RELATIVE CONTRIBUTIONS OF THE WEAK, MAIN, AND FISSION-RECYCLING $r$-PROCESS

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ABSTRACT

There has been a persistent conundrum in attempts to model the nucleosynthesis of heavy elements by rapid neutron capture (the $r$-process). Although the locations of the abundance peaks near nuclear mass numbers 130 and 195 identify an environment of rapid neutron capture near closed nuclear shells, the abundances of elements just above and below those peaks are often underproduced by more than an order of magnitude in model calculations. At the same time, there is a debate in the literature as to what degree the $r$-process elements are produced in supernovae or the mergers of binary neutron stars. In this paper we propose a novel solution to both problems. We demonstrate that the underproduction of nuclides above and below the $r$-process peaks in main or weak $r$-process models (like magnetohydrodynamic jets or neutrino-driven winds in core-collapse supernovae) can be supplemented via fission fragment distributions from the recycling of material in a neutron-rich environment such as that encountered in neutron star mergers (NSMs). In this paradigm, the abundance peaks themselves are well reproduced by a moderately neutron-rich, main $r$-process environment such as that encountered in the magnetohydrodynamical jets in supernovae supplemented with a high-entropy, weakly neutron-rich environment such as that encountered in the neutrino-driven-wind model to produce the lighter $r$-process isotopes. Moreover, we show that the relative contributions to the $r$-process abundances in both the solar system and metal-poor stars from the weak, main, and fission-recycling environments required by this proposal are consistent with estimates of the relative Galactic event rates of core-collapse supernovae for the weak and main $r$-process and NSMs for the fission-recycling $r$-process.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – supernovae: general

1. INTRODUCTION

It has been known for more than half a century (Burbidge et al. 1957) that about half of the elements heavier than iron are produced via rapid neutron capture (the $r$-process). Indeed, the basic physical conditions for the $r$-process are well constrained (Burbidge et al. 1957) by simple nuclear physics. The observed abundance distribution requires a sequence of near-equilibrium rapid neutron captures and photoneutron emission reactions far on the neutron-rich side of stability. This equilibrium is established with a maximum abundance strongly peaked on one or two isotopes far from stability. The relative abundance of $r$-process elements is then determined by the relative $\beta$-decay rates along this $r$-process path, i.e., longer $\beta$-decay lifetimes result in higher abundances.

In spite of this simplicity, however, the unambiguous identification of the site for the $r$-process nucleosynthesis has remained elusive. Parametrically, one can divide current models for the $r$-process into three scenarios roughly characterized by the number of neutron captures per seed nucleus ($n/s$). This parameter, in turn, is the consequence of a variety of conditions such as timescale, baryon density, average charge per baryon, $Y_e \equiv \langle Z/A \rangle$, and entropy (or baryon-to-photon ratio), corresponding to different astrophysical environments (e.g., Meyer & Brown 1997; Otsuki et al. 2003).

An environment in which there are few neutron captures per seed ($n/s \sim 50$) produces what has been identified as the weak $r$-process (Wasserburg et al. 1996). It can only produce the lightest $r$-process nuclei up to $A \sim 125$. Such an environment may occur, for example, in the neutrino-driven wind (NDW) of core-collapse supernovae (CCSNe; Woosley et al. 1994; Wanajo 2013), part of the outflow from the remnant of compact binary mergers (Perego et al. 2014; Rosswog et al. 2014; Just et al. 2015), the delayed magnetohydrodynamic (MHD) jet from CCSNe (Nishimura et al. 2015).

An environment with enough neutron captures per seed ($n/s \sim 100$) to produce the two $r$-process abundance peaks at $A = 130$ and 195 corresponds to what has been dubbed the main $r$-process and could correspond, for example, to the ejection of neutron-rich material via magnetic turbulence in magnetohydrodynamically driven jets (MHDJs) from CCSNe (Nishimura et al. 2006; Fujimoto et al. 2007, 2008; Ono et al. 2012; Winteler et al. 2012; Nakamura et al. 2014; Nishimura et al. 2015), or in neutron star mergers (NSMs; Wanajo et al. 2014; Goriely et al. 2015).

In this paper, we are particularly interested in a third environment that we dub the fission-recycling $r$-process. In this environment the number of neutron captures per seed nucleus can be very large ($n/s \sim 1000$). The $r$-process path then proceeds along the neutron drip line all the way to the region of fissile nuclei ($A \approx 300$), where the $r$-process is terminated by $\beta$- or neutron-induced fission. Fission recycling can then occur whereby the fission fragments continue to experience neutron captures until $\beta$ - or neutron-induced fission again terminates the $r$-process path. After a few cycles the abundances can become dominated by the fission fragment distributions (FFDs) and not as much by the $\beta$-decay flow near the closed shells.
Hence, a very different mass distribution can ensue. Such environments are often associated with the dynamical ejecta from NSMs in which the tidal ejection of neutron-rich material during the merger can lead to fission recycling and many neutron captures per seed (e.g., Goriely et al. 2011, 2013; Korobkin et al. 2012; Piran et al. 2013; Rosswog et al. 2013).

