Long, Cold, Early r Process? Neutrino-Induced Nucleosynthesis in He Shells Revisited

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A Long, Cold, Early r-process? ν-induced Nucleosynthesis in He Shells Revisited

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We revisit a ν-driven r-process mechanism in the He shell of a core-collapse supernova, finding that it could succeed in early stars of metallicity $Z \lesssim 10^{-3} Z_\odot$, at relatively low temperatures and neutron densities, producing $A \sim 130$ and 195 abundance peaks over $\sim$ 10–20 s. The mechanism is sensitive to the ν emission model and to ν oscillations. We discuss the implications of an r-process that could alter interpretations of abundance data from metal-poor stars, and point out the need for further calculations that include effects of the supernova shock.

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While the basic features of the rapid-neutron-capture or r-process have been known for over 50 years [1], the search for the specific astrophysical site has frustrated many researchers [2]. The situation has continued despite a growing set of observational constraints, including elemental abundances from metal-poor (MP) stars [3], that appear to favor core-collapse supernovae (SNe) and to disfavor some otherwise attractive sites, such as neutron star mergers (NSMs) [4, 5].

The surface compositions of old MP stars provide a fossil record of nucleosynthesis and chemical enrichment in the early Galaxy. For ultra-metal-poor (UMP) stars, where $[\mathrm{Fe/H}] \equiv \log(\mathrm{Fe/H}) - \log(\mathrm{Fe/H})_\odot \lesssim -3$, surface enrichments should reflect contributions from just a few nearby nucleosynthetic events. The data show that the r-process operated in the early Galaxy with a frequency consistent with SNe from short-lived massive progenitors. Many MP stars, including several UMP ones, also exhibit a solar-like abundance pattern of heavy r-process elements (r-elements) for $A > 130$ [3].

The similarity between the MP-star and solar r-patterns tempts one to conclude that there is a unique site for the r-process, operating unchanged over the Galaxy's history (cf. [6]). But is this the case? Epstein, Colgate, and Haxton (ECH) [7] suggested a possible r-site some years ago that would complicate such an interpretation. The ECH mechanism utilizes neutrons produced by neutral-current (NC) ν reactions in the He zones of certain low-metallicity SNe. The proposed sequences are $^4\mathrm{He}(\nu,\nu n)^3\mathrm{He}(n,p)^3\mathrm{H}(^3\mathrm{H},2n)^4\mathrm{He}$ and $^4\mathrm{He}(\nu,\nu p)^3\mathrm{H}(^3\mathrm{H},2n)^4\mathrm{He}$. For temperatures $\lesssim 3 \cdot 10^8$ K, the neutrons thus produced will not reassemble into ^{4}He by reactions involving light nuclei. Nor will they be captured by ^{4}He as ^{5}He is unbound. Instead, they will be efficiently captured by seed nuclei, such as ^{56}Fe, present in the birth material of the SN. The ECH neutron source is primary and provides a roughly fixed number of neutrons. For MP progenitors there are few Fe seeds and thus enough neutrons per seed to produce heavy r-elements. As the metallicity of the SN increases, the neutron/seed ratio decreases, limiting the production of r-elements to low A and eventually stopping the production altogether. That is, the ECH mechanism turns off with increasing metallicity.

The ECH mechanism was proposed as a candidate general r-process, and thus was critiqued in Ref. [8] for being viable only in low-metallicity, compact SNe. Subsequent re-examination of the mechanism focused on NC ν reactions only, either confirming earlier results or finding no significant production of $A > 80$ nuclei without assuming ad hoc conditions in outer He zones [9]. In this Letter we show that the charged-current (CC) reaction $^4\mathrm{He}(\bar{\nu}_e, e^+n)^3\mathrm{H}$ can be an efficient neutron source for a successful low-metallicity ECH mechanism using recently generated models of MP massive stars [10]. Because other candidate r-sites, such as NSMs, may turn on at higher metallicity, it is clearly important to explore any mechanism that might account for the r-elements generated at earlier times. Furthermore, as we have so far failed to identify "the r-process," it would be a step forward to identify "an r-process," even if the mechanism operated only for a limited time.

