A Long, Cold, Early $r$-process? $\nu$-induced Nucleosynthesis in He Shells Revisited

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We revisit a $\nu$-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 $\nu$ emission model and to $\nu$ 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, the Fe abundance is sensitive to the emission model and to $\nu$ 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.

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
\[ \tau_{\text{coll}} \approx \frac{1}{\alpha} \left( \frac{r^3}{2GM} \right) \approx 102 \left( \frac{M_*}{M} \right)^{1/2} \frac{r_{10}^{3/2}}{s}, \] (1)
where $\alpha \approx 0.6$ is the ratio of the infall velocity to the free-fall velocity, $M \approx 2.4-33 M_\odot$ is the mass enclosed within $r$, and $r_{10}$ is $r$ in units of $10^{10}$ cm. For such large $\tau_{\text{coll}}$, 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]
\[ \tau_{\text{sh}} \approx 21.8 \left( \frac{M - M_{\text{NS}}}{M_\odot} \right)^{1/2} \frac{r_{10}}{E_{50}^{1/2}} s, \] (2)
where $M_{\text{NS}} \approx 1.4 M_\odot$ 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 $\tau_{\text{sh}}$. The peak temperature (in units of $10^8$ K) of the shocked material is [8]
\[ T_{p,8} \approx 2.37 E_{50}^{1/4} r_{10}^{-3/4}. \] (3)
For such low temperatures, photo-dissociation of heavy nuclei will not occur [3]. 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 $\nu$s irrigates the He zone. While the zone’s radius, density, and temperature are unchanged, $\nu$ reactions must induce and maintain a free-neutron density $n_n \gtrsim 10^{18}$ $\text{cm}^{-3}$ to drive an r-process. We take the $\nu$ luminosity to be $L_{\nu}(t) = L_{\nu}(0) \exp(-t/\tau_{\nu})$ for each of the six flavors, with $L_{\nu}(0) = 1.67 \times 10^{52}$ erg/s and $\tau_{\nu} = 3$ s, so that the total energy carried off by $\nu$s is $3 \times 10^{53}$ ergs. We use Fermi-Dirac $\nu$ spectra with zero chemical potential. We adopt nominal temperatures $T_{\nu e}$, $T_{\nu x}$, and $T_{\nu x}$ of 4, 5.33, and 8 MeV, respectively, where $\nu_x$ stands for any heavy flavor, but explore the temperature dependence. Our nominal parameters are typical of earlier SN models (e.g., [12]). The spectra at the He zone will be affected by $\nu$ oscillations [12], as the $\nu$ mass splitting $|\delta m_{12}^2| \approx 2.4 \times 10^{-3}$ eV$^2$ produces a level crossing for a 20 MeV $\nu$ at $\rho \approx 1.6 \times 10^3$ g/cm$^3$, a density characteristic of the carbon zone. The consequences for the r-process depend critically on the assumed $\nu$ mass hierarchy.

