Growing interests in neutron star (NS) mergers as the origin of r-process elements have sprouted since the discovery of evidence for the ejection of these elements from a short-duration γ-ray burst. The hypothesis of a NS merger origin is reinforced by a theoretical update of nucleosynthesis in NS mergers successful in yielding r-process nuclides with $A > 130$. On the other hand, whether the origin of light r-process elements are associated with nucleosynthesis in NS merger events remains unclear. We find a signature of nucleosynthesis in NS mergers from peculiar chemical abundances of stars belonging to the Galactic globular cluster M15. This finding combined with the recent nucleosynthesis results implies a potential diversity of nucleosynthesis in NS mergers. Based on these considerations, we are successful in the interpretation of an observed correlation between [light r-process/Eu] and [Eu/Fe] among Galactic halo stars and accordingly narrow down the role of supernova nucleosynthesis in the r-process production site. We conclude that the tight correlation by a large fraction of halo stars is attributable to the fact that core-collapse supernovae produce light r-process elements while heavy r-process elements such as Eu and Ba are produced by NS mergers. On the other hand, stars in the outlier, composed of r-enhanced stars ([Eu/Fe] $\gtrsim +1$) such as CS22892-052, were exclusively enriched by matter ejected by a subclass of NS mergers that is inclined to be massive and consist of both light and heavy r-process nuclides.

Key words: Galaxy: evolution – Galaxy: halo – ISM: abundances – stars: abundances – stars: neutron

Online-only material: color figures
2. NUCLEOSYNTHESIS SIGNATURE OF A NEUTRON STAR MERGER IN M15

Chemical abundance of Galactic metal-poor GC M15 is unusual in the sense that it exhibits a large star-to-star variation in Eu, Ba, and La abundances with little scatter in Fe and Ca abundances (Sneden et al. 1997; Worley et al. 2013). Abundance patterns of individual stars are confirmed to be of pure r-process origin (Sneden et al. 2000). These facts suggest that heavy r-process enrichment is not associated with CCSNe that provide lighter elements such as Fe and Ca. Alternatively, the hypothesis that a single NS merger occurred after the formation of M15, and polluted the surface of stars by its ejecta well explains a large scatter in the abundance of heavy r-process elements as observed (T. Shigeyama & T. Tsujimoto 2014, in preparation). Evolved low-mass stars in the GC had supplied gas with a mass of $\sim 1000 M_\odot$ until a NS merger occurred. If the gas is distributed in the core of the GC with a radius of $\sim 0.1$ pc, this gas can stop most of r-process elements ejected from the NS merger at speeds of 10%-30% of the speed of light. The resultant [Eu/H] abundance in the gas becomes as high as $+0.1$ on average. If a 0.8 $M_\odot$ star with [Eu/H] $= -2.1$ and velocity dispersion of 15 km s$^{-1}$ accretes this r-process-rich gas at the Bondi accretion rate (Bondi 1952) for 10 Myr at minimum, then these stars form a metallicity distribution function (MDF) with respect to [Eu/H] having a peak at [Eu/H] $\sim -1.6$ when they evolve to the red giant branch. Here the accreted matter is assumed to mix with the convective envelope with a mass of 0.3 $M_\odot$. The derivation of the formula for the MDF can be found in Shigeyama et al. (2003). In addition to this peak, we anticipate the second peak at a low [Eu/H] (e.g., [Eu/H] $\sim -2.1$) due to the presence of stars that have not suffered from a pollution by the ejecta of the NS merger. They originally resided outside the core at the NS merger event, and are expected to be distributed over the whole region of the present-day GC owing to two-body relaxation (e.g., D’Ercole et al. 2008). Such a double-peak feature is compatible with the observed results (Worley et al. 2013).