An r-process requires neutron densities $n_n \gtrsim 10^{18}$ /cm^3, so that neutron capture will be fast compared to β decay, and a neutron/seed ratio $\gtrsim 80$, so that heavy r-elements can be produced from seeds like ^{56}Fe. These requirements lead us to examine the outer He shells of MP massive stars, where the low abundances of nuclei like ^{12}C, ^{14}N, and ^{16}O make iron-group nuclei an important neutron sink. (The higher temperatures found in the inner He zone, $\sim 3 \cdot 10^8$ K, lead to significant ^{12}C and ^{16}O production by He burning, regardless of metallicity. As we discuss later, a modified ECH mechanism may operate in such an environment, with ν-induced neutrons "banked" in ^{13}C and ^{17}O, then liberated on shock wave passage.)

We use models u11–u75 of 11–75 $M_\odot$ stars with an initial metallicity $Z = 10^{-4} Z_\odot$ (Z being the total mass fraction of elements heavier than He) presented in Ref. [10]. The outer He shells of these models are at radii $r \sim$

10^{10} cm, for which the gravitational collapse time is

$$\tau_{\rm coll} \sim \frac{1}{\alpha}\sqrt{\frac{r^3}{2GM}} \sim 102\left(\frac{0.6}{\alpha}\right)\left(\frac{M_\odot}{M}\right)^{1/2} r_{10}^{3/2}\ {\rm s}, \quad (1)$$

where $\alpha \sim 0.6$ is the ratio of the infall velocity to the free-fall velocity, $M \sim 2.4$–$33\,M_\odot$ is the mass enclosed within r, and r_{10} is r in units of 10^{10} cm. For such large $\tau_{\rm coll}$, we can assume that the radius, density, and temperature of the He-shell material stay constant before the SN shock arrives. We take the time of shock arrival to be approximately given by the Sedov solution [8]

$$\tau_{\rm sh} \sim 21.8\left(\frac{M - M_{\rm NS}}{M_\odot}\right)^{1/2}\frac{r_{10}}{E_{50}^{1/2}}\ {\rm s}, \quad (2)$$

where $M_{\rm NS} \sim 1.4\,M_\odot$ is the mass of the neutron star produced by the core collapse and E_{50} is the explosion energy in units of 10^{50} ergs. Following the passage of the shock, both the temperature and density of the material first increase rapidly and then decrease on timescales comparable to $\tau_{\rm sh}$. The peak temperature (in units of 10^8 K) of the shocked material is [8]

$$T_{p,8} \sim 2.37 E_{50}^{1/4} r_{10}^{-3/4}. \quad (3)$$

For such low temperatures, photo-dissociation of heavy nuclei will not occur [8]. Other effects of shock-wave passage are helpful to the r-process (see discussion below).

During the several seconds following core collapse, an intense flux of νs irradiates the He zone. While the zone's radius, density, and temperature are unchanged, ν reactions must induce and maintain a free-neutron density $n_n \gtrsim 10^{18}/{\rm cm}^3$ to drive an r-process. We take the ν luminosity to be $L_\nu(t) = L_\nu(0)\exp(-t/\tau_\nu)$ for each of the six flavors, with $L_\nu(0) = 1.67 \cdot 10^{52}$ erg/s and $\tau_\nu = 3$ s, so that the total energy carried off by νs is $3 \cdot 10^{53}$ ergs. We use Fermi-Dirac ν spectra with zero chemical potential. We adopt nominal temperatures T_{ν_e}, $T_{\bar\nu_e}$, and T_{ν_x} of 4, 5.33, and 8 MeV, respectively, where ν_x stands for any heavy flavor, but explore the temperature dependence. Our nominal parameters are typical of earlier SN models (e.g., [11]). The spectra at the He zone will be affected by ν oscillations [12], as the ν mass splitting $|\delta m_{13}^2| \sim 2.4 \cdot 10^{-3}$ eV^2 produces a level crossing for a 20 MeV ν at $\rho \sim 1.6 \cdot 10^3$ g/cm^3, a density characteristic of the carbon zone. The consequences for the r-process depend critically on the assumed ν mass hierarchy.

