Chemical Evolution of $^{244}$Pu in the Solar Vicinity and Its Implications for the Properties of r-process Production

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Received 2016 October 24; revised 2016 December 6; accepted 2017 January 2; published 2017 January 16

Abstract

Meteoritic abundances of r-process elements are analyzed to deduce the history of chemical enrichment by the r-process, from the beginning of disk formation to the present time in the solar vicinity. Our analysis combines the abundance information from short-lived radioactive nuclei such as $^{244}$Pu with the abundance information from stable r-process nuclei such as Eu. These two types of nuclei can be associated with one r-process event and an accumulation of events until the formation of the solar system, respectively. With the help of the observed local star formation (SF) history, we deduce the chemical evolution of $^{244}$Pu and obtain three main results: (i) the last r-process event occurred 130–140 Myr before the formation of the solar system; (ii) the present-day low $^{244}$Pu abundance as measured in deep-sea reservoirs results from the low recent SF rate compared to $\sim$4.5–5 Gyr ago; and (iii) there were $\sim$15 r-process events in the solar vicinity from the formation of the Galaxy to the time of solar system’s formation and $\sim$30 r-process events to the present time. Then, adopting the hypothesis that a neutron star (NS) merger is the r-process production site, we find that the ejected r-process elements are extensively spread out and mixed with interstellar matter, with a mass of $\sim$3.5 $\times$ 10$^6$ $M_\odot$, which is about 100 times larger than that for supernova ejecta. In addition, the event frequency of r-process production is estimated to be 1 per $\sim$1400 core-collapse supernovae, which is identical to the frequency of NS mergers estimated from the analysis of stellar abundances.

Key words: Galaxy: evolution – meteorites, meteors, meteoroids – nuclear reactions, nucleosynthesis, abundances – solar neighborhood

1. Introduction

The origin and evolution of r-process elements are popular research topics. The detection of a near-infrared light bump in the afterglow of a short-duration $\gamma$-ray burst (e.g., Tanvir et al. 2013) initiated the current understanding that a neutron star (NS) merger is a promising major site for the r-process (e.g., Lattimer & Schramm 1974; Eichler et al. 1989). Two vigorous and successful research activities in particular have encouraged this understanding: one is r-process nucleosynthesis calculations in NS mergers (e.g., Rosswog et al. 2014; Wanajo et al. 2014; Goriely et al. 2015) and the other is modeling the Galactic chemical evolution of r-process elements in terms of the enrichment taking place through NS mergers (e.g., Matteucci et al. 2014; Tsujimoto & Shigeyama 2014a; Ishimaru et al. 2015; Wehmeyer et al. 2015; Komiya & Shigeyama 2016).

In addition to these studies, the features of observed stellar abundances in nearby dwarf galaxies present more direct evidence for NS mergers as the site for the r-process. The properties characterizing NS merger events are their rarity and their high yield of r-process elements per event. Tsujimoto & Shigeyama (2014a) have found that faint classical dwarf spheroidal galaxies (dSphs) exhibit a constant [Eu/H] of $\sim$1.3 over the metallicity range of $-2 \lesssim [\text{Fe/H}] \lesssim -1$, which implies no Eu production events, while more than 10$^3$ core-collapse supernovae (CCSNe) increase the galactic Fe abundance. If CCSNe are associated with r-process production, a gradual increase in [Eu/H] by $\sim$0.35 to 1 dex is predicted for this [Fe/H] range, depending on the theoretical Eu yield from a CCSN (Rauscher et al. 2002; Wanajo 2013). Moreover, Ji et al. (2016) have discovered in an ultra-faint dwarf galaxy, Reticulum II, a feature suggesting that a single event with an r-process yield as high as the amount expected from an NS merger remarkably enhances r-process abundances of this galaxy (see also Roederer et al. 2016).