Observations (Sneden et al. 2008) showing the appearance of heavy-element \( r \)-process abundances early in the history of the Galaxy seem to favor the short progenitor lifetime of CCSNe over NSMs as the \( r \)-process site. However, identifying the \( r \)-process site in models of CCSNe has been difficult (Arnould et al. 2007; Thielemann et al. 2011).

The three types of environments, neutrino-driven winds, MHDJs, and NSMs, have all been studied extensively in the recent literature. The robustness of the results varies for different environments, but uncertainties in both astrophysical conditions and nuclear input are well recognized in all cases. For example, the previously popular model (Woosley et al. 1994) of \( r \)-process nucleosynthesis in the NDW above the newly forming neutron star has been shown (Fischer et al. 2010; Hüdepohl et al. 2010) to be inadequate as a main \( r \)-process site when modern neutrino transport methods have been employed. The required neutron captures per seed do not occur in the neutrino energized wind. Nevertheless, it is quite likely that the weak \( r \)-process does occur (Wanajo 2013) in the NDW, producing neutron-rich nuclei up to about \( A \approx 125 \).

Regarding the weak \( r \)-process, however, one should note that while most \( s \)-process models now produce \( r \)-process residuals for \( A \geq 120 \) that look remarkably similar, this is not the case for lighter nuclei. Hence, there is some uncertainty in determining the solar system \( r \)-process abundances via subtraction of the \( s \)-process contribution from the total abundances. Indeed, a final consensus has not yet been reached on the predicted \( s \)-process abundances of light elements. Hence, what is usually taken to be the weak \( r \)-process (or unknown light-element primary process [LEPP]) may actually correspond to a much different environment. For example, in Trippella et al. (2014) it was demonstrated that enhanced light-element abundances could arise via nonparametric MHD-driven mixing mechanisms. This enhanced light-element \( s \)-process component could obfuscate the need for a weak \( r \)-process. Nevertheless, with this caveat in mind, we adopt the NDW in SNe as representative of the weak \( r \)-process. We note, however, that our arguments below regarding the relative contribution of the weak \( r \)-process may in fact refer to the relative contribution of an \( s \)-process-driven LEPP.

Indeed, the difficulties in reproducing the \( r \)-process abundances have motivated many new studies of NSMs (e.g., Goriely et al. 2011; Korobkin et al. 2012; Goriely et al. 2013; Perego et al. 2014; Wanajo et al. 2014). Nevertheless, one scenario for the \( r \)-process in CCSNe remains viable. It is the MHDJ model (Nishimura et al. 2006; Fujimoto et al. 2007, 2008; Ono et al. 2012; Winteler et al. 2012; Nakamura et al. 2014, 2015; Nishimura et al. 2015). In this model magnetic turbulence leads to the ejection of neutron-rich material into a jet. As the jet transports this neutron-rich material away from the star, it can undergo \( r \)-process nucleosynthesis in a way that avoids the low neutron-to-seed ratios associated with neutrino interactions in the NDW model. Moreover, the required conditions of the \( r \)-process environment (timescale, neutron density, temperature, entropy, electron fraction, etc.) are well accommodated in this model.

However, there is a persistent problem in this model, and many general models (e.g., Meyer & Brown 1997; Otsuki et al. 2003) in which the \( r \)-process elements are produced in a short timescale via the rapid expansion of material away from a neutron star. In such models, the neutron density rapidly diminishes and the \( r \)-process path freezes out near the neutron closed shells far from stability. Most such models underestimate isotopic abundances just below and above the \( r \)-process abundance peaks, as we describe in more detail below.

Nearly all \( r \)-process models are fraught with uncertainties in the input nuclear physics, the astrophysical environment, and the galactic chemical evolution. Rather than give up, however, it is highly desirable to explore any possible method in which the relative contributions of each of the primary environments (weak, main, and fission recycling) could be ascertained from observation. In this paper we propose such a possibility.

With this in mind, our goal is to analyze the general advantages and disadvantages of each of the characteristic environments. Although we have noted here specific astrophysical models that are likely to be associated with the various conditions, the reader should be aware of the uncertainties involved and consider these environments as illustrative, not definitive. Nevertheless, we speculate here that it may be possible to quantify the relative contribution of each scenario to the observed solar system \( r \)-process abundance distribution and the distribution of \( r \)-process elements in the early Galaxy. The novel conclusion of this paper is that one can possibly utilize the inherent shortcomings of the three characteristic environments to estimate the relative contributions of each (weak, main, and fission recycling) to the final observed \( r \)-process abundances.

2. EFFECT OF NUCLEAR CLOSED SHELLS

Figure 1 illustrates why the abundances below and above the \( r \)-process peaks are bypassed. It shows an example of a typical calculated \( r \)-process path near the \( N = 82 \) neutron closed shell just before freezeout when the neutrons are rapidly exhausted and the abundances begin to \( \beta \)-decay back to the region of stable isotopes. Neutron captures and photoneutron emission proceed in equilibrium for nuclei with a neutron binding energy of about 1–2 MeV. Above and below a closed neutron shell,
however, this $r$-process path shifts abruptly toward the closed shell from below (or away from the closed shell for higher nuclear masses). This shifting of the $r$-process path toward the $N = 82$ neutron closed shell causes isotopes with $N = 70$–$80$ ($A \sim 110$–$120$) to be bypassed. Similarly, the $A = 140$–$147$ underproduction corresponds to the isotopes with proton closed shell $Z = 50$ and $N \sim 90$–$97$ ($A \sim 140$–$147$). These isotopes will also be bypassed in the $\beta$-decay flow, as is evident in Figure 1.

