The r-Process without Excess Neutrons

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Abstract

The r-process of nucleosynthesis requires a large neutron-to-seed nucleus abundance ratio. This does not, however, require that there be an excess of neutrons over protons. If the expansion of the matter is sufficiently rapid and the entropy per nucleon is sufficiently high, the nucleosynthesis enters a heavy-element synthesis regime heretofore unexplored. In this extreme regime, characterized by a persistent disequilibrium between free nucleons and the abundant alpha particles, heavy r-process nuclei can form even in matter with more protons than neutrons. This observation bears on the issue of the site of the r-process, on the variability of abundance yields from r-process events, and on constraints on neutrino physics derived from nucleosynthesis. It also clarifies the difference between nucleosynthesis in the early universe and that in less extreme stellar explosive environments.
Despite years of study, a proper understanding of the provenance of the solar system’s r-process isotopes remains elusive. These nuclei, comprising roughly half the isotopes heavier than iron, are suspected to have formed in environments expanding rapidly from conditions of high temperature and density. During this expansion, heavy seed nuclei form. If excess neutrons remain after seed production, each nucleus is subsequently able to capture a large number of neutrons, thereby producing the r-process isotopes. This basic mechanism has long been understood [1, 2]. The difficulty in determining the r-process site lies rather in finding a realistic astrophysical setting that can generate a sufficiently large neutron-to-seed ratio.

The requirement of a large neutron-to-seed ratio for a successful r-process has long suggested that the r-process environment must have a substantial excess of neutrons over protons. The degree of this excess depends on the entropy per nucleon and the expansion timescale. For low-entropy (entropy per nucleon $s/k_B \lesssim 1$) material, seed nucleus production is highly efficient. The material must therefore be quite neutron rich to have a large enough neutron-to-seed ratio. Such material typically requires an electron-to-nucleon ratio $Y_e \approx 0.1 - 0.2$. It should be noted that $Y_e$ is, for charge-neutral matter, the fraction of all nucleons that are protons. While ejection of neutronized matter from supernova cores (e.g., [3, 4]) or from colliding neutron stars (e.g., [5]) are promising scenarios for such low-entropy r-processes, current models have not yet established that enough neutron-rich matter is ejected to explain the solar system’s r-process abundances.

For higher entropies ($s/k_B \geq 100$) and faster expansions, such as are thought to occur in neutrino-heated ejecta from proto-neutron stars, seed nucleus production is less efficient, and the r-process may occur for larger $Y_e$, typically in the range $Y_e \approx 0.35 - 0.45$ (for example, see Refs. [6, 7]). Recent r-process calculations in the context of general-relativistic wind models show great promise. One group obtains realistic r-process yields for $Y_e = 0.4$ [8]. Another group argues that realistic supernova neutrino spectra may not allow $Y_e$ to get so low in the winds and that, if the r-process occurs in these environments, $Y_e$ is more likely in the range 0.47-0.495 [9]. A higher-$Y_e$ r-process has two advantages. First, it does not suffer from the overproduction of $N = 50$ isotones common in wind models with lower $Y_e$ (e.g., [6, 7]). Second, it is less susceptible than lower-$Y_e$ r-processes to the detrimental
effects of the neutrino-induced “alpha effect” (e.g., [10]), which may drastically diminish the neutron-richness of wind matter during seed nucleus production. The issue for the higher-$Y_e$ r-process is whether the winds can attain high enough entropy and fast enough expansion rates to make heavy r-process isotopes.

The purpose of this paper is to point out that a high neutron-to-seed ratio for the r-process does not necessarily require that the environment be neutron rich. In fact, heavy r-process nuclei can form in environments with equal numbers of neutrons and protons ($Y_e = 0.5$) or even with excess protons ($Y_e > 0.5$). The nucleosynthesis is qualitatively different from that in previously studied r-process scenarios because of a persistent disequilibrium between free nucleons and alpha particles. This observation has interesting implications for the site of the r-process, the variability of r-process yields, and constraints on neutrino physics drawn from nucleosynthesis. It also clarifies the difference between explosive nucleosynthesis in the early universe and in stars.

In order to explore this issue, calculations were made with the Clemson nucleosynthesis code [11]. This code has been recently updated to use the NACRE [12] and NON-SMOKER [13] rate compilations. Figure 1 shows the final abundances per nucleon (as a function of mass number) for three calculations, each with $Y_e = 0.5$ and entropy per nucleon $s/k_B = 150$. In each calculation, the expanding material was modeled to begin at temperature above $T_9 = T/10^9$ K = 10. The material was taken to expand with constant entropy and the density to fall with time $t$ as

$$\rho(t) = \rho_1 \exp(-t/\tau) + \rho_2 \left( \frac{\Delta}{\Delta + t} \right)^2$$

(1)

where $\rho_1 + \rho_2$ is the density at time $t = 0$ and $\Delta$ was chosen so that the two terms on the right-hand side of Eq. (1) were equal near $T_9 = 2$. This form of expansion models neutrino-driven winds from neutron stars, which initially expand roughly exponentially (the first term in Eq. (1)) but then may evolve to an outflow with constant velocity (the second term in Eq. (1)). At each timestep, the temperature was determined from the composition, entropy, and density by iteration, as described in Ref. [14].