We evaluated the nucleosynthesis for models u11–u75 and for various $\nu$ oscillation scenarios. As an example of a successful r-process, we present detailed results for zone 597 of u11, assuming an inverted $\nu$ mass hierarchy (IH, full $\nu_e \leftrightarrow \bar{\nu}_e$ conversion). Zone parameters are $\tau_{\gamma 0} = 1.10$, $M = 2.43 M_\odot$, $\rho = 50.3$ g/cm$^3$, and $T_8 = 0.848$. The zone is nearly pure $^4\text{He}$: the initial mass fractions of $^{12}\text{C}$ and $^{14}\text{N}$ are $X_{12} \sim 1.39 \times 10^{-5}$ and $X_{14} \sim 1.35 \times 10^{-6}$. The total mass fraction of $A \geq 16$ nuclei is $\sim 3.52 \times 10^{-7}$ ($\sim 3.15 \times 10^{-8}$ from $^{56}\text{Fe}$). A big bang nucleosynthesis network [13] was modified to follow the ECH mechanism, with NC and CC $\nu$ cross sections taken from Ref. [14], which agree well with those of Ref. [2]. As the network stops at $^{16}\text{O}$, 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 $^3\text{He}(n,p)^3\text{H}$ immediately consumes all neutrons produced by the NC reaction $^4\text{He}(\nu,\nu n)^3\text{He}$. Each NC reaction thus yields one proton and one $^3\text{H}$. (2) The neutron-producing reaction proposed by ECH, $^3\text{H}(^3\text{He},2n)^4\text{He}$, is inefficient. Instead, $^3\text{H}$ is destroyed by abundant $^4\text{He}$ via $^3\text{H}(^4\text{He},\gamma)^7\text{Li}$. Neutron restoration by $^7\text{Li}(^3\text{He},n)^4\text{He}$ is ineffective for the conditions of Figure 1a. (3) Neutron production is dominated by the CC reaction $^4\text{He}(\bar{\nu}_e,e^+\gamma)^3\text{H}$. (4) The principal neutron sinks are $^7\text{Li}$, $^{12}\text{C}$, and $A \geq 16$ nuclei. (5) Protons are not a significant neutron sink as $p(\nu,\gamma)^2\text{H}$ is immediately followed by $^2\text{H}(^2\text{H},n)^4\text{He}$. (6) Due to its small initial abundance, neutron capture by $^{14}\text{N}$ is also negligible.

The rate of the CC $\bar{\nu}_e$ reaction per $^4\text{He}$ nucleus is
\[ \lambda_{\bar{\nu}_e}^{CC}(t) = \frac{2.28 \times 10^{-7}}{T_{\text{He}}^4 \exp(t/\tau_{\nu})} \left( \frac{T_{\nu_e}}{6 \text{ MeV}} \right)^k s^{-1}, \] (4)
where $k \approx 6.26$ and $\tau_{\nu_e} = 4-6$ and 6–8 MeV, respectively. Based on the above discussion, $Y_n$ in Figure 1a can be estimated from
\[ \dot{Y}_n = \lambda_{\bar{\nu}_e}^{CC}(0) Y_n \exp(-t/\tau_{\nu}) - \lambda_{n,\gamma} Y_n(t), \] (5)
where $\lambda_{\bar{\nu}_e}^{CC}(0) = 8.35 \times 10^{-7}$/s for $T_{\nu_e} = 8$ MeV (IH), $Y_n \sim 1/4$ is the number fraction of $^4\text{He}$, and $\lambda_{n,\gamma} \sim 8.12 \times 10^{-2}$/s is the net rate of neutron capture on $^7\text{Li}$ (46.2%), $^{12}\text{C}$ (21.9%), and $A \geq 16$ nuclei (31.9%). We find, in good agreement with Figure 1a,
\[ Y_n(t) = \frac{\lambda_{\bar{\nu}_e}^{CC}(0) Y_n \tau_{\nu}}{1 - \lambda_{n,\gamma} \tau_{\nu}} \left[ \exp(-\lambda_{n,\gamma} t) - \exp(-t/\tau_{\nu}) \right]. \] (6)

The neutron number density in zone 597 of u11, $n_n = Y_n n_0 N_A \sim 10^{19}$/cm$^3$ where $N_A$ is Avogadro’s number, is sufficient to drive an r-process (see Figure 2). The most effective seed is $^{56}\text{Fe}$ as it is above the $N = 28$ closed neutron shell. The typical mass number of r-elements produced at time $t$ is roughly $A \sim 56 + N_{\text{cap}}(t)$, where $N_{\text{cap}}(t) = \int_0^t n_n(t') (\sigma_{\nu,n}(\text{Fe}) \text{d}t')$ and where $(\sigma_{\nu,n}(\text{Fe}))$ is the rate coefficient for neutron capture on $^{56}\text{Fe}$. For zone 597 we find $N_{\text{cap}}(t) = 88$ (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 r-process could run to completion in the pre-shock phase.
We followed the nuclear flow from $^{56}$Fe with a large network Torch \cite{15} that includes all of the relevant neutron capture, photo-disintegration, and $\beta$-decay reactions. The yields at $t = 7$, 10, 15, and 20 s are shown in Figure 1 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 $\beta$-decay reactions are required to reach $^{130}$Cd while 139 neutron-capture and 43 $\beta$-decay reactions are required to reach $^{195}$Tm. In the absence of photo-disintegration, the $r$-path is governed by $(n, \gamma)$-$\beta$ equilibrium and the rates for neutron capture and $\beta$ decay will be comparable. For $\langle n\sigma_{n\gamma}(\text{Fe}) \rangle \sim 10^{-18}$ cm$^3$/s and $n_B \sim 10^{19}$ cm$^3$/s, the neutron-capture rate on $^{56}$Fe is $\sim 10$/s. As this rate is typical along the $r$-path, $^{130}$Cd and $^{195}$Tm will be reached in $\sim 10$ and 18 s.