We emphasize that this is not just an artifact of the particular mass model employed in this study. Nearly all models in the current literature with a rapid freezeout (including the MHDJ; Nishimura et al. 2006; Fujimoto et al. 2007, 2008; Ono et al. 2012; Winteler et al. 2012; Nakamura et al. 2014; Nishimura et al. 2015) show this underproduction if the final abundances are normalized to the abundance peaks. Indeed, one is hard-pressed to find any model for the main $r$-process (including NDW models) in which this underproduction does not occur.

One can of course contrive calculations to somewhat fill the gaps on both sides of the second $r$-abundance peak. Recently, for example, Lorusso et al. (2015) were able to avoid the underproduction in a schematic high-entropy outflow model by incorporating a summation of several entropies. In such a model one can fill in the gaps similarly to the way we propose to do this by summing contributions from various physical conditions. As another example, calculations could fill the gaps by using the ETFSI mass model as displayed in Figure 7 of Nishimura et al. (2006). However, these models do so at the cost of displacing the second and third peaks and/or underproducing (or overproducing) abundances over a wide mass region between the second and third peaks. This was also a consistent feature in the original realistic NDW models of Woosley et al. (1994). Indeed, this effect is apparent in almost every $r$-process calculation since the 1970s (see review in Mathews & Ward 1985).

We note, however, that new attempts have been presented (Kratz et al. 2014) of $r$-process calculations in a parameterized NDW scenario based on the models of Freiburghaus et al. (1999). Making use of new nuclear masses and $\beta$-decay rates from the finite-range droplet model FRDM(2012) (Möller et al. 2012), it was shown that the previous discrepancies near $A = 120$ are significantly diminished compared to the same calculation based on the previous FRDM(1992) (Möller et al. 1995) nuclear properties. Hence, one must keep in mind that at least some of the apparent discrepancy may be due to the adopted nuclear input.

Although it has been speculated for some time (e.g., Woosley et al. 1994; Pfeiffer et al. 2001; Farouqi et al. 2010) that this could be due to quenching of the strength of the shell closure or $\beta$-decay rates near the closed neutron shell, this explanation is unlikely. Recent $r$-process calculations (Nishimura et al. 2012) based on new measurements (Nishimura et al. 2011) of $\beta$-decay half-lives near the $A = 130$ $r$-process path have confirmed the absence of shell quenching effects in the $\beta$ flow. Moreover, recently the first-ever studies (Watanabe et al. 2013) of the level structure of the waiting-point nucleus $^{128}\text{Pd}$ ($Z = 46, N = 82$ in Figure 1) and $^{126}\text{Pd}$ have been completed. This study clearly indicates that the shell closure at the neutron number $N = 82$ is fairly robust. Hence, there is absolutely no evidence of the hypothesized quenching effects in either the $\beta$-decay rates or nuclear masses. One must suppose that some other resolution of this underproduction is necessary.

One goal of this paper is, therefore, to point out that a solution to the underproduction of nuclei above and below the $r$-process abundance peaks can be obtained if one considers that a fission-recycling environment (e.g., NSMs) has contributed to the solar system $r$-process abundance distribution in addition to the environments responsible for the weak and main $r$-process (like CCSNe). Indeed, this novel solution not only resolves this dilemma but can quantify the answer to the question of the relative contributions to the $r$-process abundances of the weak and main $r$-process environments (such as those due to CCSNe) versus long-duration fission-recycling environments (such as NSMs).

3. FISSION-RECYCLING $r$-PROCESS

For this paper we highlight the possible role of fission recycling to account for the underproduction problem above and below the $r$-process peaks often found in models for the main $r$-process abundances. For our purposes we employ a specific NSM model, although we note that this is illustrative of any fission-recycling $r$-process environment. Nevertheless, the most natural current site for such fission recycling to occur is in the NSM models. The ejected matter from NSMs is very neutron-rich ($Y_e \sim 0.1$). This means that the $r$-process path proceeds along the neutron drip line all the way to the onset of fission recycling. As noted above, after a few cycles the abundances can become dominated by the FFDs and not as much by the $\beta$-decay flow near the closed shells. Hence, a very different mass distribution can ensue.

In this regard we note that a number of recent studies (Goriely et al. 2011; Korobkin et al. 2012; Goriely et al. 2013; Perego et al. 2014; Wanajo et al. 2014) have indicated that the $r$-process in NSMs can involve a distribution of neutron-rich environments. Such models can produce a final abundance pattern that is similar to the solar system $r$-abundances. Here, even though we use the term NSM model, it is intended to refer to the portion of the ejecta that experiences fission recycling, while the other ejecta is similar to an NDW- or MHDJ-like model. Hence, when we refer to the NSM model, we really mean the ejecta that experiences fission recycling that fills in the bypassed abundances produced in trajectories that produce the main $r$-process.

An important point is that models including fission-recycling effects produce a final abundance pattern that is relatively insensitive to the astrophysical uncertainties (Korobkin et al. 2012), although the total (including non-recycling ejecta) abundances can be sensitive to the detailed model.