In addition to capturing electromagnetic waves, we can assess an r-process site and its properties by analyzing meteoritic abundances of r-process elements. In particular, abundances of short-lived radioactive nuclei, such as $^{129}$I or $^{244}$Pu, produced by the r-process inside meteorites, have been known to be used to measure the time interval, $t_{\text{LE}}$, between the last r-process production event and solar system formation since the 1960’s (Reynolds 1960; Wasserburg et al. 1969; Podosek 1970). From the timescale thus obtained, we can infer the rarity of r-process events. According to many reports, a relatively long timescale of $t_{\text{LE}} \approx 100$ Myr is deduced (e.g., Clayton 1983; Dauphas 2005; Lugaro et al. 2014, see Section 2.1). On the other hand, meteoritic abundances of radionuclides such as $^{26}$Al (half-life: 1.03 Myr) and $^{60}$Fe (half-life: 2.2 Myr) imply an injection from a nearby CCSN, since their abundances are higher than the steady-state abundance inferred from $\gamma$-ray observations and Galactic chemical evolution (Huss et al. 2009). Thus, we anticipate that r-process production events may occur much less frequently than CCSNe.

A recent finding of the current low abundance of $^{244}$Pu in deep-sea reservoirs highlights the rarity of r-process events (Wallner et al. 2015). It was found that the current abundance is lower than expected from continuous production in CCSNe by about two orders of magnitude. This current abundance, together with that in the early solar system (ESS), indeed...
provides evidence for the chemical evolution of $^{244}\text{Pu}$ in the solar vicinity, which is found to support the rarity of r-process events. This rarity is compatible with an NS merger frequency (Hotokezaka et al. 2015). Additionally, $^{244}\text{Pu}$ abundance can trace the local star formation (SF) history with a rigid time-resolution since its short half-life of 81 Myr should make its abundance sensitive to the star formation rate (SFR) in individual epochs. On the other hand, the local SFR(t) has been well studied by several age-dating methods for stars (Hernandez et al. 2000; Rocha-Pinto et al. 2000; Vergely et al. 2002; Cignoni et al. 2006; Fuchs et al. 2009). These studies have established our current understanding that the local SFR(t) is not constant: it is oscillatory (Hernandez et al. 2000), or it has a few burst SF events (Rocha-Pinto et al. 2000) that will significantly impact $^{244}\text{Pu}$ time evolution.

A new method for analyzing meteoritic abundances of r-nuclides provides key information on the history of r-process enrichment. While abundances of short-lived radioactive r-nuclides essentially reflect only the most recent r-process event, abundances of stable r-nuclides reflect the accumulation of all r-process events until the ESS. Thus, combining these two sources of information will lead to accounting for the total number of events that contribute to the local r-process enrichment. In this Letter, we present $^{244}\text{Pu}$ time evolution by combining analysis results of meteoritic abundances (Section 2) with the observed local SF history (Section 3). Our study further explores the deduction of the properties of r-process production, i.e., its frequency and its propagation, both of which are of great significance but remain unsolved (Section 4).

### 2. Assessment from Unstable and Stable Nuclei

We start by extracting information on local r-process enrichment in the ESS from analyses of meteoritic abundances. We estimate the following three parameters: (i) how much a single r-process event enriches the fraction of a particular r-nuclide in the surrounding interstellar matter (ISM) per volume; (ii) how many times r-process events occur locally and enrich the ISM from the initial SF until the ESS; and (iii) when does the last r-process event occur before the ESS. For this purpose, we need two types of r-nuclides: short-lived radioactive r-nuclides and stable r-nuclides. In our analysis, we adopt $^{244}\text{Pu}$ (half-life: 81 Myr), which is present in the form of fissionogenic Xe isotopes as the former and Eu as the latter.

#### 2.1. Mass Fraction of $^{244}\text{Pu}$ in the ISM by a Single r-process Event

Meteoritic abundances of short-lived radioactive r-nuclides are dominated by the nuclides ejected from the last r-process production event as long as the time interval between r-process events is much longer than the half-lives of the r-nuclides. $^{244}\text{Pu}$, along with other r-nuclides such as $^{247}\text{Cm}$ and $^{129}\text{I}$, meets this condition. From this fact, we will deduce how much a single r-process event enriches the surrounding ISM with r-nuclides.