We evaluated the nucleosynthesis for models u11–u75 and for various ν oscillation scenarios. As an example of a successful r-process, we present detailed results for zone 597 of u11, assuming an inverted ν mass hierarchy (IH, full $\bar\nu_e \leftrightarrow \bar\nu_x$ conversion). Zone parameters are $r_{10} = 1.10$, $M = 2.43\,M_\odot$, $\rho = 50.3$ g/cm^3, and $T_8 = 0.848$. The zone is nearly pure ^{4}He: the initial mass fractions of ^{12}C and ^{14}N are $X_{12} \sim 1.39 \cdot 10^{-5}$ and $X_{14} \sim 1.35 \cdot 10^{-6}$. The total mass fraction of $A \geq 16$ nuclei is $\sim 3.52 \cdot 10^{-7}$ ($\sim 3.15 \cdot 10^{-8}$ from ^{56}Fe). A big bang nucleosynthesis network [13] was modified to follow the ECH mechanism, with NC and CC ν cross sections taken from Ref. [14], which agree well with those of Ref. [7]. As the network stops at ^{16}O, neutron capture on $A \geq 16$ nuclei was approximated by a constant loss rate corresponding to the initial abundances of such nuclei. As discussed below, the evolution of the neutron number fraction Y_n is not significantly altered by neglecting changes in the $A \geq 16$ composition.

Figure 1a, the number-fraction evolution with time t, can be readily understood: (1) The extremely efficient reaction ^{3}He$(n,p)^3$H immediately consumes all neutrons produced by the NC reaction ^{4}He$(\nu,\nu n)^3$He. Each NC reaction thus yields one proton and one ^{3}H. (2) The neutron-producing reaction proposed by ECH, ^{3}H(^{3}H,$2n$)^{4}He, is inefficient. Instead, ^{3}H is destroyed by abundant ^{4}He via ^{3}H(^{4}He,γ)^{7}Li. Neutron restoration by ^{7}Li(^{3}H,$2n$)2^4He is ineffective for the conditions of Figure 1a. (3) Neutron production is dominated by the CC reaction ^{4}He$(\bar\nu_e, e^+n)^3$H. (4) The principal neutron sinks are ^{7}Li, ^{12}C, and $A \geq 16$ nuclei. (5) Protons are not a significant neutron sink as $p(n,\gamma)^2$H is immediately followed by ^{2}H(^{3}H,n)^{4}He. (6) Due to its small initial abundance, neutron capture by ^{14}N is also negligible.

The rate of the CC $\bar\nu_e$ reaction per ^{4}He nucleus is

$$\lambda^{\rm CC}_{\bar\nu_e\alpha}(t) = \frac{2.28\times 10^{-7}}{r_{10}^2\exp(t/\tau_\nu)}\left(\frac{T_{\bar\nu_e}}{6\ {\rm MeV}}\right)^k\ {\rm s}^{-1}, \quad (4)$$

where $k \sim 6.26$ and ~ 5.17 for $T_{\bar\nu_e} = 4$–6 and 6–8 MeV, respectively. Based on the above discussion, Y_n in Figure 1a can be estimated from

$$\dot Y_n = \lambda^{\rm CC}_{\bar\nu_e\alpha}(0) Y_\alpha \exp(-t/\tau_\nu) - \lambda_{n,\gamma} Y_n(t), \quad (5)$$

where $\lambda^{\rm CC}_{\bar\nu_e\alpha}(0) = 8.35 \cdot 10^{-7}$/s for $T_{\bar\nu_e} = 8$ MeV (IH), $Y_\alpha \sim 1/4$ is the number fraction of ^{4}He, and $\lambda_{n,\gamma} \sim 8.12 \times 10^{-2}$/s is the net rate of neutron capture on ^{7}Li (46.2%), ^{12}C (21.9%), and $A \geq 16$ nuclei (31.9%). We find, in good agreement with Figure 1a,

$$Y_n(t) = \frac{\lambda^{\rm CC}_{\bar\nu_e\alpha}(0) Y_\alpha \tau_\nu}{1 - \lambda_{n,\gamma}\tau_\nu}[\exp(-\lambda_{n,\gamma}t) - \exp(-t/\tau_\nu)]. \quad (6)$$

