Is Germanium (Ge, Z=32) A Neutron-Capture Element?

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ABSTRACT

Historically, Ge has been considered as a neutron-capture element. In this case, the r-process abundance of Ge is derived through subtracting the s-process abundance from total abundance of the solar system. However, the Ge abundance of the metal-poor star HD 108317 is lower than that of the scaled “residual r-process abundance” in the solar system about 1.2 dex. In this work, based on the comparison between the Ge abundances of the metal-poor star and stellar yields, we find that the Ge abundances would not be produced as the primary-like yields in the massive stars and mainly come from the r-process. Based on the observed abundances of metal-poor stars, we derived the Ge abundances of the weak r-process and main r-process. The contributed percentages of neutron-capture process to Ge in the solar system are about 59%, which means that the contributed percentage of Ge “residual abundance” in solar system is about 41%. We find that the Ge “residual abundance” would be produced as the secondary-like yields in the massive stars. This implies that Ge element in the solar system is not only produced by the neutron-capture process.

Key words: nucleosynthesis, abundances - stars: abundances - stars: metal poor - element: germanium

1 INTRODUCTION

Investigation of astrophysical origins of the elements is an important task of modern astrophysics. The elements more heavier than iron-group elements are mainly produced by slow neutron-capture process (s-process) and rapid neutron-capture process (r-process) (Burbidge et al. 1957). The s-process contains two categories: the weak s-process and the main s-process. The weak s-process mainly produces the lighter neutron-capture elements (e.g., Sr) and occurs in massive stars (Lamb et al. 1977; Raiteri et al. 1991, 1993; The et al. 2000). The contribution of s-process to the heavier neutron-capture elements (e.g., Ba) is due to the main s-process. The low-mass and intermediate-mass AGB stars are usually considered to be the sites in which the main s-process occurs (Busso et al. 1999). By subtracting the s-process abundances from the solar system abundances, Arlandini et al. (1999) derived the r-process abundances, which are called as “residual r-process abundances”.

There are many evidences supporting that SNe II are the sites of the r-process nucleosynthesis (Cowan et al. 1991; Sneden et al. 2008). Because of the large overabundance of r-process element Eu ((Eu/Fe)~ −1.6), the two “main r-process stars” CS 22892-052 and CS 31082-001 arouse special attention: their abundance patterns of the heavier neutron-capture elements fitted the r-process pattern of solar system very closely (Cowan et al. 1999; Truran et al. 2002; Wanajo & Ishimaru 2004; Sneden et al. 2008). However, their lighter neutron-capture elements (i.e., from Rb to Ag) are too deficient to agree with the “residual r-process abundances” (Sneden et al. 2000; Hill et al. 2002). This implies that, for explaining the r-process abundances of the solar system, another process, referred to as the “lighter element primary process” (Travaglio et al. 2004) or “weak r-process” (Ishimaru et al. 2005), is required.

By comparison, the abundance patterns of weak r-process stars, HD 122563 and HD 88609, show excess of lighter neutron-capture elements and deficiency of heavier neutron-capture elements, which are obviously different from the patterns of the main r-process stars (Westin et al. 2000; Johnson 2002; Honda et al. 2007). Based on the abundance analyze of metal-poor stars, Montes et al. (2007) found that the weak r-process abundance pattern is uniform and unique. Kratz et al. (2007) have performed the r-process calculations. They found that the main r-process abundances can only be matched under the conditions of high neutron densities (23 < logn_n < 28). On the other hand, their calculations indicate that smaller neutron number densities (20 < logn_n < 22) could reproduce the weak r-process abundances. Recently, Li et al. (2013a) found that the abundances of neutron-capture elements in all metal-poor stars, including main r-process stars and weak r-process stars, contain the contributions of two r-processes.

The element germanium is in the transition between the iron group elements and neutron-capture elements. To date, the quan-
titative contributions of germanium (Ge, Z = 32) from various astrophysical scenarios are rarely known in the studied metal-poor stars. Traditionally, Ge (Z = 32) has been considered as one of the lightest neutron-capture elements (Sneden et al. 1998). It is thought to be produced through the s-process and r-process. Based on chemical evolution calculations, Travaglio et al. (2004) reported that about 12% of Ge abundance in the solar system is produced in the AGB stars. On the other hand, about 43% of the Ge abundance has been produced by the weak s-process via neutron captures through the \( ^{22}N(e,\alpha)^{25}Mg \) reaction in massive stars (Raiteri & Bussell 1993) and around 45% of the Ge abundance belongs to “residual r-process abundance” (Travaglio et al. 2004; Sneden et al. 2008). Note that the r-process abundances in solar system are derived through subtracting the s-process abundances from total abundances of solar system (Arlandini et al. 1999; Simmerer et al. 2004).

Adopting updated neutron-capture cross sections, Pignatari et al. (2010) presented new weak s-process calculations for a massive star with 25 M\(_{\odot}\) at solar metallicity. They found that Ge is the one of the most abundant s-elements in the He core and the C shell of the massive star and speculated that the weak s-process is responsible for about 80% of Ge abundance in the solar system. However, they point out that their calculated results cannot be regarded as the weak s-component of the solar system, because the results come from only one stellar model. They suggested that, for deriving the weak s-component, the contributions from massive stars with various masses must be considered. In this case, the averaged yields weighted by the initial mass function (IMF) should be more effective than the yields of individual massive star (e.g. Raiteri et al. 1993). Furthermore, based on the observed [Ge/Fe] ratios of the metal-poor stars, they estimated that the contribution from the primary-like yields produced in massive stars to the solar germanium is about 5%-8%. Recently, Frischknecht et al. (2012) reported that large variations in weak s-process yields could occur since the rotating of the metal-poor massive stars.