First, we deduce the mass fraction of $^{244}\text{Pu}$ at the ESS. The number fraction of $^{235}\text{U}$ relative to hydrogen at the ESS is estimated to be $6.37 \times 10^{-13}$ from meteorites, considering the radioactive decay (half-life: 4.47 Gyr) until the present over 4.56 Gyr (Lodders et al. 2009). Then, from the abundance of $^{244}\text{Pu}$ relative to $^{235}\text{U}$ (0.008) at the ESS (Turner et al. 2004, 2007) and a typical number density of hydrogen in the ISM (1 cm$^{-3}$), the number density of $^{244}\text{Pu}$ at the ESS is deduced to be $5.10 \times 10^{-15}$ cm$^{-3}$ with a corresponding mass fraction of $8.90 \times 10^{-13}$.

The amount of $^{244}\text{Pu}$ thus obtained includes small contributions from a few events before the last one. By removing these small contributions, we obtain how much a single r-process event polluted the ISM with $^{244}\text{Pu}$ at the ESS. For this estimate, two timescales are required. One is the time interval $t_{\text{LE}}$ between the last r-process event and solar system formation. The other is the mean time interval $t_{\text{int}}$ between individual r-process events before the ESS epoch. $t_{\text{LE}}$ is necessary to know the remaining fraction of $^{244}\text{Pu}$ owing to radioactive decay from the last r-process event. This, together with $t_{\text{int}}$, gives the contributing fraction from prior events to meteoritic $^{244}\text{Pu}$ abundance.

$t_{\text{LE}}$ is deduced from a comparison of the ratio of unstable to stable r-process isotopes between meteoritic abundances and the theoretical production yields. Since $t_{\text{LE}}$ critically depends on the assumed production ratio, we need several combinations of unstable/stable isotopes to make an independent estimate of $t_{\text{LE}}$. For instance, the useful isotope combinations are $^{247}\text{Cm}/^{235}\text{U}$, $^{129}\text{I}/^{127}\text{I}$, and $^{244}\text{Pu}/^{238}\text{U}$, where the unstable isotopes have half-lives of 1.56 $\times 10^9$ yr, 1.57 $\times 10^9$ yr, and 8.1 $\times 10^7$ yr, respectively. From $^{244}\text{Pu}/^{238}\text{U}$ and $^{129}\text{I}/^{127}\text{I}$, a relatively long interval of $t_{\text{LE}} \approx 100$ Myr is obtained (Reynolds 1960; Wasserburg et al. 1969; Clayton 1983; Dauphas 2005). More recently, using the latest nucleosynthesis results of $^{127}\text{I}$ and $^{129}\text{I}$, Lugano et al. (2014) deduced $t_{\text{LE}} = 109$ Myr together with $t_{\text{LE}} = 123$ Myr from $^{247}\text{Cm}/^{235}\text{U}$. Though the value of $t_{\text{LE}}$ thus obtained should be revised, as will be discussed in Section 2.3, we here adopt $t_{\text{LE}} = 120$ Myr as an initial input. In addition, we assume $t_{\text{int}} = 200$ Myr, which will yield the adopted $t_{\text{LE}}$ as one of the plausible cases.

From $t_{\text{LE}} = 120$ Myr, the remaining fraction of $^{244}\text{Pu}$ from the last event at the ESS is estimated to be 35.8%. Then, from both $t_{\text{LE}} = 120$ Myr and $t_{\text{int}} = 200$ Myr, we deduce that the fraction of $^{244}\text{Pu}$ from the last event with respect to the total $^{244}\text{Pu}$ in meteoritic abundance is 82%, which is confirmed to be a large fraction as expected. These values, combined with the prior estimate of $8.90 \times 10^{-13}$ result in $2.03 \times 10^{-12}$ as the mass fraction of $^{244}\text{Pu}$ in the ISM yielded from an injection by a single r-process event.