The neutron number density in zone 597 of u11, $n_n = Y_n \rho N_A \sim 10^{19}/{\rm cm}^3$ where N_A is Avogadro's number, is sufficient to drive an r-process (see Figure 2). The most effective seed is ^{56}Fe as it is above the $N = 28$ closed neutron shell. The typical mass number of r-elements produced at time t is roughly $A \sim 56 + N_{\rm cap}(t)$, where $N_{\rm cap}(t) = \int_0^t n_n(t')\langle v\sigma_{n,\gamma}({\rm Fe})\rangle dt'$ and where $\langle v\sigma_{n,\gamma}({\rm Fe})\rangle$ is the rate coefficient for neutron capture on ^{56}Fe. For zone 597 we find $N_{\rm cap}(t) = 88$ (226) for $t = 7$ (20) s, which correspond to the shock arrival times for $E_{50} \sim 12$ (1). We conclude, for weak explosions, that the r-process could run to completion in the pre-shock phase.

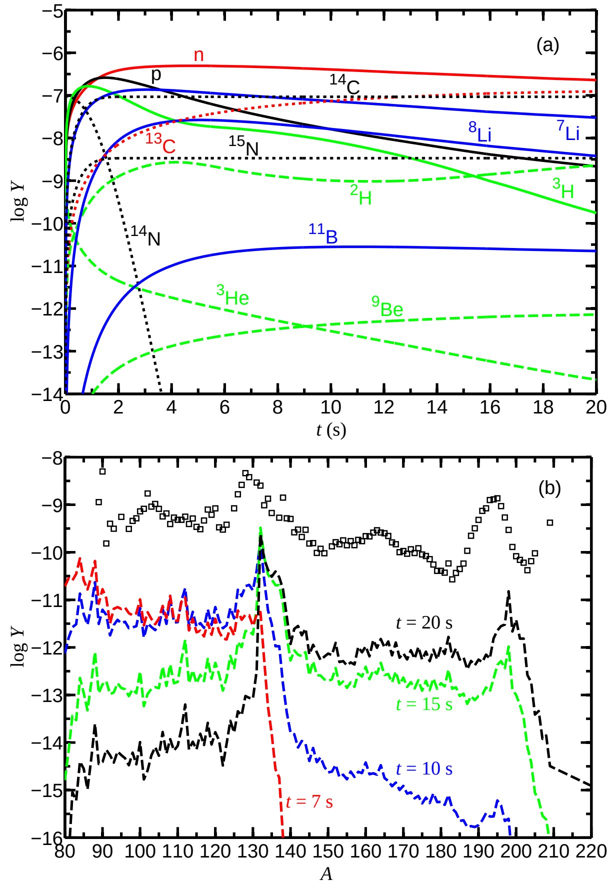

FIG. 1: ν-induced nucleosynthesis in u11, zone 597: (a) Number fractions $Y_i(t)$ of $A < 16$ nuclei; (b) r-process yields at $t = 7$, 10, 15, and 20 s compared to solar r-pattern (squares).