Based on the abundance analysis of neutron-capture elements for metal-poor stars, Cowan et al. (2005) found that the abundances of the third r-process peak elements correlate with the abundances of the r-process element Eu, implying a common origin or site for r-process nucleosynthesis of heavier (Z > 56) elements. On the other hand, the Ge abundances correlated with the Fe abundances well. They estimated that the observed relation is [Ge/H] = [Fe/H] − 0.79, which is lower than the ratio of the solar system about 0.8 dex. The abundance relation between Ge and Fe would mean that an explosive process or charged-particle process, rather than neutron-capture process, would be responsible for the production of Ge at low metallicities (Cowan et al. 2005). Recently, Roederer (2012c) and Roederer & Lawler (2012b) analyzed the abundances of the metal-poor star HD 108317 and found that the abundances cannot be matched by the s-process pattern or by the scaled “residual r-process” pattern of the solar system. HD 108317 shows over-abundance of the heavier neutron-capture elements from Eu to Pt, but the discovery that Ge, which is one of the lightest neutron-capture element, is deficient is puzzling. The Ge abundance of HD 108317 is about 1.2 dex lower than that of scaled Ge “residual r-process abundance” in the solar system. They proposed that the elements heavier than Ge (i.e., As and Se) should be the point where the r-process turns on. Siqueira et al. (2013) point out that the observed Ge abundance in metal-poor stars should serve as the key conditions in constraining the r-process nucleosynthesis. Obviously, understanding of the astrophysical origins of Ge abundance in our Galaxy is a challenging task (Roederer & Lawler 2012c).

In this paper, based on the abundance approach for metal-poor stars presented by Li et al. (2013a), we calculate the relative contributions from the individual neutron-capture process to the abundances of metal-poor stars in which Ge abundances have been observed. In Section 2, we extract abundance clues of the weak r-process and main r-process for Ge from weak r-process star HD 122563 and main r-process star CS 31082-001. In Section 3, based on the observed abundances, we derived the abundances of weak r-process and main r-process for Ge element. The calculated results are discussed in Section 4 and Section 5. In Section 6, the astrophysical origin of “residual abundance” of Ge was investigated. Our conclusions are given in Section 7.

2 ABUNDANCE CLUES

The element germanium is in the transition between charged-particle synthesis of the iron-group elements and neutron-capture synthesis of heavier elements. There are 19 stars that have been observed for Ge abundance. The values of log\(_{10}(\text{Ge})\), log\(_{10}(\text{Fe})\) and log\(_{10}(\text{Eu})\) (Cowan et al. 2005; Roederer et al. 2012c; Roederer et al. 2012d; Siqueira et al. 2013; Westin et al. 2000) for the sample stars are listed in Table 1. The standard definitions of elemental abundances and abundance ratios are used throughout the paper. For element X, the abundance is defined as the logarithm of the number of atoms of element X per 10\(^{12}\) hydrogen atoms, log\(_{10}(X)=\log(N_X/N_H)+12.0\). The abundance ratio relative to the solar ratio of element X and element Y is defined as [X/Y]=log\(_{10}(N_X/N_Y)\). The ratios of [Ge/H], [Fe/H] and [Eu/H] have been rescaled to corresponding solar logarithm abundances of log\(_{10}(\text{Fe})=7.50\), log\(_{10}(\text{Eu})=0.54\) and log\(_{10}(\text{Ge})=3.62\) (Anders & Grevesse 1989). In this section, we wish to compare the observed Ge abundances of the metal-poor stars which are formed in the interstellar medium (ISM) with the yields of the massive stars to investigate the astrophysical origin of Ge. In this case, the averaged yields weighted by IMF should be more effective than the yields of individual massive star. The solid lines in Figure 1 (a) and (b) show the average yields of massive star with a mass range from 10 M\(_{\odot}\) to 100 M\(_{\odot}\) for zero metallicity (standard mixing of 0,1, explosion energy of 5.0 (×10\(^{51}\)ergs)) presented by Heger & Woosley (2010), which have been weighted by the Salpeter initial mass function (IMF) and scaled to the Fe abundances of the weak r-process star HD 122563 and main r-process star CS 31082-001, respectively. The observed elemental abundances of HD 122563 (Honda et al. 2007; Westin et al. 2000) and CS 31082-001 (Hill et al. 2002; Siqueira et al. 2013) marked by filled circles are also shown to facilitate comparison. The scaled IMF-weighted yields of massive stars with a mass range from 10 M\(_{\odot}\) to 50 M\(_{\odot}\) for zero metallicity presented by Kobayashi et al. (2006) (see their Table 3) are also plotted in Figure 1(a) and (b) by dashed lines. From the figure we can see that the scaled Ge abundances are lower than the Ge abundances of the weak r-process star HD 122563 ([Ge/Fe]=−0.9) and main r-process star CS 31082-001 ([Ge/Fe]=−0.63) about 1.0 dex and 1.3 dex respectively. Note that the ratio of [Ge/Fe]=−0.9 listed in Table 1 corresponds to that the scaled Ge abundance is lower than the observed Ge abundance about 1.0 dex. Because the observed ratios of [Ge/Fe] in the metal-poor stars ([Fe/H] isolated −1.8) lies in the range of −0.63 − −1.2 (Cowan et al. 2005), for the other metal-poor stars, the scaled Ge abundances produced in the massive stars are lower than the ob-
served Ge abundances about 0.7 dex at least. The compared results mean that the Ge abundances in the metal-poor stars would not be produced as the primary-like yields in the massive stars. Obviously, another process, which is responsible for the Ge abundances in the metal-poor stars, is needed. Because HD 122563 is a weak r-process star and CS 31082-001 is a main r-process star, their Ge abundances, similar to the abundances of other neutron-capture elements, should mainly come from the r-process.

