Recent hydrodynamical and nucleosynthesis studies have suggested binary mergers (NSMs) of double neutron star (and black-hole–neutron-star) systems as major sites of r-process elements in the Galaxy. It has been pointed out, however, that the estimated long lifetimes of neutron star binaries are in conflict with the presence of r-process-enhanced halo stars at metallicities as low as [Fe/H] ~ −3. To resolve this problem, we examine the role of NSMs in the early Galactic chemical evolution with the assumption that the Galactic halo was formed from merging sub-halos. We present simple models for the chemical evolution of sub-halos with total final stellar masses between $10^4 M_\odot$ and $2 \times 10^8 M_\odot$. The typical lifetimes of compact binaries are assumed to be 100 Myr (for 95% of their population) and 1 Myr (for 5%), according to recent binary population synthesis studies. The resulting metallicities of sub-halos and their ensemble are consistent with the observed mass–metallicity relation of dwarf galaxies in the Local Group and the metallicity distribution of the Galactic halo, respectively. We find that the r-process abundance ratios [r/Fe] start increasing at [Fe/H] $\lesssim$ −3 if the star formation efficiencies are smaller for less-massive sub-halos. In addition, sub-solar [r/Fe] values (observed as [Ba/Fe] $\sim$ −1.5 for [Fe/H] $<$ −3) are explained by the contribution from short-lived (~1 Myr) binaries. Our results indicate that NSMs may have contributed substantially to the r-process element abundances throughout the history of the Galaxy.

Key words: galaxies: dwarf – Galaxy: evolution – Galaxy: halo – nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: neutron
scenario of galaxy formation. Prantzos (2006, 2008) has shown that the overall shape of the Galactic halo’s metallicity distribution (MD) can be well reproduced by a merging subhalo model with smaller subhalos having suffered larger outflows (see also Komiya 2011). More importantly for the issue of the r-process, Prantzos (2006) showed that if the subhalos evolved at different rates, then there would be no more unique relation between time and metallicity; in that case, he argued that the observed “early” (in terms of metallicity) appearance of r-elements and their large dispersion can be explained even if the main source of those elements is long-lived (~100 Myr) NSMs. A recent study using a high resolution, cosmological simulation, supports that idea (Shen et al. 2015).

In this Letter, we study the role of NSMs in the early Galaxy with a GCE model based on the framework of such a hierarchical merging scenario and on recent estimates of the progenitor binary lifetimes.

2. CHEMICAL EVOLUTION OF SUB-HALOS

Each sub-halo is modeled as a one-zone, well-mixed single system that is losing gas due to outflow (because of stellar winds, SN explosions and tidal interactions). The GCE model used in this work is the same as that for the ISM evolution of the Galactic halo in Ishimaru & Wanajo (1999), Ishimaru et al. (2004), and Wanajo & Ishimaru (2006) but it differs in what follows. Each sub-halo is composed of stars with a final total stellar mass M*, evolving homogeneously (i.e., with its ISM well mixed at every time). We consider sub-halos with M/MD = 10^4, 10^5, 10^6, 10^7, 10^8, and 2 × 10^8. The heaviest mass is set to be about half the estimated stellar mass of the Galactic halo, ~4 × 10^8 M⊙ (Bell et al. 2008). The lowest mass corresponds to those of recently discovered ultra-faint dwarf galaxies (Kirby et al. 2008).

Although we have no direct observational clues as to the property of each sub-halo, recent observations of MDs of dwarf galaxies in the Local Group can provide some hints (Helmi et al. 2006). We know that [Fe/H] at the peak of an MD, [Fe/H]peak, corresponds to the effective yield paren, i.e., the iron productivity of a galaxy system which depends on the adopted stellar yields and IMF (Helmi et al. 2006; Prantzos 2008). If a dwarf galaxy loses a significant amount of iron through outflow with the rate (OFR) proportional to the star formation rate (SFR), then paren is approximately proportional to paren, where OFR ≡ paren (Prantzos 2008). In practice, limited data are available for MDs, and thus the observed median metallicities ([Fe/H]0) of dwarf galaxies are used instead of [Fe/H]peak. The observed mass–metallicity relation for dwarf galaxies suggests that [Fe/H]0 approximately scales as M−0.3 (Kirby et al. 2013). We thus assume paren ≈ paren = 5.0 (M/MD)^−0.3 as in Prantzos (2008).6 This can be naturally interpreted as a result of smaller SFR and/or greater OFR because of the shallower gravitational well for a less-massive sub-halo (see also Section 4). SFR is assumed to be proportional to the mass of the ISM, (MISM): SFR = kSF MISM, where the constant kSF corresponds to the star formation efficiency, and OFR = kOFR MISM, where kOFR = kSF. However, we cannot constrain either kSF or kOFR based on observations. Thus, we assume two extremes: Cases 1 and 2 for the fixed ratios of paren, respectively (Table 1). The sub-halo of 6 The values of the coefficient and the index are updated from Prantzos (2008) by adopting the latest mass–metallicity relation (Kirby et al. 2013).