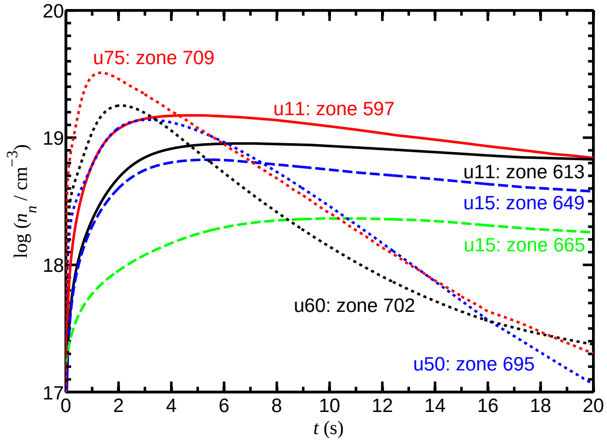

FIG. 2: Neutron number density $n_n(t)$ evolution for selected outer He zones in models u11, u15, u50, u60, and u75.

We followed the nuclear flow from ^{56}Fe with a large network Torch [15] that includes all of the relevant neutron capture, photo-disintegration, and β-decay reactions. The yields at $t = 7$, 10, 15, and 20 s are shown in Figure 1b along with the scaled solar r-pattern. The r-process is cold: photo-disintegration is unimportant for He zone temperatures. It is also much slower than usually envisioned. At $t = 7$ s, the r-process flow barely reaches the $A \sim 130$ peak. Significant production of nuclei with $A > 130$ occurs only for $t > 10$ s, and formation of a significant peak at $A \sim 195$ requires $t \sim 20$ s. These times are readily understood. The peaks at $A \sim 130$ and 195 correspond to parent nuclei $\sim {}^{130}$Cd and $\sim {}^{195}$Tm with closed neutron shells of $N = 82$ and 126. With ^{56}Fe as the seed, 74 neutron-capture and 22 β-decay reactions are required to reach ^{130}Cd while 139 neutron-capture and 43 β-decay reactions are required to reach ^{195}Tm. In the absence of photo-disintegration, the r-path is governed by (n, γ)-β equilibrium and the rates for neutron capture and β decay will be comparable. For $\langle v\sigma_{n,\gamma}(\mathrm{Fe})\rangle \sim 10^{-18}$ cm^3/s and $n_n \sim 10^{19}$/cm^3, the neutron-capture rate on ^{56}Fe is ~ 10/s. As this rate is typical along the r-path, ^{130}Cd and ^{195}Tm will be reached in ~ 10 and 18 s.

We examined other u11 zones and other progenitors. For the IH case with $T_{\bar{\nu}_e} \sim 8$ MeV, neutron densities of $\sim 10^{18}$–10^{19}/cm^3 are produced in many zones of models u11–u16 and u49–u75. Conditions in u11–u16 are similar to those of zone 597 of u11, but the u49–u75 zones are hotter and denser, $T_8 \sim 2$–3 and $\rho \sim 200$–600 g/cm^3. Figure 2 shows $n_n(t)$ for selected zones of u11, u15, u50, u60, and u75. A much higher rate of neutron capture in u50, u60, and u75 leads to more rapid decline of $n_n(t)$. Substantial r-yields are expected in the outer He zones of 11–16 and 49–75 $M_\odot$ stars at $Z \sim 10^{-4} Z_\odot$. An r-process is not expected for stars between 17 and 48 $M_\odot$ because the outer He zone has too much hydrogen, a neutron poison.

The total yield of heavy r-elements from each SN is $\Delta M_r \sim 10^{-8}\,M_\odot$, comparable to $\sim 4 \cdot 10^{-8}\,M_\odot$ in the Sun. Abundances of heavy r-elements in MP stars with [Fe/H] < -2.5 are $\sim 3 \cdot 10^{-4}$–10^{-1} times those in the Sun [3]. At least some r-enrichments in this range could be produced by an SN in the early interstellar medium, but this process then turns off as progenitor metallicity increases. Both $n_n(t)$ and the $A > 56$ yields decrease significantly with increasing progenitor Z. In the scenarios studied here, r-process conditions are not found beyond $Z \sim 10^{-3} Z_\odot$. Yet net neutron production by νs is insensitive to metallicity, depending only on SN energy, $\bar{\nu}_e$ temperature, and shell radius, so neutron capture continues on stable seeds like ^{56}Fe, modestly increasing the $A > 56$ yields. The net mass of heavy nuclei continues to be incremented by $\sim 10^{-8}\,M_\odot$. The associated Galactic chemical evolution [19] should be studied to determine how the ν-driven mechanism might merge into other r-processes, such as NSMs, that may only be viable for [Fe/H] $\gtrsim -2.5$ [5].