3 WEAK R-PROCESS AND MAIN R-PROCESS ABRUNDANCES OF GE

Travaglio et al. (1999) have found that the main s-process contributions are significant starting from [Fe/H] = -1.5. On the other hand, for the weak s-process, little contribution is expected in halo stars (Travaglio et al. 2004), because of the strong decrease in its efficiency with decreasing metallicity. These results imply that the abundances of neutron-capture elements in the metal-poor stars dominantly come from the r-process. For exploring the origin of the Ge abundances in metal-poor stars quantitatively, we adopt the abundance approach presented by Li et al. (2013a). The abundance of the ith element can be calculated as:

\[ N_i(Z) = (C_{r,m}N_{i,r,m} + C_{r,w}N_{i,r,w}) \times 10^{[Fe/H]} \]  

where \( N_{i,r,m} \) is the abundance produced by the main r-process, and \( N_{i,r,w} \) is the abundance produced by the weak r-process, whereas \( C_{r,m} \) and \( C_{r,w} \) are the corresponding component coefficients.

For weak r-process star HD 122563, the r-process component coefficients are \( C_{r,m} = 0.26 \) and \( C_{r,w} = 4.07 \). The corresponding values of main r-process star CS 31082-001 are \( C_{r,m} = 52.04 \) and \( C_{r,w} = 3.89 \) (Li et al. 2013a). Based on the observed Ge abundances of HD 122563 (Westin et al. 2000) and CS 31082-001 (Siqueira et al. 2013), from equation (1), the values of \( N_{Ge,r,m} \) and \( N_{Ge,r,w} \) can be derived as:

\[ N_{Ge,r,m} = 0.38; \quad N_{Ge,r,w} = 3.87 \]  

Li et al. (2013) have used the “percentage of weak r-process” \( f_{r,w} \) (i.e., \( N_{r,w}/(N_{r,m} + N_{r,w}) \)) and the “percentage of main r-process” \( f_{r,m} \) (i.e., \( N_{r,m}/(N_{r,m} + N_{r,w}) \)) to calculate the relative contributions to r-process abundances in the solar system. They found that there are the linearity decrease trend in \( f_{r,w} \) from atomic number Z=30 to Z=63. Based on our calculation, “percentage of weak r-process” \( f_{r,w} = 0.91 \) for Ge, which is higher than “percentage of weak r-process” for Sr, Y and Zr (~0.7). Our calculated results are consistent with the decrease trend in the “percentage of weak r-process” \( f_{r,w} \). Further more, our result is also consistent with Ishimaru et al. (2005), who found that the contribution from weak r-process to the r-process abundances decreases with increasing atomic number.

In the early Galaxy, a part of iron group elements and light elements were produced in first generations of very massive stars. The corresponding abundance pattern was called as the prompt (P) component (Qian & Wasserburg 2001). Li et al. (2013a) derived the P-component from the low-[Sr/Fe] star BD-18 5550. Considering the contribution from P-component, the r-process component and P-component coefficients of weak r-process star HD 122563 are \( C_{r,m} = 0.26, \quad C_{r,w} = 3.63 \) and \( C_p = 0.16 \), respectively. The r-process component and P-component coefficients of main r-process star CS 31082-001 are \( C_{r,m} = 3.23, \quad C_{r,w} = 52.32 \) and \( C_p = 0.15 \) and the corresponding values of metal-poor star HD 115444 are \( C_{r,m} = 7.98, \quad C_{r,w} = 4.90 \) and \( C_p = 0.0 \) (Li et al. 2013a), respectively. Based on the observed Ge abundances of HD 122563 (Westin et al. 2000), CS 31082-001 (Siqueira et al. 2013) and HD 115444 (Cowan et al. 2005), from equation (4) presented by Li et al. (2013a), the values of \( N_{Ge,r,m}, N_{Ge,r,w}, N_{Ge,P} \) can be derived as: \( N_{Ge,r,m} = 0.296; \quad N_{Ge,r,w} = 4.29; \quad N_{Ge,P} < 0.0 \). As a test, using Ge abundance of another metal-poor star HD 221170 (Cowan et al. 2005) and its component coefficients (Li et al. 2013a) to replace those of HD 115444, we also derived \( N_{Ge,P} < 0.0 \). Our calculated results imply that the contributions from P-component to Ge abundance for the metal-poor stars could be negligible. Li et al. (2013a) have found that the contributions of the P-component to the light elements and iron group elements are observable only for the low-[Sr/Fe] star ([Sr/Fe] < -1.0). Because there is no low-[Sr/Fe] star in the sample stars, the contributions of P-component are not included in our calculation.

The main r-process abundance \( N_{Ge,r,m} \) and weak r-process abundance \( N_{Ge,r,w} \) are listed in Table 2. For comparison, the solar abundance \( N_{Ge, total} \) (Anders & Grevesse 1989), main s-process abundance \( N_{Ge,s,m} \) (Travaglio et al. 2004) and weak s-process abundance \( N_{Ge,s,w} \) (Raiteri & Bussel 1992) are listed in Table 2, respectively. It is important to note that the solar Ge abundance is higher than the sum of \( N_{Ge,r,m}, N_{Ge,r,w}, N_{Ge,s,m} \) and \( N_{Ge,s,w} \). Namely, there is “residual abundance” of Ge, which is listed in Table 2, between the abundance of solar system and the sum of contributions from all neutron-capture processes. The contributed percentages of main r-, weak r-, main s-, weak s- process and “residual abundance” of Ge to solar system are 0.32%, 3.25%, 12.0%, 43.0% and 41.43% respectively, which are also listed in Table 2. Note that the contributed percentage of Ge “residual abundance” to solar system is larger than 40% and the Ge “residual abundance” do not come from neutron-capture processes. (Anders & Grevesse 1989) reported that the nuclear statistical equilibrium (NSE) process should be responsible for the production of Ge partly. The astrophysical relation related to the Ge residual abundance will be investigated in Section 6. There is a fact that the Ge abundances of the metal-poor stars are lower than the scaled “residual r-process abundance” in the solar system (Roederer et al. 2012) about 1.0 dex. From Table 2 we can see that the contributed percentage of the sum of the r-process for Ge is only about 4%, which is smaller than that of the “residual r-process abundance” in the solar system about one order of magnitude. This should be the astrophysical reason that the Ge abundances of metal-poor stars are lower than that of the scaled “residual r-process abundance” in the solar system.