To host a NS merger event at a rate of about one per 1000–2000 CCSNe (T. Tsujimoto & T. Shigeyama 2014, in preparation), a GC should be as massive as several $10^5 M_\odot$ like M15. In addition, a low probability that an NS merger occurs while the GC has a high gas density core should make the origin (Sneden et al. 2000). These facts suggest that heavy elements such as Fe and Ca. Alternatively, the hypothesis that a single NS merger occurred after the formation of M15, and polluted the surface of stars by its ejecta well explains a large scatter in the abundance of heavy r-process elements as observed (T. Shigeyama & T. Tsujimoto 2014, in preparation). Evolved low-mass stars in the GC had supplied gas with a mass of $\sim 1000 M_\odot$ until a NS merger occurred. If the gas is distributed in the core of the GC with a radius of $\sim 0.1$ pc, this gas can stop most of r-process elements ejected from the NS merger at speeds of 10%-30% of the speed of light. The resultant [Eu/H] abundance in the gas becomes as high as $+0.1$ on average. If a 0.8 $M_\odot$ star with [Eu/H] $= -2.1$ and velocity dispersion of 15 km s$^{-1}$ accretes this r-process-rich gas at the Bondi accretion rate (Bondi 1952) for 10 Myr at minimum, then these stars form a metallicity distribution function (MDF) with respect to [Eu/H] having a peak at [Eu/H] $\sim -1.6$ when they evolve to the red giant branch. Here the accreted matter is assumed to mix with the convective envelope with a mass of 0.3 $M_\odot$. The derivation of the formula for the MDF can be found in Shigeyama et al. (2003). In addition to this peak, we anticipate the second peak at a low [Eu/H] (e.g., [Eu/H] $\sim -2.1$) due to the presence of stars that have not suffered from a pollution by the ejecta of the NS merger. They originally resided outside the core at the NS merger event, and are expected to be distributed over the whole region of the present-day GC owing to two-body relaxation (e.g., D’Ercole et al. 2008). Such a double-peak feature is compatible with the observed results (Worley et al. 2013).

In contrast to a large variation in heavy r-process abundance among stars, abundances of light neutron-capture elements, Sr, Y, and Zr, do not display any scatter (Otsuki et al. 2006; Sobeck et al. 2011). Therefore we conclude that a NS merger in M15 exclusively produced heavy r-process elements.

3. PRODUCTION SITES OF LIGHT AND HEAVY R-PROCESS ELEMENTS

Galactic halo stars have a tight correlation of [Sr, Y, Zr/Eu] with [Eu/Fe] (Montes et al. 2007) while the same stars exhibit a large scatter in the [Sr, Y, Zr/Eu] versus [Fe/H] diagram, which is more frequently used as a diagram displaying chemical features between light and heavy r-process elements. Here we try to unravel the origin of the correlation between [light r-process/Eu] and [Eu/Fe] utilizing the elements Y and Zr since the abundance determination of Sr from the measurement of only a single strong line is less reliable than the other two elements (e.g., Otsuki et al. 2006). There are three key points to be highlighted in the following theoretical flow: (1) the presence of outlier stars deviating from the tight correlation, (2) two kinds of nucleosynthesis in NS mergers, and (3) different ways of the propagation of ejecta between CCSN and NS merger.

Figure 1 demonstrates that a large fraction of halo stars obey a decreasing trend of [Y/Zr/Eu] with increasing [Eu/Fe] in the range of $-0.6 < [Eu/Fe] < +1.2$. This trend is not an end result of a single evolutionary track because in the [Eu/Fe] versus [Fe/H] diagram, a large scatter in [Eu/Fe] at the early phase of [Fe/H] $\lesssim -1.5$ converges to the plateau-like ratio of [Eu/Fe] $\sim +0.5$ in the metallicity range of $-1.5 < [Fe/H] < -1$ (e.g., Sneden et al. 2008). Thus, at least two tracks starting from either [Eu/Fe] $\sim -0.6$ or +1.2 and heading for [Eu/Fe] $\sim +0.5$ are required to explain the overall correlation. In addition, some stars deviate from this correlation, in particular all stars with [Eu/Fe] $\gtrsim +1.2$ including CS2289-052, stay at a ratio of [Y/Eu] $\sim -1.2$ and constitute the outlier.

First, we discuss the origin of a large contrast of [Y/Eu] in the correlation ranging from $\sim -1.2$ to +0.2. Its contrast can be
similar amount of ISM and thus yield a low abundance. Eu nuclides ejected from a NS merger are mixed with a largeamount of ISM, whereas their high velocities while CCSNe locally distribute newly synthesized heavy elements only inside the regions swept up by the blast waves (T. Tsujimoto & T. Shigeyama 2014, in preparation). This scheme suggests that in a massive (small-mass) fragment, Eu nuclides ejected from a NS merger are mixed with a large (small) amount of ISM and thus yield a low (high) abundance of Eu while Y nuclides from CCSNe are always mixed with a similar amount of ISM. The ratio of Eu/Fe and thus Y/Fe is determined to reproduce the observed feature (see below). On the other hand, CCSNe synthesize light r-process elements together with Fe, and their ejecta are mixed with the ISM locally swept up by supernovae of the mass $5 \times 10^4 M_\odot$. Here we adopt the Y yields that have a mass dependence similar to Fe in CCSNe. We also consider s-process contribution to Y from massive stars in the metallicity range of $[Fe/H] > -2$ so that the Y yields increase in proportion to the metallicity (Tsujimoto 2011).