| Case 1 | Case 2 |
|--------|--------|
| 100 Myr | 100 Myr |
| 10^6 | 10^6 |
| 10^7 | 10^7 |
| 10^8 | 10^8 |

M = 10^8 M⊙ is (arbitrary) set to have the same values of kSF and kOFR for both Cases 1 and 2.

The CCSN abundances of Mg and Fe (which we assume to be representative of CCSN products and metallicity, respectively) are taken from Nomoto et al. (2006). We ignore the Fe contribution from Type Ia SNe because they appear to have played a negligible role during the Milky Way halo evolution (the observed α/Fe ratio of halo stars is ~constant). The evolution of each sub-halo is computed up to 2 Gyr, which is considered to be a reasonable estimate of the timescale of the Milky Way halo formation suggested from the observed ages of globular clusters (Roediger et al. 2014). The value of kSF for the sub-halo with M = 10^8 M⊙ is set to account for the most metal-rich stars in the Galactic halo.

Binary population synthesis models indicate an average binary lifetime of (~NSM) ~ 1 Gyr (e.g., Dominik et al. 2012), which is comparable with the lifetimes of sub-halos. A significant fraction of NSMs are, however, expected to have ~NSM ≤ 100 Myr (~40%, Belczynski et al. 2008). In addition, a short-lived channel of ~NSM ≤ 1 Myr is also predicted (Belczynski & Kalogera 2001; Belczynski et al. 2002; De Donder & Vanbeveren 2004). Dominik et al. (2012) estimate the fraction of such a putative short-lived channel to be up to ~7% (for the solar metallicity case). For illustrative purposes, here we assume a bimodal distribution of ~NSM = 1 and 100 Myr with corresponding fractions of 5% and 95%, respectively (Table 2). For the total average frequency of NSMs (~NSM) relative to that of CCSNe, we assume ~NSM = 2 × 10^3 (~CCSN) adopting the estimates of recent population synthesis calculations (Dominik et al. 2012). The mass of the ejected Eu, representative of r-process elements in the Galactic halo, is taken from the latest nucleosynthesis result of Wanajo et al. (2014), Meu,NSM = 2 × 10^5 M⊙ (see also Goriely et al. 2011; Kob- okin et al. 2012). The mass of the ejected Ba, which is also predominantly produced by the r-process in the early Galaxy, is set to be Meu,NSM = 9 Meu,NSM according to the solar r-process ratio of these elements (Burris et al. 2000).

3. ENRICHMENT OF r-PROCESS ELEMENTS

Our results for Case 1 (with constant kSF) are shown in Figure 1. Those results for less (more) massive sub-halos are
indicated by the thinner (thicker) curves. The cumulative number of CCSNe in each sub-halo monotonically increases with time (Figure 1(a)). For NSMs, the cumulative number steeply rises when the long-lived binaries start contributing at 100 Myr. [Fe/H] monotonically increases with time for all of the sub-halos; at a given time, [Fe/H] is greater for more massive sub-halos because of their higher $k_{\text{SF}}$. MDs for all of the sub-halos are also shown in Figure 1(c). The metallicity at the peak of each MD, $[\text{Fe/H}]_{\text{peak}}$ (Table 3), is in agreement with the observed mass–metallicity relation (Kirby et al. 2013) scaled downward by $-0.4$ dex to exclude the SNe Ia contribution. The dark halo mass of each sub-halo, $M_D$ (Table 3), estimated from the initial baryonic mass and the initial baryon to dark mass ratio (which is assumed to be equal to the cosmic value $\Omega_B/\Omega_D = 0.046/0.24 \sim 0.19$), implies $M_D \propto M_\star^{0.7}$. Since the reasonable mass function of $M_D$ can be regarded as $dN/dM_D \propto M_D^{-2}$ (e.g., Prantzos 2008 and references therein), we obtain the sub-halo mass function as $\propto M_\star^{-1.7}$. We find that the total MD (thick black curve) weighted with the sub-halo mass function is in reasonable agreement with the observed one (gray hatched region, An et al. 2013). We also find that the evolution of Mg (Figure 1(d), representative of CCSN products) is in reasonable agreement with the observed stellar abundances of Galactic halo stars. In contrast to r-process elements, the observed scatter in [$\alpha$/Fe] is known to be as small as the measurement errors (e.g., Cayrel et al. 2004). This result is consistent with such small scatter in [Mg/Fe] because each evolutionary trend is almost independent of $M_\star$.