In order to investigate the origin of Ge, [Ge/H] as a function of metallicity is particularly useful (Cowan et al. 2005; Siqueira et al. 2013). The variation of the logarithmic ratio [Ge/H] with metallicity is shown in Figure 2. The dashed line and solid line indicate the Ge abundance ratios of solar system (i.e., [Ge/H]=[Fe/H]) and weak r-process star HD122563, respectively. It is clearly that the ratio [Ge/H] of the weak r-process star is lower than that of the solar system about 0.9 dex. We can see that for the most metal-poor stars, the observed [Ge/H]~[Fe/H] correlation is close to the line of abundance ratio of weak r-process star HD122563, which is close to the findings of Cowan et al. (2005). The results imply that the Ge abundances in these stars mainly come from the weak r-process. Note that, for the main r-process star CS 31082-001, the ratio [Ge/H] is higher than the line of abundance ratio of weak r-process star about 0.3 dex, which should be the evidence that its Ge abundance partly comes from main r-process material. Based on the ratios [Ge/H], the sample stars revealed the existence of two distinct groups, i.e., Ge-enhanced stars having [Ge/H] > -2.4 and Ge-deficient stars having [Ge/H] <= -2.5. The Ge-deficient stars should be formed in regions...
Table 1. The values of log$_{10}$(Ge I), log$_{10}$(Fe I), log$_{10}$(Fe II) and log$_{10}$(Eu II)

| Star       | log$_{10}$(Ge I) | log$_{10}$(Fe I) | log$_{10}$(Fe II) | log$_{10}$(Eu II) | References |
|------------|------------------|------------------|-------------------|-------------------|------------|
| sun        | 3.63             | 7.5              | 7.5               | 0.54              | 1          |
| HD 108317  | 0.17             | 4.97             | 5.13              | -1.37             | 2          |
| HD 126587  | 0.03             | 4.57             | 4.69              | -1.89             | 3          |
| HD 186478  | 0.35             | 4.94             | 5.06              | -1.5              | 3          |
| HD 221170  | 0.69             | 5.15             | 5.47              | -0.85             | 3          |
| BD +17$^\circ$ 3248 | 0.46        | 5.42             | 5.4               | -0.67             | 3          |
| HD 6268    | 0.32             | 5.08             | 5.14              | -1.33             | 3          |
| HD 128279  | -0.03            | 5.02             | 5.04              | -1.96             | 2          |
| HD 126238  | 0.02             | 5.52             | 5.57              | -1.19             | 2          |
| HD 122956  | 0.84             | 5.55             | 5.81              | -0.79             | 3          |
| HD 6755    | 1.08             | 5.82             | 5.93              | -0.5              | 3          |
| HD 115444  | -0.05            | 4.54             | 4.52              | -1.63             | 4          |
| CS 31082-001 | 0.1          | 4.6              | 4.58              | -0.75             | 5          |
| HD 122563  | -0.03            | 4.78             | 4.78              | -2.59             | 4          |
| HD 175305  | 1.28             | 6.02             | 6.14              | -0.29             | 3          |
| HD 94028   | 1.56             | 5.75             | 5.88              | -0.88             | 6          |
| HD 76952   | 2.4              | 6.32             | 6.58              | -0.13             | 6          |
| HD 107113  | 2.54             | 6.71             | 6.97              | <0.4              | 6          |
| HD 2454    | 2.7              | 6.78             | 7.06              | 0.04              | 6          |
| HD 16220   | 3.11             | 6.94             | 7.09              | 0.14              | 6          |
| HD 140283  | <0.6             | 4.79             | 4.88              | <1.7              | 6          |
| CS 22892-052 | <0.2         | 4.4              | 4.41              | <0.95             | 3          |
| HD160617   | <1.2             | 5.58             | 5.73              | -0.81             | 7          |

References: -1 Anders & Grevesse1989; 2 Roederer et al.2012a; 3 Cowan et al. 2005; 4 Westin et al.2000; 5 Siqueira Mello et al.2012; 6 Roederer 2012d; 7 Roederer et al.2012b

Figure 1. The solid lines show the averaged yields of the massive stars with zero metallicity presented by Heger & Woosley (2010), which have been weighted by the Salpeter IMF and scaled to the Fe abundances of the weak r-process star HD 122563 (a) (Westin et al. 2000) and main r-process star CS 31082-001 (b) (Hill et al.2002; Siqueira et al.2013), respectively. The dashed lines in Figure 1(a) and (b) show the IMF-weighted yields of massive star with zero metallicity presented by Kobayashi et al. (2006) and also scaled to the Fe abundances of the two stars. The observed elemental abundances marked by filled circles are also shown to facilitate comparison.

For providing a more direct comparison of Ge abundance to the main r-process abundance, Figure 3 shows the abundance ratios [Ge/H] as a function of the abundance ratios [Eu/H]. The ratios [Ge/H] for the most Ge-deficient stars are lower than the solar ratio about 1.4 dex at similar [Eu/H]. We can see that the Ge abundance ratios of most metal-poor stars, except for the weak r-process star...
HD 122563, are lower than that of the scaled “residual r-process abundance” of Ge in the solar system at least 0.8 dex, which suggests that the Ge deficient is a common phenomenon in the metal-poor stars, agreeing with the finding of Roederer et al. (2012a). For the most Ge-deficient stars, the ratios [Ge/H] increase with increasing [Eu/H], except for the weak r-process star HD 122563 and main r-process star CS 31082-001. It is very interesting to note that, for the most Ge-deficient stars, the ratios [Ge/H] are close to the r-process abundance ratio in the solar system, which is plotted by solid line in Figure 3. The result is consistent with the suggestion that the Ge abundances in the metal-poor stars mainly come from the r-process. Furthermore, from the figure we can see that the ratio [Ge/H] of the main r-process star CS 31082-001 is lower than the ratio of solar about 2.0 dex, since the main r-process produce large amount of main r-process element Eu and small amount of Ge. On the other hand, because the weak r-process produce larger amount of Ge and hardly produce Eu, the ratio [Ge/H] of the weak r-process star HD 122563 is lower than the ratio of solar only about 0.3 dex and close to the ratio of “residual r-process abundance” in the solar system. Obviously, the abundance ratios of Ge-enhanced stars are higher than the r-process abundance ratio in the solar system, which should be the evidence that their Ge abundances have contained the contributions of the s-process and other astrophysical process.