#### 2.2. Total Frequency of r-process Events until Solar System Formation

Next, we relate the above $^{244}\text{Pu}$ mass fraction to that of stable Eu nuclei by introducing the theoretical production ratio between the two nuclei. The production of radioactive r-nuclides such as Th, U, and Pu is investigated by Goriely & Arnould (2001), and according to their latest nucleosynthesis results (Goriely & Janka 2016), the updated production ratio for $^{244}\text{Pu}/^{238}\text{U}$ is 0.33. This value is identical to other estimates by Cowan et al. (1987) (=0.4) and Eichler et al. (2015) (=0.33).

On the other hand, regarding the existing r-nuclides in meteorites (or solar photosphere), we anticipate that the production pattern follows the solar r-process pattern. This hypothesis is justified by the observation that Galactic metal-poor halo stars exhibit the universality of r-process abundance distribution for heavy r-nuclides, which matches the solar r-process pattern (e.g., Montes et al. 2007; Sneden et al. 2008).
Accordingly, the relative production ratio for $^{238}$U/Eu is inferred from the solar r-process ratio corrected by the radioactive decay for $^{238}$U (Eu: 0.0984, $^{238}$U: 0.018 (atoms/10$^8$ Si); Lodders et al. 2009), as well as by a 3% contribution to Eu from the s-process. The mass ratio is found to be 0.2955. This, together with $^{244}$Pu/$^{238}$U = 0.33, results in $^{244}$Pu/Eu = 0.097. Then, we finally obtain the value of the Eu mass fraction due to enrichment by a single r-process event as $2.10 \times 10^{-11}$.

The solar r-process abundance of Eu, $3.75 \times 10^{-10}$, is the end result of the accumulation of Eu by individual r-process events in the solar vicinity until the ESS. Thus, using the enrichment caused by each event, we can count the total number of events until the ESS. Dividing $3.75 \times 10^{-10}$ by $2.10 \times 10^{-11}$, we obtain the total number of r-process events until the ESS as $\sim 18$. Here we ignore the mixing process of the ISM on the $\sim 100$ Myr timescale, which may allow Eu atoms to move into and out of the ISM, yielding the solar system over $\sim 7.5$ Gyr. Simulations of r-process enrichment that are combined with hydrodynamics of the ISM in the Galaxy are indeed awaited.

### 2.3. Last r-process Event Time

Since the total number $N_r$ of r-process events determines the abundances of stable r-nuclei at the ESS, $t_{LE}$ is largely influenced by $N_r$. This is understood from the abundance ratio $R_{LE}$ of a radioactive isotope to a stable isotope after the last event within meteorites, which is given by the following equation (Lugaro et al. 2014):

$$R_{LE} = R_{yield} \times \frac{1}{N_r} \times \left(1 + \frac{e^{-\tau/t_{int}}}{1 - e^{-\tau/t_{int}}\tau}\right),$$

where $R_{yield}$ is the production ratio of each single event and $\tau$ is the mean lifetime (half-life/ln2) of a radioactive isotope. Thus, $t_{LE}$ should be updated with our result. To calculate $t_{LE}$, we need to assume $t_{int}$ for a period of $\leq 1$ Gyr before the ESS, in addition to $N_r$. Then, incorporating $N_r = 18$ with $t_{int} = 200$ Myr before the ESS into calculations, we deduce $t_{LE} = 137$, 139, and 145 Myr from $^{129}$I/$^{271}$I, $^{247}$Cm/$^{235}$U, and $^{244}$Pu/$^{238}$U, respectively. Accordingly, we here adopt $t_{LE} = 140$ Myr. This revised $t_{LE}$ modifies the prior $^{244}$Pu remaining fraction of the last event in meteorites from 0.358 to 0.302. Then the resultant mass fractions of $^{244}$Pu and Eu by one r-process event are slightly modified to $2.41 \times 10^{-12}$ and $2.49 \times 10^{-11}$, respectively. These new values result in $N_r \sim 15$. Hereafter we adopt $N_r = 15$, though this value can be improved further, as there are still uncertainties in $t_{LE}$ and $t_{int}$. A further update of $t_{LE}$ will be done with a variable $t_{int}$ in the next section.