We examined other u11 zones and other progenitors. For the IH case with $T_{\nu_e} \sim 8$ 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 $\sim 4 \times 10^{-8} M_\odot$ in the Sun. Abundances of heavy $r$-elements in MP stars with [Fe/H] $< -2.5$ are $\sim 3 \times 10^{-4}$--$10^{-1}$ times those in the Sun \cite{19}. 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 $\nu$s is insensitive to metallicity, depending only on SN energy, $\nu_e$ 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 \cite{19} should be studied to determine how the $\nu$-driven mechanism might merge into other $r$-processes, such as NSMs, that may only be viable for [Fe/H] $\gtrsim -2.5$ \cite{19}.

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 $^7\text{Li}$ and $^{13}\text{C}$ are included, and because the calculations confirm that the total number of neutrons captured per $^{56}\text{Fe}$ nucleus is $\ll Y_n$. Nevertheless, future studies should use a complete network for both neutron capture and $\nu$ 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 $\sim 7$ times the pre-shock value and then decreases slowly on timescales $\sim \tau_{sh}$. So while larger explosion energies, $E_{50} \sim 12$, might appear to limit the duration of the $r$-process to $\tau_{sh} \sim 7\,s$, 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 $^{13}\text{C}(^4\text{He},n)^{16}\text{O}$ and $^{17}\text{O}(^4\text{He},n)^{20}\text{Ne}$: $^{12}\text{C}$ and $^{16}\text{O}$ are the principal neutron sinks in the inner He shell. If shock heating to $\gtrsim 5\times 10^8\text{K}$ 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 $\nu$ channels in neutron production (which in the outer He zone lead to $^7\text{Li}$). One source of uncertainty comes from the $^{12}\text{C}$ and $^{16}\text{O}$ $(n,\gamma)$ cross sections, which differ by factors of $\sim 3$ and $45$ (10 and 160) at $T_8 \sim 0.85$ (3) between Evaluated Nuclear Data File and Japanese Evaluated Nuclear Data Library 10. 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 $\nu_e$ reaction on $^4\text{He}$ plays a crucial role in the $\nu$-induced r-process presented here. The rate of this reaction is quite sensitive to the $\nu_e$ spectrum [see Eq. 4] and thus to both $\nu$ emission parameters and flavor oscillations. For our adopted $\nu$ 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 $\nu$ mass hierarchy (strong $\nu_e \leftrightarrow \nu_x$ conversion). If we lower $T_{\nu_e}$ from 8 to 6 MeV at emission, only nuclei with $A \sim 70–80$ can be produced even with full $\nu_e \leftrightarrow \nu_x$ conversion (III). Recent SN simulations for 8.8–18 $M_\odot$ progenitors yielded significantly softer $\nu$ spectra at emission than adopted above 17. In contrast, spectra similar to ours were obtained for $\sim 40–50\,M_\odot$ progenitors associated with black-hole formation 18. Recent progress in SN modeling and in the nuclear microphysics governing $\nu$ opacity is impressive and should encourage further efforts needed to determine $\nu$ temperatures with small error bars.

In conclusion, we have explored one scenario for a cold $r$-process — the $\nu$-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 $\nu$-induced mechanism is intriguing because it can be evaluated quantitatively in realistic progenitors, and because it is remarkably sensitive to new $\nu$ 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 $\nu$-driven winds. The mechanism could be part of a multiple-$r$-process explanation of Galactic chemistry.

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