] ratios. In addition, we also found that the f_{odd,Ba} in r-II stars has no trends with the metallicity. Thus, we inferred that the f_{odd,Ba} value for the main r-process is stable and universal throughout the whole Galaxy history, which is about 0.46.

Our results suggest, except [Ba/Eu], f_{odd,Ba} is also an important indicator to study the relative importance of the r- and s-process during the chemical evolution history of the Milky Way or the enhancement mechanism of the abundance peculiar stars for neutron-capture elements. We found that comparing to [Ba/Eu], f_{odd,Ba} in r-II stars has smaller scatter about 0.08 dex with a mean f_{odd,Ba} of 0.48 ± 0.01, shows good agreement with the solar pure r-process value 0.46. In addition, the mean f_{odd,Ba} in r-II stars supports that the r-process contributed 100% of their heavy elements beyond Ba and up to Pb, which is slightly different with that only small contribution from the s-process for the s-nuclei deduced from their mean [Ba/Eu] (Mashonkina et al. 2010).

The isotopic fractions including f_{odd,Ba}, f_{151}, etc. are very important observational constraints for the theoretical calculations of the main r-process, which provides the opportunity to further and reliably identify the origin site from type II supernova or neutron star merger events. It would be very interesting to perform more such kind measurements in future to shed light on this issue.

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Software: SIU (Reetz 1991)

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