We have used two separate networks to estimate $n_n(t)$

and the corresponding r-yields. In estimating $n_n(t)$, we adopt a constant neutron capture rate for $A \geq 16$ nuclei. This approximation should be valid because the important neutron sinks ^{7}Li and ^{12}C are included, and because the calculations confirm that the total number of neutrons captured per ^{56}Fe nucleus is $\ll Y_n$. Nevertheless, future studies should use a complete network for both neutron capture and ν interactions.

The effects of shock passage through the He shell have not been included, though we argued that r-nuclei will survive the associated heating. Other consequences may be beneficial, extending the range for interesting nucleosynthesis. The density of shocked material jumps to ~ 7 times the pre-shock value and then decreases slowly on timescales $\sim \tau_{\rm sh}$. So while larger explosion energies, $E_{50} \sim 12$, might appear to limit the duration of the r-process to $\tau_{\rm sh} \sim 7$ s, in fact there may be a post-shock phase where densities higher than those of Fig. 2 aid the nucleosynthesis. Another potentially beneficial effect of the shock may come from neutrons released by ^{13}C(^{4}He,n)^{16}O and ^{17}O(^{4}He,n)^{20}Ne: ^{12}C and ^{16}O are the principal neutron sinks in the inner He shell. If shock heating to $\gtrsim 5 \cdot 10^8$K could liberate these neutrons without increasing the abundance of seeds, one might exploit both the more favorable $1/r^2$ of the inner He zone and NC ν channels in neutron production (which in the outer He zone lead to ^{7}Li). One source of uncertainty comes from the ^{12}C and ^{16}O (n,γ) cross sections, which differ by factors of ~ 3 and 45 (10 and 160) at $T_8 \sim 0.85$ (3) between Evaluated Nuclear Data File and Japanese Evaluated Nuclear Data Library [16]. The differences reflect the energy range over which s-wave capture is assumed to dominate. Pending resolution of this discrepancy, parametric studies will be needed [19].

The CC $\bar{\nu}_e$ reaction on ^{4}He plays a crucial role in the ν-induced r-process presented here. The rate of this reaction is quite sensitive to the $\bar{\nu}_e$ spectrum [see Eq. (4)] and thus to both ν emission parameters and flavor oscillations. For our adopted ν emission parameters, only nuclei with $A \sim 70$–80 can be produced in the outer He zone without oscillations, while no interesting nucleosynthesis occurs for the normal ν mass hierarchy (strong $\nu_e \leftrightarrow \nu_x$ conversion). If we lower T_{ν_x} from 8 to 6 MeV at emission, only nuclei with $A \sim 70$–80 can be produced even with full $\bar{\nu}_e \leftrightarrow \bar{\nu}_x$ conversion (IH). Recent SN simulations for 8.8–18 $M_\odot$ progenitors yielded significantly softer ν spectra at emission than adopted above [17]. In contrast, spectra similar to ours were obtained for ~ 40–50 $M_\odot$ progenitors associated with black-hole formation [18]. Recent progress in SN modeling and in the nuclear microphysics governing ν opacity is impressive and should encourage further efforts needed to determine ν temperatures with small error bars.

In conclusion, we have explored one scenario for a cold r-process — the ν-driven He-shell mechanism — as a counterpoint to more conventional high-temperature SN r-process mechanisms that typically run into problems of seed overgrowth. The ν-induced mechanism is intriguing because it can be evaluated quantitatively in realistic progenitors, and because it is remarkably sensitive to new ν physics. We believe this cold, early mechanism merits investigation in other astrophysical settings, including the inner He zone discussed above and the late stages of ν-driven winds. The mechanism could be part of a multiple-r-process explanation of Galactic chemistry.

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