4 CALCULATED RESULTS ABOUT THE GE-DEFICIENT STARS

Based on Equation (1), using the observed data of the Ge-deficient stars (Honda et al. 2004; Mishenina & Kovtyukh 2001; Roederer et al. 2010c; Ivanov et al. 2004; Cowan et al. 2002, 2005; Roederer et al. 2012a), we can obtain the best-fit \( C_{r,m} \) and \( C_{r,w} \) by looking for the minimum \( \chi^2 \). The component coefficients and \( \chi^2 \) are listed in Table 3. As an example, Figure 4(a) shows the best-fit results for the sample star HD 221170. The observed elemental abundances marked by filled circles are also shown to facilitate comparison.

The Ge-deficient star HD 108317 shows enrichment by the s-process (Roederer et al. 2012c). Considering the s-process contribution, the ith element abundance can be calculated as:

\[
N_i(Z) = (C_{r,m}N_{i,r,m} + C_{r,w}N_{i,r,w} + C_{s,m}N_{i,s,m}) \times 10^{[Fe/H]}(3)
\]

where \( N_{i,s,m} \) is the abundance produced by the main s-process in the AGB star and \( C_{s,m} \) is the main s-process component coefficient (see Sect 5 for details on the s-processes). The adopted abundance \( N_{i,s,m} \) in Equation (3) is taken from the main s-process abundance with [Fe/H]=−2.6 for 1.5M⊙ given by Bisterzo et al. (2010) (see their Table B6), which has been normalized to the s-process abundance of Ba in the solar system (Arlandini et al. 1999). The component coefficients are listed in Table 3 and fitted results are presented.
in Figure 4(b). In the top panel of Figure 5, the individual offsets \( \Delta \log \varepsilon \) for 12 Ge-deficient stars compared to the calculated results are shown. The r.m.s. offsets in \( \log \varepsilon \) are shown in the bottom panel. Typical observational errors are 0.2 ~ 0.3 dex (dotted lines). It could be found from Figure 5 that the individual relative offsets for most elements are smaller than 0.30 dex and the root-mean-square offsets are close to zero. It is clear from Figure 4 and Figure 5 to confirm the validity of the values of \( N_{\text{Ge},r,w} \) and \( N_{\text{Ge},r,m} \) derived in this work.

Siqueira et al. (2013) found a clear anticorrelation between the Ge enhancement and the r-process richness. Figure 6 shows the homogenized Ge abundances relative to the level of the main r-process element Eu as a function of the enrichment in r-process element Eu. The dash line corresponds to the abundance ratio of weak r-process star and dotted line represents the abundance ratio of the main r-process component. We find that the observed abundance ratios are close to the dash line for the sample stars with [Eu/Fe] \( \leq 1 \). However, the observed abundance ratios are close to the main r-process line but not weak r-process line for the sample star(s) with [Eu/Fe] \( > 1 \). At low metallicities the abundances can be well described by a mixture of two r-processes. We can adopt the abundances of weak r-process star HD 122563 as the initial abundances of Ge-deficient stars, since its abundances contain the lowest contribution of the main r-process. The abundance of ith element in the Ge-deficient stars can be calculated as

\[
N_i = N_{i,HD122563} + C_{r,m}N_{i,r,m}
\]

(4)

where \( N_{i,HD122563} \) is the abundance of weak r-process star HD 122563. To find an explanation of the relation between [Ge/Eu] and [Eu/Fe] quantitatively, taking \( C_{r,m} \), ranging from 0.2 to 200, based on equation (4), in Figure 6, the solid line correspond to the abundance ratios enriched by main r-process material. For the metal-poor stars with [Eu/Fe] \( \leq 1 \), the Ge abundances dominantly come from weak r-process. The increasing of [Eu/Fe] directly leads to a decline of [Ge/Eu]. Furthermore, based on the calculation, [Ge/Eu] flattened for higher [Eu/Fe], since the contributions from the main r-process component to Ge increase. We can see that, for the Ge-deficient stars, the observed [Ge/Eu]~[Eu/Fe] relation can be explained by the calculated results. From the figure we can see that the Ge abundances of the Ge-enhanced stars fall above the r-process line, whose astrophysical reasons will be studied in Section 5 and Section 6.

Based on the abundance analysis of neutron-capture element, we found that the Ge abundances of Ge-deficient stars mainly come from the weak r-process, except for the main r-process stars. Although light and iron group elements are not produced by weak r-process nucleosynthesis, both iron group elements and the weak r-process elements at low metallicity would be produced in the massive stars (Li et al. 2013a). The Ge yield and Fe yield possess primary nature (i.e., yields that are not effect by the initial metallicity approximately), which contributed Ge and iron group elements to ISM for various metallicity. So the abundances of iron group elements could be correlated closely with those of the weak r-process elements in Ge-deficient stars. In this case, the observed correlation of the [Ge/H] with the [Fe/H] shown in Figure 2, which had been found by Cowan et al. (2005), could be understood.

### 5 THE CONTRIBUTIONS OF THE NEUTRON-CAPTURE PROCESSES TO GE ABUNDANCES

Several previous studies on the abundances of the neutron-capture elements have indicated that the observed abundances of the heavy elements cannot be matched by only one neutron-capture process (Travaglio et al. 1999; Allen & Barbuy 1989; Li et al. 2013b). Based on the analysis of the observed ratios [Ge/Fe] in the metal-poor stars, Pignatari et al. (2010) estimated that the contribution from the primary-like yields of the massive stars to the solar Ge abundance is about 5%~8%. Travaglio et al. (2004) have found that the contributions from the weak s-process to the abundances of metal-poor stars could be negligible, since the secondary-like nature of major neutron source \( ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \).