### 3. Incorporation with the Local SF History

Incorporating the total number of r-process events until the ESS into the observed local SF history, we calculate the evolution of $^{244}$Pu density in the solar neighborhood over the entire period up to the present. Our approach has two steps: (i) we integrate the SFR from the beginning of the Galaxy to the time of ESS and bin by the inferred number of contributing r-process events during that time; and (ii) we integrate the SFR forward from the ESS time to the present, and at any time that the integrated number of newly formed stars reaches the threshold number, $^{244}$Pu is ejected into the ISM. We utilize the two observed SF histories obtained by Cignoni et al. (2006) and Rocha-Pinto et al. (2000) because these two papers attempt to provide the whole SF history while others limit it to the most recent gigayears. Their results are shown by red and blue lines, respectively, in Figure 1. Applying the above procedures to the SF histories, we find that each SF history results in 26 and 31 events of r-process production in total. Then, from the assigned individual r-process events as a function of time, we calculate the time evolution of $^{244}$Pu density in the ISM (Figure 2). Owing to the observed tendency that the SFR during the recent 2 Gyr is relatively low compared with that at over 2–5 (6) Gyr ago, including the ESS epoch, $t_{int}$ changes from $\sim 250$ Myr around the ESS to $\sim 400$ Myr at the current time. A relatively lower SFR in recent times is also deduced from white dwarf cosmochronology (Tremblay et al. 2014). Since the oscillatory lowest level of $^{244}$Pu density is determined by the length of $t_{int}$, the recent long $t_{int}$ makes the $^{244}$Pu density drop to a value as
low as the measurement in ocean archives (Wallner et al. 2015) during the last 2 Gyrs. The time interval of the latest r-process event inferred from the $^{244}$Pu density measured in ocean sediments is 360 Myr. If we assume the SFR prior to the ESS time, a Poisson distribution of r-process events gives a no-event probability of 0.2 within the time interval. On the other hand, the observed current low SFR lifts the probability to 0.4 and further to 0.65 for the upper limit of the sediment abundance.

In addition, from our predicted $^{244}$Pu evolution, we deduce $t_{LE}$ with a variable $t_{min}$, which is calculated based on the SFR-$t$ relation in Figure 1. Then, we eventually obtain $t_{LE} = 130$ Myr from the SF history of Cignoni et al. (2006) and 140 Myr from that of Rocha-Pinto et al. (2000). This longer value of $t_{LE}$ compared with the values thus far is mainly caused by the small $N_e$ until the ESS, which results in a high initial $^{244}$Pu/$^{238}$U ratio at the last r-process event, owing to a low $^{238}$U abundance that reflects the accumulation of the past r-process events.

4. Properties of r-process Events

4.1. Propagation

By comparing the deduced $^{244}$Pu density ejected in the ISM by a single r-process event with the $^{244}$Pu nucleosynthesis yield from an r-process site, we can estimate how much the ISM will be eventually mixed with the ejecta-carrying r-process elements. Considering the implied rarity of frequency as a countable number of $\sim 30$ events over the period of 12 Gyr in the solar vicinity, together with a detailed discussion in a previous work (Hotokezaka et al. 2015), the r-process production site can be reasonably identified with an NS merger. Then, we assume a typical ejecta mass for an NS merger of 0.01 $M_{\odot}$ and individual element production obeying the solar r-process pattern. In addition, we assume that light r-process elements such as Sr, Y, and Zr ($A \approx 90$) are not synthesized in an NS merger from the implication of an elemental feature among Galactic halo stars (Tsujimoto & Shigeyama 2014b, see also Montes et al. 2007). According to the calculations claiming the production of $A \gtrsim 130$ by an NS merger (e.g., Bauswein et al. 2013), we set the lower boundary at $A = 127$, since the discussion based on the last r-process event (see Section 2.1) suggests that the production site of iodine is the same as that of heavier r-nuclei such as Pu.