The calculated features of [Y/Eu] are shown with respect to [Eu/Fe] as well as [Fe/H] in Figure 2. There are two major evolutionary tracks denoted by blue and red colors. They make a tight correlation between [Y/Eu] and [Eu/Fe] (left panel) and are matched with a large part of the observed data in the [Y/Eu] versus [Fe/H] diagram (right panel). These are the results of models for massive ($\sim 10^5 M_\odot$) blue and $10^7 M_\odot$ (red) fragments with NS mergers ejecting only heavy r-process elements. In addition to them, to cover outlier stars in the [Y/Eu]–[Eu/Fe] correlation, we introduce an additional model in which one of five NS mergers releases the ejecta composed of both light and heavy r-process nuclides in a $10^7 M_\odot$ fragment. Defining $x$ as Eu yield in units of that of a NS merger ejecting only heavy r-process elements and $y$ as the yield ratio of Y/Eu, our adopted assumptions on NS mergers and CCSNe are as follows. NS mergers occur at a rate of one per 1000 CCSNe with a time delay of 10–30 Myr (Belczynski et al. 2006), and the ejecta are mixed with the entire ISM inside a fragment. A large fraction of NS mergers exclusively release heavy stars of mass $> 130 M_\odot$ and a minor population produces both light and heavy r-process elements. Their ejected yields are determined to reproduce the observed feature (see below). On the other hand, CCSNe synthesize light r-process elements together with Fe, and their ejecta are mixed with the ISM locally swept up by supernovae of the mass $5 \times 10^4 M_\odot$. Here we adopt the Y yields that have a mass dependence similar to Fe in CCSNe. We also consider s-process contribution to Y from massive stars in the metallicity range of $[Fe/H] > -2$ so that the Y yields increase in proportion to the metallicity (Tsujimoto 2011).

4. CHEMICAL EVOLUTION OF [Y/EU] AGAINST [EU/FE] AND [FE/H]

To validate our interpretation presented in the previous section, we model the chemical evolution of the halo and calculate the Y/Eu evolution. The basic model ingredients are the same as in T. Tsujimoto & T. Shigeyama (2014, in preparation). The model represents the chemical evolution for each of gaseous fragments which give birth to halo field stars in the scheme that the halo was formed through accretion of protogalactic fragments. Fragments with two different masses are considered, that is, a massive fragment with a mass of $10^9 M_\odot$ where NS merger events steadily occur, and the other with $10^7 M_\odot$ where only five events are expected.

Figure 2. Predicted correlations of [Y/Eu] with [Eu/Fe] (left panel) and [Fe/H] (right panel) in the Galaxy halo, compared with the observed data with [Fe/H] < -1 and [Ba/Eu] < 0 (Suda et al. 2008). Our model results are represented by three components with different colors. Most of the observed features are reproduced by blue and red colored tracks. These correspond to stars born from protogalactic fragments with different masses—massive (blue) and small (red) ones. In these models, all NS mergers are assumed to release only heavy r-process nuclides. On the other hand, green track represents the small-mass fragment hosting one NS merger associated with the production of all r-process nuclides. In all models, CCSNe are assumed to produce light r-process elements.

(A color version of this figure is available in the online journal.)
nucleosynthesis yield for this NSM \((x, y)\) is expressed as \((5, 2)\), and the results are shown by green tracks. It should be of note that though such NS mergers are expected to occur in massive fragments as well, their signature will not become apparent in stellar abundances owing to numerous NS merger events and a high \(Y\) abundance in the ISM.