Nevertheless, the distribution of nuclear fission products can affect the abundance pattern. Hence, one must carefully extrapolate FFDs to the vicinity of the $r$-process path (see Martínez-Pinedo et al. 2007; Erler et al. 2012). We argue that by incorporating the expected broad distribution of fission fragments based on phenomenological fits to observed FFDs, the effect of the neutron closed shells becomes smoothed out, thereby providing a means to fill in the isotopes bypassed in the main $r$-process.

For the present study we have made use of self-consistent $\beta$-decay rates, $\beta$-delayed neutron emission probabilities, and $\beta$-delayed fission probabilities taken from Chiba et al. (2008). The spontaneous fission rates and the $\alpha$-decay rates are taken from Koura (2004). In our $r$-process calculations, $\beta$-delayed
fission is the dominant nuclear fission mode. Hence, for the most part other fission modes like neutron-induced fission can be neglected (Chiba et al. 2008).

To generate FFDs far from stability, we have made use of a semiempirical model (Tatsuda et al. 2006; Ohta et al. 2007; Chiba et al. 2008) that well reproduces the systematics of known FFDs. This model can be naturally extrapolated to the required heavy neutron-rich isotopes of the r-process. As such, it is a robust alternative means to predict yields from fission recycling.

A key ingredient of this model is that it can account for FFDs that can either be single humped, bimodal, or even trimodal. This is achieved by a weighted superposition of up to three Gaussian functions:

\[
f(A, A_p) = \sum_{i=0}^{3} \frac{1}{\sqrt{2\pi} \sigma_i} W_i \exp \left( -\frac{(A - A_i)^2}{2\sigma_i^2} \right),
\]

where \( A \) is the mass number of each fission fragment, \( A_p \) is that of the parent nucleus, \( \sigma \) is the width of the three Gaussian functions, and the sum is over the possible FFDs, \( i = L, H, M, \) with

\[
A_H = \frac{(1 + \alpha)}{2} (A_p - N_{\text{loss}}),
\]

\[
A_L = \frac{(1 - \alpha)}{2} (A_p - N_{\text{loss}}),
\]

and

\[
A_M = \frac{(A_H + A_L)}{2}.
\]

The factor \( W_i \) is a weighting given by \( (1 - \omega_i) \) for \( i = L \), \( H \) and \( 2\omega_i \) for \( i = M \). The quantities \( \omega \) and \( \alpha \) are shape-symmetry and mass-asymmetry parameters, respectively, as defined below. \( N_{\text{loss}} \) is the number of prompt neutrons.

For the present application we include the dispersion in the FFDs (\( \sigma = 7.0 \)) and \( N_{\text{loss}} = 2 \) from measured experiments on actinides. The adopted fission neutron emission is an average value for all possible fission events. We have run calculations in which this number \( N_{\text{loss}} \) is varied from 2 to 8 and found that the results are nearly indistinguishable, although a very small change is found below \( A < 100 \) and near the valley around \( A = 180 \). The atomic number and neutron number of each fission fragment are determined by the assumption that the proton-to-neutron ratio is the same as that of the parent nucleus after correcting for prompt neutron emission, i.e., \( Z_p/N_p = Z/(N + N_{\text{loss}}/2) \).

We have run calculations in which the Gaussian width parameter \( \sigma \) is varied from 4 to 14 and compared with the result with \( \sigma = 7 \). We found that the rare-earth peak changes by only \( \pm 20\% \), \( \pm 25\% \) so that the abundance decreases slightly for larger \( \sigma \). Although the abundances below \( A < 100 \) and near the valley around \( A = 180 \) increase as \( \sigma \) increases, these changes do not change the overall distribution drastically, and the conclusions of this article are not affected by fixing \( \sigma = 7 \).

The quantity \( \alpha \) in Equations (2) and (3) is the average mass-asymmetry parameter corresponding to the valley of the potential energy surface of the parent nucleus near the scission point for nuclear fission. This has been calculated in the liquid drop model (Myers & Swiatecki 1999) with shell energy corrections determined (Iwamoto et al. 1976; Sato et al. 1979) from the two-center shell model in the three-dimensional shape parameter space composed of \( \alpha \), the distance between the centers of the two-harmonic oscillators \( z \), and the deformation parameter of the fission fragments \( \delta \). The quantity \( \omega \) is determined as \( \omega = -0.2(V_\beta - V_\alpha - 20.0) \) for \( V_\beta - V_\alpha < 2.0 \text{MeV} \) and \( \omega = 0 \) otherwise, where \( V_\beta \) and \( V_\alpha \) denote the potential values at symmetric and asymmetric valleys, respectively, at the fragment distance \( z \) corresponding to scission. This approximate formula is derived to account for the observed rapid change between asymmetric- and symmetric-mass distributions around \( ^{256}\text{Fm} \), i.e., \( V_\beta \) is adjusted relative to \( V_\alpha \) to reproduce the observed mass distributions of the Fm isotopes with Equation (1).