The above hypotheses, together with the radio-decay correction, find the $^{238}$U mass fraction inside the ejecta to be $2.55 \times 10^{-3} M_{\odot}$. Then, from $^{244}$Pu/$^{238}$U = 0.33, the mass fraction of $^{244}$Pu is estimated to be $8.42 \times 10^{-4}$, which is equivalent to a mass of $8.42 \times 10^{-6} M_{\odot}$ in the ejecta with a mass of 0.01 $M_{\odot}$. Combining this ejected mass of $^{244}$Pu with its resultant density in the ISM, the mass of ISM mixed with the r-process ejecta is deduced to be $8.42 \times 10^{-6} M_{\odot}$/$2.41 \times 10^{-12} \approx 3.5 \times 10^6 M_{\odot}$. It turns out that the mass mixed with the ejecta of an NS merger that expands with a velocity of 10% to 30% of the speed of light is much larger than that swept-up by an SN of $5.1 \times 10^4 M_{\odot}$ (Shigeyama & Tsujimoto 1998). The corresponding radius of the cylindrical disk is found to be 370 pc, assuming a local surface density of gas (H I + H$_2$) of $8 M_{\odot}$ pc$^{-2}$ (Koda et al. 2016). The timescale to pervade the ISM could be as short as on the order of Myr (Tsujimoto & Shigeyama 2014a) and is thus negligible.

4.2. Frequency

Utilizing the propagation of r-process ejecta, we can deduce the event frequency of r-process production with respect to the occurrence rate of CCSNe. The current time interval between r-process production events is found to be about 400 Myr. Thus, it turns out that the total number of CCSNe inside a cylindrical disk with a 370 pc radius for a period of 400 Myr eventually yields one r-process production event. Here we assess a local CCSN rate from two approaches. For the Galaxy as a whole, the current SFR and CCSN rates are estimated to be $1.65 M_{\odot}$ yr$^{-1}$ (Licquia & Newman 2015) and 2.3 CCSNe per century (Li et al. 2011), respectively; these two rates establish the correlation that an SFR of 1 $M_{\odot}$ yr$^{-1}$ is equal to 1.4 CCSNe per century. Then, from the present-day local SFR of 0.48–1.1 $M_{\odot}$ Gyr$^{-1}$ pc$^{-2}$ (Fuchs et al. 2009; Tsujimoto 2011), we obtain a CCSN rate of 1 per 2.1–4.8 Myr, within a 100 pc radius. On the other hand, the recent detection of $^{60}$Fe in deep-sea sediments reveals that two CCSNs occurred 1.5–3.2 Myr and 6.5–8.7 Myr ago (Wallner et al. 2016), within a distance of 100 pc (Breitschwerdt et al. 2016). Then, putting the two results together, we finally adopt a CCSN rate of 1 per 4 Myr, within a 100 pc radius.

The derived CCSN rate gives 1370 CCSNe in total inside a cylindrical disk with a 370 pc radius for a period of 400 Myr. This estimate is equivalent to the rate of r-process production by NS merger of 1 per 1370 CCSNe. The rate is in fairly good agreement with the estimate of 1 per 1000–2000 CCSNe that was made from the correlation of stellar abundances between [Fe/H] and [Eu/H] in dSphs, as well as from Galactic chemical evolution (Tsujimoto & Shigeyama 2014a). We reanalyze its frequency from abundance correlation between [Mg/H] and [Eu/H] among Galactic stars to avoid uncertainties in the chemical enrichment process in dSphs and contributions from Type Ia supernovae. By inputting the Mg nucleosynthesis yield from a CCSN deduced by the observed two quantities, i.e., an average Fe mass of $0.07 M_{\odot}$ (light curve analysis; Hamuy 2003) and the plateau of $[\text{Mg/Fe}] = 0.4$ among halo stars, we obtain a frequency of 1 per $\sim 1400$ CCSNe for Eu production.

This work benefited from support by the National Science Foundation under grant No. PHY-1430152 (JINA Center for the Evolution of the Elements), and was supported by JSPS KAKENHI grant numbers 15K05033, 15K13602, and 16H04081.

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