Recently, Frischknecht et al. (2012) studied the impact of the initial rotation rate on the production of several elements in the massive stars and reported that rotating models can produce significant amounts of elements up to Ba, even though in low-metallicity environments. However, they found that the yields of light neutron-capture elements have the secondary-like nature, which is different with the primary nature for the r-process.

For exploring the astrophysical origin of elements Ge, we will compare the observed abundances with the abundances contributed from neutron-capture processes. In this case, the abundance of neutron-capture element can be calculated as:

\[
N_i(Z) = (C_{r,m}N_{i,r,m}+C_{r,w}N_{i,r,w}+C_{s,m}N_{i,s,m}+C_{s,w}N_{i,s,w}) \times 10^{[\text{Fe/H}]}\tag{5}
\]

where \( N_{i,r,m}, N_{i,r,w}, N_{i,s,m}, \) and \( N_{i,s,w} \) are the abundances of the ith element produced by the main r-process, weak r-process, main s-process and weak s-process respectively, which have been normalized to corresponding abundances of the solar system. The component coefficients \( C_{r,m}, C_{r,w}, C_{s,m} \) and \( C_{s,w} \) represent the relative contributions from the main r-process, the weak-r process, the main s-process, the weak s-process, respectively. Equation (5) has been used by Li et al. (2013b) to study the stellar abundances of the dwarf spheroidal galaxy. The adopted metallicity-dependent abundance \( N_{i,s,m} \) in Equation (5) is taken from the main s-process abundance given by Busso et al. (2001) (see their Figure 1) and Bisterzo et al. (2010) (see their table B6). The abundances of the weak s-process are taken from Travaglio et al. (2004) for the metal-rich stars. Obviously, there are some differences in the abundance patterns of the weak s-process between the metal-poor stars and the metal-rich stars. For the metal-poor stars, the abundances of the weak s-process are taken from Frischknecht et al. (2012) (model B4, \( u_{\text{mix}}/u_{\text{cool}} = 0.5 \)), since the calculated results show that the abundance ratio [Ge/Zr] \( \simeq -1.1 \), which is close to the average observed ratio of [Ge/Zr] \( \simeq -1.1 \). Using Equation (5) and the observed data of the sample stars Honda et al. (2004, 2007; Mishenina & Kovtyukh 2001; Roederer et al. 2011; Ivans et al. 2004; Cowan et al. 2002, 2005; Roederer et al. 2014; Roederer 2014; Siqueira et al. 2013; Hill et al. 2002; Westin et al. 2000), we can obtain the best-fit \( C_{r,m}, C_{r,w}, C_{s,m} \) and \( C_{s,w} \) by looking for the minimum \( \chi^2 \). In this step, the observed Ge abundances have not been included, because Ge should not be a "pure" neutron-capture element. There should have another astrophysical origin to Ge, except for neutron-capture process, for higher metallicity stars and the solar system. The component coefficients and \( \chi^2 \) are listed in Table 4. From Table 4 we find that, for the Ge-deficient stars(i.e., the most metal-poor stars from the sample stars - see also Table 3), the weak s-process component coefficients are smaller than 0.01 and the main s-process component coefficients are smaller than 0.02, which are smaller

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Figure 3. The [Ge/H] ratios as a function of [Eu/H]. The dashed line shows the solar abundance ratio of Ge, the dotted line indicates the solar “residual r-process abundance” ratios of Ge, while the solid line indicates the solar r-process abundance ratios of Ge. The observed data as in Figure 2. The arrows represent the upper limits for CS 22892-052 ([Eu/H]=-1.49) and HD 160617 ([Eu/H]=-1.35).

Table 3. The component coefficients of the two r-processes, main s-process and $\chi^2$ and $K - K_{\text{free}}$ for Ge-deficient stars. ($\log \varepsilon = \log N + 1.55$)

| Star          | [Fe/H] | $C_{r,m}$ | $C_{r,w}$ | $C_{s,m}$ | $\chi^2$ | $K - K_{\text{free}}$ |
|---------------|--------|-----------|-----------|-----------|----------|---------------------|
| HD 108317     | -2.53  | 4.3       | 3.5       | 0.016     | 0.84     | 30                  |
| HD 126587     | -2.93  | 5.2       | 5.9       | 1.47      | 26       |                     |
| HD 186478     | -2.56  | 4.8       | 4.7       | 0.71      | 28       |                     |
| HD 221170     | -2.35  | 9.1       | 5.5       | 1.11      | 41       |                     |
| BD +17° 3248  | -2.08  | 10.2      | 3.8       | 2.59      | 35       |                     |
| HD 6268       | -2.42  | 3.2       | 2.4       | 1.92      | 29       |                     |
| HD 128279     | -2.48  | 0.8       | 2.9       | 2.06      | 22       |                     |
| HD 126238     | -1.98  | 2.2       | 3.3       | 0.4       | 30       |                     |
| HD 122956     | -1.95  | 7.2       | 5.1       | 0.52      | 9        |                     |
| HD 6755       | -1.68  | 6.1       | 4.2       | 0.3       | 9        |                     |
| HD 115444     | -2.9   | 6.1       | 4.1       | 1.06      | 29       |                     |
| HD 175305     | -1.48  | 2.1       | 2.2       | 1.26      | 31       |                     |

than those of the r-processes about two orders of magnitude. The calculated results imply that the contributions of the s-process to the abundances of the Ge-deficient stars are much smaller than those of the r-process, which is consistent with the suggestion that the neutron-capture elements of the Ge-deficient stars mainly come from the r-process. These results can be naturally explained by the shorter lifetimes of massive stars: massive stars in the early times of the Galaxy evolve quickly, ending as SNe II producing r-process elements. On the other hand, for the Ge-enhanced stars (the last 5 sample stars in Table 4), the two s-component coefficients are larger than those of the Ge-deficient stars, which means that the contributions of the s-process to the abundances of these stars become important. Based on the calculations of galactic chemical evolution, Travaglio et al. (1999) have found that the main s-process contributions are significant starting from [Fe/H] $\approx -1.6$, since the longer lifetimes of low- and intermediate-mass AGB stars. On the other hand, for the weak s-process, little contribution is expected in halo stars, because of the strong decrease in its efficiency with decreasing metallicity Travaglio et al. (2004). Our calculated results are consistent with the conclusions of Travaglio et al. (2004).