The astrophysical environment in which the r-process is thought to occur is the neutron-deficient electron capture site in the binary NSM of two neutron stars with \( M = 1.0 \text{M}_\odot \) each. Although 1.0 \( \text{M}_\odot \) is not the typical neutron star mass (Valentim et al. 2011), it has been shown (Korobkin et al. 2012) that the resulting abundances are nearly independent of the neutron star masses in the binary. The hydrodynamic simulations are based on the SPH method of Rosswog (2009), the equation of state (EOS) of Shen et al. (1998a, 1998b), an opacity-dependent multiflavor neutrino leakage scheme (Rosswog & Liebendörfer 2003), and Newtonian gravity. We use 30 available trajectories of NSM ejecta to calculate the nucleosynthesis. The ejected mass from this binary merger is \( \sim 0.01 \text{M}_\odot \) (Korobkin et al. 2012). After the end of the hydrodynamic simulation at \( t_{\text{inj}} \sim 15 \text{ms} \), the thermodynamic evolution can be continued (Rosswog et al. 2014) as a free adiabatic expansion.

The reason for the use of these trajectories is that they are publicly available and lead to robust fission recycling. Moreover, a main point of this paper is the importance of the fraction of r-process material that involves fission recycling. If some fraction of the ejecta in the NSM calculations as in Goriley et al. (2011), Korobkin et al. (2012), Goriley et al. (2013), Wanajo et al. (2014), and Perego et al. (2014) do not involve fission recycling, then this paper deals with the fraction of material in their models that leads to fission recycling, while the other trajectories would be absorbed into what we label as other components.

In contrast to CCSNe, baryons participating in the r-process constitute a large fraction of the total mass–energy in the NSM.
Thus, the nuclear energy released by the $r$-process nuclear reactions must be included after $t_{\text{fin}}$ by an entropy source term,

$$dS = -\epsilon_{\text{th}} \sum_i (m_i c^2/k_B T + \mu_i/k_B T) dY_i,$$

where a heating efficiency parameter $\epsilon_{\text{th}} \approx 1$ is introduced to account for neutrino energy losses.

The nucleosynthesis calculations were started at a temperature $T = 9.0 \times 10^8$ K. At this point all nuclei are in nuclear statistical equilibrium, and the composition is completely determined from the density and charge per baryon $Y_c$ of the material ejected from the neutron stars. At this point the material almost entirely consists of free neutrons plus some heavy seed nuclei with $A \approx 70$.

As the temperature and density decrease, however, the material is evolved using an updated version of the nuclear network code of Terasawa et al. (2001). The neutron radiative capture rates are as summarized in Terasawa et al. (2001); however, for both the weak and main hot $r$-process considered here, the abundance patterns mainly depend on the nuclear masses and $\beta$-decay rates but not on the radiative neutron-capture rates. This is because the system proceeds in ($n, \gamma$) equilibrium until a rapid freezeout of the neutron abundance. On the other hand, the fission-recycling NSM $r$-process considered here depends on the radiative neutron-capture rates because, when the temperature is low, the ($n, \gamma$) and $\beta$-decay rates (in the so-called "cold $r$-process") determine the final abundances. In the fission-recycling model adopted here, the $r$-process path terminates in a region where $\beta$-induced fission is much faster than the neutron-induced fission so that the $r$-process is always terminated by $\beta$-induced fission. We note, however, that this depends on the treatment of fission barriers (e.g., Korobkin et al. 2012).

Once the $r$-process path fissions, we utilize the FFDs given in Ohta et al. (2008) and also the nuclear masses from the KTUY model (Koura et al. 2005). The fission barriers are extracted from the same KTUY model. However, since the KTUY model treats only symmetric fission, we adopted here the two-center shell model to allow more general FFDs. The KTUY model has been shown within the GT2 theory to reproduce recent measurements of $\beta$-decay half-lives of exotic neutron-rich isotopes (Nishimura et al. 2011). In a separate forthcoming paper we will summarize a detailed comparison of the predictions of this model with known FFDs.

We also note that there have been numerous studies (e.g., Pfeiffer et al. 2001; Otsuki et al. 2003) of the sensitivity of this type of paradigm on various nuclear physics parameters. However, almost all MHDJ (or NDW) models (without shell quenching) show the abundance deficiencies on either side of the closed $r$-process abundance peaks. Moreover, the NDW and MHDJ SN models often involve little or no fission recycling. As such, they do not depend on the details of fission rates and fragment distributions.

We note, however, that our NSM calculation (as shown below in Figure 2) produces a different abundance pattern than that of previous NSM studies (Goriely et al. 2011; Korobkin et al. 2012; Goriely et al. 2013), especially in the region spanning between the second and third $r$-process peaks. There are two reasons for this difference: (1) the FFDs and (2) the number of fissioning nuclei contributing to fission recycling and the freezeout of the $r$-process distribution.

Regarding the FFDs, it has often been noted (e.g., Goriely et al. 2011; Korobkin et al. 2012; Goriely et al. 2013) that the elemental abundances from NSM calculations depend strongly on the FFD model. Admittedly, this is a major uncertainty in all calculations of fission recycling in the $r$-process. As noted above, our FFD model is based on the KTUY model plus a two-center shell model to predict both symmetric and asymmetric FFDs with up to three components. As such, fissile nuclei in our approach can span a wide mass range ($A = 100$–$180$) of fission fragments. This is illustrated in the upper panel of Figure 2, which shows the final abundance distribution compared with the FFDs of three illustrative nuclei.