The resulting evolution of Eu (representative of r-process elements) is presented in Figure 1(c) and compared to observed stellar values. We note a transition from slow to rapid evolution of [Eu/Fe] for each sub-halo at $\sim$100 Myr as a result of the contribution from long-lived binaries beginning. The corresponding [Fe/H] (see Figure 1(b)) differs from one sub-halo to another, being lower than $[\text{Fe}/\text{H}] \sim -3$ for $M_\star \lesssim 10^6 M_\odot$. This indicates that the presence of stars at $[\text{Fe}/\text{H}] \sim -3$ with star-to-star scatter in [Eu/Fe] ($\lesssim 0.5$) can be interpreted as a result of NSM activity in sub-halos with various $k_{\text{SF}}$. Our model cannot, however, explain the presence of r-process-enhanced stars with [Eu/Fe] $> 1$. In addition, our result predicts the presence of stars with [Eu/Fe] $\sim -1$ for $[\text{Fe}/\text{H}] \lesssim -3$. This is due to the contribution of the short-lived NSM at early times ($<100$ Myr). Measurements of Eu in such stars would be challenging because of the weak spectral lines. Such a signature has been seen in the Ba abundances of EMP stars, $[\text{Ba}/\text{Fe}] \sim -2$ to $-1$ at $[\text{Fe}/\text{H}] \lesssim -3$ (Figure 1(f)), which could also be explained as being due to the contribution of short-lived

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**Figure 1.** Evolution of the sub-halos with $M_\star/M_D = 10^4, 10^5, 10^6, 10^7,$ and $2 \times 10^8$, respectively, indicated by the thinnest to thickest curves for Case 1. (a) Cumulative numbers of NSMs (solid) and CCSNe (dashed) as functions of time. The horizontal dashed line marks the number of unity (see text for implications). (b) [Fe/H] temporal evolutions. (c) MDs of sub-halos weighted with the sub-halo mass function and their sum (thick-black). Observational data of the Galactic halo (gray-hatched histogram) are taken from the calibration catalog of An et al. (2013). (d)–(f) [Mg/Fe], [Eu/Fe], and [Ba/Fe] as functions of [Fe/H], respectively. The horizontal and vertical lines indicate the solar values. Observational stellar values (dots) are taken from the SAGA database (Suda et al. 2008), excluding carbon-enhanced stars that may have been affected by gas transfer in binaries.

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**Table 3**

| $M_\star$ ($M_\odot$) | $M_D$ ($M_\odot$) | $[\text{Fe/H}]_{\text{peak}}$ |
|---------------------|------------------|------------------|
| $10^7$              | $7.6 \times 10^6$ | $6.6 \times 10^6$ | $-2.63$ | $-2.56$ |
| $10^5$              | $3.8 \times 10^7$ | $3.3 \times 10^7$ | $-2.33$ | $-2.30$ |
| $10^6$              | $1.9 \times 10^8$ | $1.7 \times 10^8$ | $-2.03$ | $-2.02$ |
| $10^7$              | $1.0 \times 10^9$ | $9.0 \times 10^8$ | $-1.74$ | $-1.74$ |
| $10^8$              | $5.3 \times 10^9$ | $5.3 \times 10^8$ | $-1.46$ | $-1.46$ |
| $2 \times 10^8$     | $8.8 \times 10^9$ | $9.3 \times 10^9$ | $-1.38$ | $-1.39$ |
binaries. Note that the [Ba/Fe] values for [Fe/H] $\geq -2.5$ are underpredicted compared to the observed ones; in this metallicity, the contribution from the s-process becomes important (Burris et al. 2000).

Figure 2 shows the results for Case 2, where a constant $k_{57}$ is assumed. We find that the cumulative numbers of NSMs and CCSN are similar to those in Case 1 (Figure 1(a)). However, the evolutions stop earlier for less-massive sub-halos. This is due to the termination of star formation because of gas removal by their significant outflows with greater values of $k_{OF}$. In contrast to Case 1, the [Fe/H] evolution (Figure 2(b)) is identical among sub-halos because of the same $k_{OF}$, although the termination points differ depending on their $k_{57}$. The resulting MDs (Figure 2(c)) as well as the evolutions of Mg (Figure 2(d)) are similar between Cases 1 and 2. In Figure 2(e), we find that the r-process abundances increase to values greater than [Eu/Fe] $\sim 1$ for the sub-halos with $M_\ast \leq 10^8 M_\odot$. This is a consequence of the fact that the higher $k_{OF}$ lead to smaller amounts of Fe, and thus higher Eu/Fe ratios. It is interesting to note that even without invoking the inhomogeneity of the ISM, the enhancement of Eu can be explained in part by our sub-halo models. However, our result here cannot account for the r-process enrichment at [Fe/H] $\sim -3$ because the [Eu/Fe] starts rising at [Fe/H] $\sim -2.4$ for all of the sub-halos.