Based on the the discussions above, the Ge abundances in Ge-enhanced stars would reflect the sum of contributions of the r-process, s-process and the additional astrophysical process. Although the observed Ge abundances have not been included in the fitted process, it was possible to calculate the sum of Ge abundances of the four components (i.e., neutron-capture process) using the component coefficients and equation (5). To investigate whether the contributions of the neutron-capture process can not interpret the observed Ge abundances of the Ge-enhanced stars, we subtract the sum of Ge abundances of the neutron-capture processes from the observed Ge abundances. In this case, we define $\Delta \log \varepsilon (Ge)$ as: $\Delta \log \varepsilon (Ge) = \log \varepsilon_{\text{obs}} - \log \varepsilon_{\text{cal}}$. The values of $\Delta \log \varepsilon (Ge)$ for the Ge-enhanced stars as the function of metallicity [Fe/H] are shown in Figure 7(a). From this figure we can see that the val-
Figure 4. Best fitted results of 2 sample stars. The filled circles with error bars are the observed element abundances, the solid line represents the calculated results.

Figure 5. Top panel: the individual relative offsets \( \Delta \log \varepsilon(X) \equiv \Delta \log \varepsilon(X)_{\text{cal}} - \Delta \log \varepsilon(X)_{\text{obs}} \) for the Ge-deficient stars with respect to the predictions from the abundance approach. Bottom panel: the root-mean-square offset of these elements in \( \log \varepsilon \), typical observational uncertainties in \( \log \varepsilon \) are \( \sim 0.2 - 0.3 \) dex (dotted lines).

Values of \( \Delta \log \varepsilon(\text{Ge}) \) increase with increasing of metallicity. There is a trend that the values of \( \Delta \log \varepsilon(\text{Ge}) \) reached the corresponding value in the solar system at \([\text{Fe/H}]=0\). The calculated results imply that, similar to the solar system, the contributions of the neutron-capture processes cannot interpret the observed Ge abundances of the Ge-enhanced stars. Figure 7(b) shows the Ge “residual abundances” \((=N_{\text{obs}} - N_{\text{cal}})\) as the function of metallicity \([\text{Fe/H}]\). The increased trend is visible. Figure 7(c) shows the contribution percentages of the “residual process” to the Ge abundances of the Ge-enhanced stars. We can find that there is a trend that the contribution percentages increase with increasing metallicity. Recall that there is a trend in Figure 2 that the ratios \([\text{Ge/H}]\) increase from the line of the ratio of the weak r-process star to the higher ratio started with \([\text{Fe/H}] \approx -1.6\). Based on the analysis above, we can find that the increased trend should be attributed to the contributions of the weak s-process, main s-process and the additional secondary process (i.e., the yields increase with increasing initial metallicity). This secondary process, which contributed Ge to ISM only for higher metallicity \(([\text{Fe/H}] > -1.6)\), is responsible for the Ge “residual abundance” in the solar system and some higher metallicity stars. Note that the contribution of the weak r-process to Ge abundances in metal-poor stars could not be replaced by those of the “residual process”, since the yields of the “residual process” possess the secondary nature.
Figure 6. The observed abundances of Ge relative to Eu as a function of the abundance ratios of Eu are shown. The solid line corresponds to the abundance ratios enriched by a mixture of both weak and main r-process material. The dash line corresponds to the abundance ratio of weak r-process star and dotted line represents the abundance ratio of the main r-process component. The observed data as in Figure 2. The arrows represent the upper limits for CS 22892-052 ([Eu/Fe] = 1.6) and HD 160617 ([Eu/Fe] = 0.42).

Table 4. The component coefficients of the two r-processes, two s-process, and $\chi^2$ for sample stars. ($\log \varepsilon = \log N + 1.55$)

| Star          | [Fe/H] | $C_{r,m}$ | $C_{r,w}$ | $C_{s,m}$ | $C_{s,w}$ | $\chi^2$ |
|---------------|--------|-----------|-----------|-----------|-----------|----------|
| HD 108317     | -2.53  | 4.3       | 3.5       | 0.016     | 0         | 0.86     |
| HD 126587     | -2.93  | 5.2       | 5.9       | 0.02      | 0         | 1.58     |
| HD 186478     | -2.56  | 4.8       | 4.7       | 0         | 0         | 0.76     |
| HD 221170     | -2.35  | 9.1       | 5.5       | 0         | 0         | 1.16     |
| BD +17° 3248  | -2.08  | 10.2      | 4.7       | 0         | 0         | 2.75     |
| HD 6268       | -2.42  | 3.2       | 2.4       | 0.01      | 0         | 2.36     |
| HD 128279     | -2.48  | 0.6       | 2.9       | 0.02      | 0         | 1.99     |
| HD 126238     | -1.99  | 2.1       | 3.3       | 0.01      | 0         | 0.34     |
| HD 122956     | -1.95  | 7.2       | 5.1       | 0         | 0         | 0.67     |
| HD 6755       | -1.68  | 6         | 4.2       | 0.01      | 0         | 0.40     |
| HD 115444     | -2.90  | 6.0       | 4.1       | 0         | 0         | 1.46     |
| CS 31082-001  | -2.9   | 50.9      | 3.8       | 0         | 0         | 0.68     |
| HD 122563     | -2.72  | 0.3       | 4.1       | 0         | 0         | 1.89     |
| HD 175305     | -1.48  | 2.1       | 2.2       | 0.02      | 0.01     | 1.31     |
| HD 94028      | -1.75  | 2         | 4.9       | 2         | 0.2       | 0.57     |
| HD 76932      | -1.18  | 5.1       | 3.9       | 0.4       | 0.9       | 0.63     |
| HD 107113     | -0.79  | 8.7       | 2.4       | 0.4       | 0.5       | 0.37     |
| HD 2454       | -0.72  | 1.3       | 2.5       | 10.9      | 0.6       | 0.58     |
| HD 16220      | -0.56  | 1.6       | 2.4       | 2.3       | 1.3       | 0.11     |