On the other hand, the models of Korobkin et al. (2012) are mostly based on a simple two-fragment distribution as in Panov et al. (2001) or alternatively the prescription of Kodama & Takahashi 1975. The assumption of only two fission daughter nuclei tends to place a large yield near the second $r$-process peak, leading to a distribution that looks rather more like the solar $r$-process abundances. In contrast, the FFDs of Goriely et al. (2013) are based on a rather sophisticated SPY revision (Panebianco et al. 2012) of the Wilkinson fission model (Wilkins et al. 1976). The main ingredient of this model is that the individual potential of each fission fragment is obtained as a function of its axial deformation from tabulated values. Then a Fermi gas state density is used to determine the main fission distribution. This leads to a multiple-hump FFD similar to that considered here, but even with up to four humps. Although this arguably represents a more fundamental approach than that employed in the present work, we prefer the phenomenological FFD approach here as an alternative means to estimate fission yields far from stability.
An even more important difference between the present work and that of previous studies is the termination of the \( r \)-process path and the number of fissioning nuclei that contribute to fission recycling and the freezeout of the \( r \)-process abundances. The \( r \)-process path in our NSM calculations proceeds rather below the fssile region until nuclei with \( A \approx 320 \), whereas the \( r \)-process path in Goriely et al. (2013) terminates at \( A \approx 278 \) (or for a maximum \( \langle Z \rangle \) for Korobkin et al. 2012). Moreover, we find that only \( \sim 10\% \) of the final yield comes from the termination of the \( r \)-process path at \( N = 212 \) and \( Z = 111 \), while almost \( 90\% \) of the \( A = 160 \) bump shown in Figure 2 comes from the fission of more than 200 different parent nuclei mostly via \( \beta \)-delayed fission. This is in contrast to the yields of Goriely et al. (2013), which are almost entirely due to a few \( A \approx 278 \) fissioning nuclei with a characteristic four-hump FFD. This is the reason why they obtain a solar-like \( r \)-process-like distribution.

To illustrate this point, in the lower panel of Figure 2 we compare the yields of our model with a calculation in which we assume that the \( r \)-process path is terminated by the symmetric fission of nuclei with \( A = 285 \). Clearly, in this case a solar-like distribution is obtained similar to that of Goriely et al. (2011), Korobkin et al. (2012), and Goriely et al. (2013). This highlights the importance of detailed fission probabilities along the \( r \)-process path.

Finally, we note that the apparent suppression of the third \( r \)-process peak in our final abundances relative to that of other works is caused by the large increase in the rare-earth elements resulting from the FFDs of repeated fission recycling.

4. RELATIVE \( r \)-PROCESS CONTRIBUTIONS

Figure 3 shows the main result of this paper. The red line in Figure 3 shows the result of our fission-recycling nucleosynthesis simulation summed over all trajectories of material ejected from the binary NSM model adopted here. This is compared with the abundances in the ejecta from the main \( r \)-process (blue line) from the MHDJ model of Nishimura et al. (2012) and also the NDW weak \( r \)-process abundances (green line) produced in the 1.8 \( M_\odot \) SN core model of Wanajo (2013).

The key point of this figure is the important role that each process plays in producing the total abundance pattern of solar system \( r \)-process abundances (black filled circles with error bars; Goriely 1999). The total abundance curve from all processes is shown as the black line in Figure 3. The weighting factor \( f_{\text{fission}} \) was determined from a normalization to isotopes near \( A = 145-155 \) for the fission-recycling (NSM) model. The factor \( f_{\text{weak}} \) was determined from a fit to light isotopes near \( A = 100 \) for the NDW model. The MHDJ yields were normalized to the second \( r \)-process peak. The best-fit (black) line in Figure 3 is for \( f_{\text{fission}} = 0.16 \) and \( f_{\text{weak}} = 4.3 \), or roughly \( 79\% \) weak, versus \( 18\% \) main, and \( \sim 3\% \) fission-recycling contributions with some uncertainty in the different models as noted above. Nevertheless, these estimated relative contributions are at least consistent with roughly estimated Galactic yields as described below.

Of particular relevance to the present study is that the underproduction of nuclides above and below the \( A = 130 \) \( r \)-process peak shown by the blue line is nearly accounted for by the fission-recycling (NSM) and weak \( r \)-process (NDW) models. The final NSM \( r \)-process isotopic abundances from our adopted model for fission yields exhibit a very flat pattern due to several episodes of fission cycling. Thus, we find that fission recycling has the potential to resolve most of the underproduction problems for the elements just below and above the abundance peaks in models of the main \( r \)-process. The remaining underproduction below the \( A = 130 \) peak is most likely due to the weak \( r \)-process, as illustrated in Figure 3.

The main point of this paper is that one can deduce the relative contributions of each \( r \)-process model based on their relative shortcomings. However, it is important to ask whether the inferred fractions, of \( \sim 79\% \) NDW, \( \sim 18\% \) MHDJ, and \( \sim 3\% \) NSM, are plausible.