5. CONCLUSIONS

We have assessed the origin of light and heavy \(r\)-process elements from detailed analysis of chemical abundances of Galactic halo field stars together with an implication from chemical feature of the GC M15 and theoretical predictions of nucleosynthesis in NS mergers. Finally, we draw the conclusion that the production site of light \(r\)-process elements is multiple; CCSNe are the major source of light \(r\)-process elements and a subclass (minority) of NS mergers also release light \(r\)-process elements as well as heavy \(r\)-process elements. On the other hand, heavy \(r\)-process elements have a unique production site—NS mergers. In other words, there are two types of NS mergers; one type exclusively ejects heavy \(r\)-process nuclides and the other produces both light and heavy \(r\)-process nuclides. In this scheme, the universality of \(r\)-process pattern seen among \(r\)-enhanced stars is reproduced by the abundance pattern of one class of NS mergers that copiously synthesize all \(r\)-process nuclides. However, such stars can be regarded as outlier stars, thus we expect that most of halo stars should not follow the universality.

The authors wish to thank the anonymous referees for their valuable comments which have considerably improved the paper. This paper is based upon work supported in part by the JSPS Grants-in-Aid for Scientific Research (23224004) and under the hospitality of the Institute for Nuclear Theory, University of Washington (Report No.: INT-PUB-14-043).

REFERENCES

Aoki, W., Honda, S., Beers, T. C., et al. 2005, ApJ, 632, 611
Argast, D., Samland, M., Thielemann, F.-K., & Qian, Y.-Z. 2004, A&A, 416, 997
Barnes, J., & Kasen, D. 2013, ApJ, 775, 18
Bauswein, A., Goriely, S., & Janka, H.-T. 2013, ApJ, 773, 78
Belczynski, K., Perna, R., Bulik, T., et al. 2006, ApJ, 648, 1110
Berger, E., Fong, W., & Chornock, R. 2013, ApJ, 773, 78
Bondi, H. 1952, MNRAS, 112, 195
Cohen, J. G. 2011, ApJL, 740, L38
D’Ercole, A., Vesperini, E., D’Antona, F., McMillan, S. L. W., & Recchi, S. 2008, MNRAS, 391, 825
François, P., Depagne, E., Hill, V., et al. 2007, A&A, 476, 935
Honda, S., Aoki, W., Ishimaru, Y., Wanajo, S., & Ryan, S. G. 2006, ApJ, 643, 1180
Hotokezaka, K., Kyutoku, K., Tanaka, M., et al. 2013, ApJL, 778, L16
Just, O., Bauswein, A., Adrevel, P. R., Goriely, S., & Janka, H.-T. 2014, MNRAS, submitted (arXiv:1406.2687)
Korobkin, O., Rosswog, S., Arcones, A., & Winteler, C. 2012, MNRAS, 426, 1940
Mathews, G. J., & Cowan, J. J. 1990, Natur, 345, 491
Metzger, B. D., & Berger, E. 2012, ApJ, 746, 48
Metzger, B. D., Martinez-Pinedo, G., Darbha, S., et al. 2010, MNRAS, 406, 2650
Montes, F., Beers, T. C., Cowan, J., et al. 2007, ApJ, 671, 1685
Otsubu, K., Honda, S., Aoki, W., Kajino, T., & Mathews, G. J. 2006, ApJL, 641, L117
Qian, Y.-Z., & Wasserburg, G. J. 2007, PhR, 444, 237
Roederer, I. U., & Sneden, C. 2011, AJ, 142, 22
Shigeyama, T., & Tsujimoto, T. 1998, ApJL, 507, L135
Shigeyama, T., & Tsujimoto, T., & Yoshii, Y. 2003, ApJ, 586, L57
Sneden, C., Cowan, J. J., & Gallino, R. 2008, ARA&A, 46, 241
Sneden, C., Cowan, J. J., Lawler, J. E., et al. 2003, ApJ, 591, 936
Sneden, C., Johnson, J., Kraft, R. P., et al. 2000, ApJL, 536, L85
Sneden, C., Kraft, R. P., Shetrone, M. D., et al. 1997, AJ, 114, 1964
Sobeck, J. S., Kraft, R. P., Sneden, C., et al. 2011, AJ, 141, 175
Suda, T., Katsuya, Y., Yamada, S., et al. 2008, PASJ, 60, 1159
Tanvir, N. R., Levan, A. J., Fruchter, A. S., et al. 2013, Natur, 500, 547
Tsujimoto, T. 2011, ApJ, 736, 113
Tsujimoto, T., & Shigeyama, T. 2014, A&A, 565, L5
Wanajo, S., Sekiguchi, Y., Nishimura, N., et al. 2014, ApJL, 789, L39
Worley, C. C., Hill, V., Sobeck, J., & Carretta, E. 2013, A&A, 553, A47