6 INVESTIGATION OF ASTROPHYSICAL ORIGIN OF GE “RESIDUAL ABUNDANCE”

From Table 1 we can see that the contributed percentage of Ge “residual abundance” to the solar system is about 41%, which is larger than the corresponding “individual” values of main s-, weak r-, main r-process. Considering the fitted results for metal-poor stars, we find that Ge “residual abundance” should appear with higher metallicity [Fe/H] $\geq -1.6$. This means that the Ge yields related to “residual abundance” should have secondary nature. Since Ge “residual abundance” do not produced by the neutron-capture processes, it must be produced by another process.

Historically, Ge (Z = 32) has been considered as a neutron-capture element. It is noteworthy that the r-process abundances in the solar system are derived through subtracting the s-process abundances from total abundances of solar system (Arlandini et al. 1999). If a heavy element (e.g. Ge) was produced by the neutron-capture process partly, the r-process abundance in solar system should have contained the contribution of the other process (e.g. charged-particle synthesis). We will investigate the astrophysical
origin of Ge “residual abundances” appeared at higher metallicity and in the solar system.

The element germanium is in the transition between charged-particle synthesis of the iron-group elements and neutron-capture synthesis of heavier elements. The substantial fractions of the iron-group elements, such as Sr and Zr, must have been produced by neutron-capture process. Elements between these two extreme cases, such as Ga and Ge, may be produced by each of these mechanisms. This implies that Ge “residual abundance” in the solar system would be produced in the massive stars. To test this point, the dashed lines in Figure 8(a) and (b) show average yields of massive star with the zero metallicity presented by Heger & Woosley (2010) and Kobayashi et al. (2006) respectively, which have been weighted by the IMF and scaled to the Fe abundances contributed from massive stars in the solar system. The Ge “residual abundance” in the solar system is also shown in Figure 8(a) and (b) by filled circles. We can see that the scaled Ge abundances are lower than the Ge “residual abundance” about 2.0 ~ 3.0 dex, which means that the Ge “residual abundance” would not be produced as the primary-
like yields in the massive stars. The dotted line in Figure 8(a) shows the SNe Ia yields presented by Woosley et al. (1997), which have been normalized to the Fe abundances contributed from SNe Ia in the solar system. The normalized Ge abundance is lower than the Ge “residual abundance” in the solar system. The solid lines in Figure 8(a) and (b) show averaged yields of the massive stars with the solar metallicity ($Z_\odot = 0.000$) presented by Kobayashi et al. (2006), respectively, which also have been weighted by the IMF and scaled to the Fe abundances contributed from massive stars in the solar system. We can see that, the scaled Ge abundance is higher than Ge “residual abundance” in the solar system about 1.2 ~ 1.7 dex. This should imply that, similar to iron-group elements, the Ge “residual abundance” in the solar system is produced in the massive stars. The Ge yields related to “residual abundance” should have secondary nature, which can be observable for stars with higher metallicity ($[\text{Fe}/\text{H}] \geq -1.6$).

7 CONCLUSIONS

In our Galaxy, nearly all chemical evolution and nucleosynthetic information is imprinted in the elemental abundances of stars with various metallicities. In this respect, main r-process stars and weak r-process stars are very significant, because their abundances are polluted by only a few processes. On the other hand, the chemical abundances of the metal-poor stars and metal-rich stars can also provide important information. Our results can be summarized as follows:

1. The Ge abundance in the metal-poor stars could not be produced as the primary-like yields in the massive stars and should be produced by the r-process. The Ge abundances of weak r-process and main r-process are derived from the observed abundances of weak r-process star and the main r-process star. We find that the observed correlation of $[\text{Ge}/\text{H}]$ and $[\text{Eu}/\text{H}]$ are close to the r-process abundance ratio in the solar system and the Ge abundances of metal-poor stars can be fitted by combined contributions of the weak r- and main r-processes.

2. Because both iron group elements and the weak r-process elements would be produced in the massive stars at low metallicity, the observed correlation of the $[\text{Ge}/\text{H}]$ with the $[\text{Fe}/\text{H}]$ could be understood. Furthermore, since the Ge abundances dominantly come from the weak r-process for the most Ge-deficient stars, the increasing of $[\text{Eu}/\text{Fe}]$ directly leads to the observed decline of $[\text{Ge}/\text{Eu}]$.

3. For the Ge-enhanced stars, there is a increased trend in $[\text{Ge}/\text{H}]$ started from the line of abundance ratio of the weak r-process star at $[\text{Fe}/\text{H}]=-1.6$ to the line of $[\text{Ge}/\text{H}]=[\text{Fe}/\text{H}]$, which should be attributed to the contributions of the weak s-process, main s-process and the secondary process occurred in the massive stars.

4. The contributed percentages of main r-, weak r-, main s- and weak s-processes for Ge to the abundance of the solar system are about 0.32%, 3.25%, 12.02% and 43.03% respectively, which means that the contributed percentage of “residual abundance” to the solar system is about 41%. Our investigations imply that the Ge “residual abundance” would be produced as the secondary-like yields in the massive stars.

Our calculated results should give the constraints on models of the r-process that produced Ge element in the Galaxy. We hope that the results here will present interesting information to more complete models of Galactic chemical evolution. A more precise knowledge about the Ge abundances in metal-poor stars and in population I stars is needed.

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