Our results imply that the reality may be between these two extremes, Cases 1 and 2; reasonable combinations of $k_{57}$ and $k_{OF}$ might account for the presence of r-process-enhanced stars at [Fe/H] $\sim -3$. It is also important to note that the cumulative numbers for the least-massive sub-halos ($M_\ast = 10^4 M_\odot$) are $\sim 0.1$ around the end of their evolutions. This could be another source of large enhancements of [Eu/Fe] ($\geq 1$). The [Eu/Fe] values would be substantially higher than the averaged curves of our models, provided that only a fraction of sub-halos experienced NSMs.

4. SUMMARY AND DISCUSSION

We studied the role of NSMs for the chemical evolution of r-process elements in the framework of Galactic halo formation from merging sub-halos. It has been found that the appearance of Eu at [Fe/H] $\sim -3$ with star-to-star scatter in [Eu/Fe] ($\leq 0.5$) at [Fe/H] $\sim -3$ can be interpreted as a result of lower star formation efficiency $k_{57}$ for less-massive sub-halos. On the other hand, the presence of highly r-process-enhanced EMP stars ([Eu/Fe] $\geq 0.5$) can be explained if values of $k_{OF}$ (the multiplicative factor for the outflow rate) are higher for less massive sub-halos. These may be reasonable assumptions because less massive sub-halo systems have weaker gravitational potential (as indicated by $M_{\odot}$ in Table 3), and thus are expected to form stars less efficiently and/or expel the ISM more easily. The ratio of OFR–SFR, $\eta$, is assumed to be proportional to $M_{\odot}^{-0.3}$. Recent observations of relatively massive galaxies ($10^7–10^10 M_{\odot}$) also suggest a similar anti-correlation between $M_\ast$ and $\eta$ (Chisholm et al. 2014). Under this assumption, the metallicity at the peak of each sub-halo’s MD (Table 3) appears to be consistent with the observed mass–metallicity relation. In addition, the total MD weighted with the sub-halo mass function shows reasonable agreement with that observed for the Galactic halo.

The low-level Ba abundances ([Ba/Fe] $\sim -1.5$) observed in the EMP stars of [Fe/H] $\leq -3$ may be due to contribution from the short-lived binaries (with $t_{NSM} = 1$ Myr in this study). Thus, the main features of the r-process abundances observed in EMP stars, their appearance at [Fe/H] $\sim -3$ with large star-to-star scatter and their sub-solar amounts for [Fe/H] $\leq -3$, can potentially be explained solely by the contribution of NSMs.

The highly Eu enhanced stars at [Fe/H] $\sim -3$ may be accounted for by reasonable combinations of $k_{57}$ and $k_{OF}$. The small cumulative numbers of NSMs ($<1$) for the least-massive sub-halos could be another reason for the observed large scatter in [Eu/Fe] because NSMs may occur only in some, while no NSMs occur in others. Once NSMs occur in such less-massive
systems, their ISM must be highly enriched by r-process elements.

In conclusion, our results imply that the current observational evidence of r-process signatures in EMP stars can be interpreted as a consequence of Galactic halo formation from merging sub-halos. If the model is a reasonable simplification for such chemo-dynamical evolutions of sub-halos, NSMs can be the main r-process contributors throughout the Galactic history. Contributions from CCSNe are not necessarily needed as invoked in previous GCE studies. Note that our assumption of a well-mixed ISM might not necessarily be an over-simplification, at least for less-massive sub-halos, in which a small number of explosive events would easily homogenize their smaller amount of ISM before the next episode of star formation. The observed small scatters of abundance ratios of other elements such as iron-peak elements or α-elements in EMP stars should be examined using a consistent assumption. Possible effects of ISM inhomogeneity as well as of stochastic nature of NSM events (i.e., \( N_{\text{NSM}} < 1 \)) will be discussed in a forthcoming paper.

This work was supported by the RIKEN iTHES Project and the JSPS Grants-in-Aid for Scientific Research (26400232, 26400237).

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