Although there are many uncertainties in the astrophysical and galactic chemical evolution parameters (Argast et al. 2000; Komiya et al. 2014), it is worthwhile to estimate weight parameters \( f_{\text{fission}} \) and \( f_{\text{weak}} \) from observed Galactic event rates and expected yields. In particular, we write

\[
f_{\text{fission}} \approx \frac{R_{\text{NSM}} M_{r,\text{NSM}}}{\epsilon_{\text{MHDJ}} R_{\text{CCSN}} M_{r,\text{MHDJ}}},
\]

and

\[
f_{\text{weak}} \approx \frac{R_{\text{CCSN}} M_{r,\text{Weak}}}{\epsilon_{\text{MHDJ}} R_{\text{CCSN}} M_{r,\text{MHDJ}}},
\]

where \( M_{r,\text{NSM}}, M_{r,\text{MHDJ}}, \) and \( M_{r,\text{Weak}} \) are the ejected masses of \( r \)-elements from the NSM, MHDJ, and NDW \( r \)-process models, respectively, while \( R_{\text{CCSN}} \) and \( R_{\text{NSM}} \) are the corresponding relative Galactic event rates of CCSNe and NSMs.

The ejected mass of \( r \)-process elements in the models of Wanajo (2013) is \( \approx 2 \times 10^{-5} M_\odot \) and nearly independent of assumed core mass. The quantity \( \epsilon_{\text{MHDJ}} \) is the fraction of CCSN that result in magnetorotationally driven jets. This was estimated in Winteler et al. (2012) to be \( \sim 1\% \) of the CCSN rate based on the models of Woosley & Heger (2006). However, this is probably uncertain by at least a factor of two. Indeed, the fraction could be larger as most massive stars are fast rotators and the conservation of magnetic flux should often lead to high magnetic fields in the newly formed proto-neutron star. Hence, this fraction could easily range from \( \sim 1\% \) to \( \sim 5\% \), which incorporates the \( \sim 1\% \) fraction of observed magnetars compared...
to normal neutron stars. (We treat this as a lower limit because some fraction of observed normal neutron stars may have had a larger magnetic field in the past.) The mass of synthesized r-process elements from MHDJs is estimated to be $6 \times 10^{-3}M_\odot$ (Winteler et al. 2012), while that of a typical binary NSM is expected to be $(2 \pm 1) \times 10^{-2}M_\odot$ (Korobkin et al. 2012). If the Galactic NSM rate is $80^{+200}_{-70}$ Myr$^{-1}$ (Kalogera et al. 2004) and the Galactic SN rate is $(1.9 \pm 1.1) \times 10^{4}$ Myr$^{-1}$ (Diel et al. 2006), then one should expect $f_{\text{fusion}} \sim 0.6 \pm 0.4$ and $f_{\text{Weak}} \approx 8 \pm 6$, corresponding to relative contributions of $\sim 80\%$ weak, $\sim 10\%$ main, and $\sim 10\%$ fission recycling. Thus, although there are large uncertainties, these fractions are plausibly consistent with our fit parameters. This suggests that such a fit may be a way of constraining the relative contribution of NSMs and CCSNe to solar system material.

We note, however, that other NSM calculations predict about $10^{-4}$ to $10^{-2}M_\odot$ of r-process material to be ejected (e.g., Bauswein et al. 2013; Hotokezaka et al. 2013). Adopting a value of $10^{-3}M_\odot$ could lead to $f_{\text{fusion}} \sim 0.02$, i.e., about an order of magnitude below that suggested in our fit to Figure 3.

Of course, this needs to be better quantified in more detailed chemical evolution (Cescutti & Chiappini 2014; Komiyama et al. 2014; Tsujimoto & Shigeyama 2014a, 2014b; Cescutti et al. 2015; Ishimaru et al. 2015; Wehmeyer et al. 2015) and chemodynamical studies (Shen et al. 2015; van de Voort et al. 2015; Hirai et al. 2015), along with better r-process hydrodynamic models (Winteler et al. 2012; Perego et al. 2014; Rosswog et al. 2014; Wanajo et al. 2014; Goriely et al. 2015; Just et al. 2015; Nishimura et al. 2015). Nevertheless, based on the models adopted here, the inferred division of r-process contributions remains at least plausible.

5. UNIVERSALITY OF R-PROCESS ELEMENTAL ABUNDANCES

In the above we have not discussed a very important clue to the origin of r-process abundances. It is by now well established (Sneden et al. 2008) that the elemental abundances in many metal-poor stars show a pattern that is very similar to that of the solar system r-process distribution, particularly in the range of $55 < Z < 70$. This, however, can pose a difficulty (Mathews et al. 1992; Argast et al. 2000) for NSM models (either in the present work or in other studies). That is because metal-poor stars are thought to have arrived very early in the history of the Galaxy, whereas NSMs require a relatively long gravitational radiation orbit decay time prior to merger ($\sim 0.1$ Gyr). Whatever the situation, it is of value to examine the impact of the possible late arrival of fission-recycling material on the r-process elemental abundance distribution in metal-poor stars.

Figure 4 shows the elemental abundance distribution calculated in two scenarios, i.e., with and without the fission-recycling yields of NSMs. These are compared with the observed elemental r-process abundances in two well-studied metal-poor r-process-enhanced stars, HD 1601617 (Roederer & Lawler 2012) and CS 22892-052 (Sneden et al. 2003). Here we note that there is little distinction between the two curves (although the fit is slightly better when the fission-recycling yields are included). The reason for this insensitivity is that the fission-recycling environment only contributes about 3% to the total r-process abundance. Although this yield is important to fill in the isotopic abundances above and below the r-process peaks, and also to make the rare-earth bump near $A = 160$, there is little apparent difference in the elemental abundances with or without NSMs. Among other things, this is because the region below the peak ($Z \sim 50$) is poorly sampled, and moreover, summing over isotopes to produce elemental averages somewhat washes out the underproduction above and below the r-process mass peaks. Hence, the elemental r-process abundances in metal-poor stars do not clearly require that fission recycling occurred early in the Galaxy.

We do note, however, that the dispersion in the stars themselves for the lightest elements ($30 < Z < 50$) is suggestive that not all CCSNe contribute both a weak and main r-process. This is consistent with the expectation that the NDW could occur in all CCSNe while the main r-process from the MHDJ will only occur in a limited fraction of CCSNe, i.e., those with rotation and strong magnetic fields.

6. DISCUSSION

The fits to the abundance distribution (e.g., Figure 3) are as good as or better than most models in the literature. Nevertheless, it is worthwhile to address some of the detailed deficiencies in both Figures 2 and 3. For example, although the r-process peaks at $A = 130$ and 195 along with the rare-earth peak region $A = 145$–180 in Figure 3 are remarkably well reproduced, there are some differences just above the main r-process peaks in the regions of $A = 140$–145 and 200–205. We note, however, that these isotopes have the largest uncertainties in the r-process abundances themselves, as is visible in Figure 3. Hence, these discrepancies may simply reflect the abundance uncertainties, although the possibility remains of a shortcoming in the models for these isotopes.

Similarly, in Figure 4 there is an underproduction of elements at $Z = 58$ and 60. The abundance of Ce ($Z = 58$) in Figure 4 is well determined observationally for CS 22892-052 as follows: log $\epsilon$(Ce) = $-0.50 \pm 0.07$ (Sneden et al. 2003) and $-0.38 \pm 0.08$ (Honda et al. 2004). This corresponds to the deficient isotopes with $A = 140$ and 142 in Figure 3. However, the odd elements with $Z = 57$ (La) and $Z = 59$ (Pr) are reproduced. This suggests that the odd–even effect in the
region of lanthanide elements may be underestimated in the mass model employed here. Nevertheless, the main point of this paper is not to give a precise reproduction of $r$-process elemental abundances, but rather to demonstrate the possibility that fission recycling supplements the underproduced elements. Clearly, a better understanding of the nuclear uncertainties within this context is still needed.

We also note that there is a possible deficiency of Pb ($Z = 82$) in Figure 4. This, however, may relate to observational uncertainties. There are two measured Pb abundances for CS 22892-052 in Sneden et al. (2003). One was a ground-based measurement, while the other was obtained with HST. However, both of these values should be considered upper limits. In Sneden et al. (2003) it was noted that the suggested detections of the two Pb I lines in the ground-based spectra should be nearly 10 times weaker than the $\lambda = 2833.05$ line, which could not be detected in the HST spectrum. Hence, the derived Pb abundance upper limit from the $\lambda = 2833$ line is probably more reliable than the abundances determined from the questionable detections of the other two Pb I lines. Thus, $\log \epsilon (\text{Pb}) < -0.2$ from the ground-based observation in favor of the HST observation. We also note that the more recent observation of Roederer et al. (2009) also obtains $\log \epsilon (\text{Pb}) < -0.15$. These upper limits are consistent with our calculation.

Another issue worthy of discussion is that of Th ($Z = 90$) and U ($Z = 92$) production in Figure 4. Th has been observed in a number of metal-poor stars and U in a few. This indicates that the $r$-process mechanism at work in the early Galaxy could produce the actinide elements and beyond. Although one tends to think that the production of actinide elements requires a fission-recycling $r$-process, in fact the production of Th and U is possible even in models that do not lead to fission recycling. For example, the MHDJ models with strong magnetic fields in Nishimura et al. (2015) could produce Th and U in as much as their solar abundances. On the other hand, MHDJ models with weak magnetic fields tend to produce actinides below solar abundances. Hence, the observation of Th and U in metal-poor stars constrains the early astrophysical environment, but does not necessarily require that a fission-recycling $r$-process (such as the NSM model) contributed to metal-poor stars.

7. CONCLUSIONS

In summary, we have considered the relative contributions of three generic $r$-process environments to the solar system $r$-process abundances and the abundances in $r$-process-enhanced metal-poor stars. These environments are discussed in the context of NSMs, neutrino-driven winds, and MHDJs, although these environments should be considered as illustrative and not definitive of the specific $r$-process environments. Nevertheless, based on our adopted FFDs, we find that the relative contributions from each environment have the possibility of explaining a unique feature of the $r$-process abundances. Moreover, the deduced relative contributions are plausibly consistent with galactic chemical evolution considerations.

Clearly, more work along this line is required to explain details. Nevertheless, we suggest that the possibility that all three general environments occur in detectable amounts in the $r$-process distribution should be taken seriously in future investigations of the origin of $r$-process nuclides.

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