As Figure 1 shows, expansions with $\tau = 0.03$ or 0.003 seconds produce significant quantities of $^4$He and iron group nuclei (particularly isotopes of nickel), as expected for high entropy and $Y_e = 0.5$ matter. For the expansion with a $\tau$ of 0.0003 seconds, however, considerably heavier nuclei form. While the resulting abundance pattern does not match the
solar system r-process abundance distribution in detail, many heavy r-process nuclei have
been synthesized.

The nuclear dynamics that allows matter without neutron excess to produce heavy r-
process nuclei is qualitatively different from that in more standard r-processes. This is
best illustrated in Figure 2, which shows the quantity $R(\alpha)/R(p)^2R(n)$ in the three calculations.
The quantity $R_i$ at a particular point in an expansion is the ratio of the abundance of
species $i$ (with proton number $Z_i$ and neutron number $N_i$) in the actual reaction network
to the abundance that species would have in nuclear statistical equilibrium at the same
temperature, density, and $Y_e$. $R_i/R(Z_i)^pR(N_i)$ is unity if the free nucleons are in equilibrium
with species $i$ and less than unity if species $i$ is underabundant relative to equilibrium [15].
In slower and lower-entropy expansions, reactions converting nucleons into alpha particles
and back proceed rapidly enough to maintain an equilibrium among these species down to
relatively low temperatures ($T_9 \approx 3 - 4$). The result is that $R(\alpha)/R(p)^2R(n)$ stays near unity
throughout much of the expansion (cf. Fig. 8 of Ref. [15]). In the present calculations this
is not the case. The equilibrium begins to fail as the material cools below $T_9 \approx 9$. In the
$\tau = 0.03$ and $0.003$ s expansions, this equilibrium recovers around $T_9 = 6$ and then persists
down to $T_9 \approx 3.5$. In the $\tau = 0.0003$ s expansion, the equilibrium never recovers.

The equilibrium between the nucleons and alpha particles first fails near $T_9 \approx 9$ because
of the high entropy and low abundance of light nuclear species. Figure 3 shows that $^2$H, $^3$H,
and $^3$He all remain in excellent equilibrium with the nucleons in the $\tau = 0.0003$ s expansion
down to $T_9 \approx 3$ for the heavier two species and $T_9 \approx 1$ for deuterium. These isotopes
behave similarly in the two slower expansions. Because of the high entropy, however, the
light isotope abundances are extremely low. Production of $^4$He occurs primarily via capture
on these species, so, as the temperature falls, their low abundances fail to maintain $^4$He at
its equilibrium abundance.

The return to equilibrium in the two slower expansions happens because of the produc-
tion of heavy nuclei. As Figure 3 shows, these two expansions begin producing significant
numbers of heavy nuclei near $T_9 \approx 6$. Once sufficiently many heavy nuclei have formed, they
are able to catalyze the equilibrium between the nucleons and $^4$He via fast reaction cycles
such as $^{62}$Ni($p, \gamma$)$^{63}$Cu($n, \gamma$)$^{64}$Cu($n, \gamma$)$^{65}$Cu($p, \alpha$)$^{62}$Ni and their inverses. For the $\tau = 0.0003$
s expansion, however, considerably fewer nuclei form. The smaller number of heavy nuclei
are then unable to restore the equilibrium between the nucleons and $^4$He.
For temperatures below $T_9 \approx 6$, equilibrium in these expansions strongly favors locking most free nucleons into $^4$He. In the $\tau = 0.03$ and $0.003$ s expansions, then, few free nucleons are available at lower temperatures for subsequent capture. By contrast, because the equilibrium fails early for the $\tau = 0.0003$ s expansion and is never restored, the few free nuclei that form co-exist with a huge overabundance of free neutrons and protons down to low temperature. This is shown in Figures 5 and 6. At $T_9 = 4$, there are roughly $10^3$ times more free protons and $10^6$ times more neutrons per seed nucleus in the $\tau = 0.0003$ s expansion than in the two slower ones. This excess of nucleons leads to heavier seed nuclei than would be expected in the less extreme expansions. Furthermore, the free neutrons are available at lower temperatures for r-process nucleosynthesis. More details of the three expansions, including movies, are available in the electronic addendum to this paper [16].

The presence of a persistent disequilibrium between free nucleons and alpha particles can even allow proton-rich matter to produce heavy r-process nuclei. For example, figure 7 shows the final abundances for a calculation with $\tau = 0.0003$ s, $s/k_B = 200$, and $Y_e = 0.505$. The overall yield is low, and the final distribution does not match the solar r-process pattern. Nevertheless, heavy r-process nuclei have formed even though the matter, in bulk, actually has more protons than neutrons.

Although the expansion timescales and/or entropies needed for an r-process without excess neutrons are considerably more extreme than current models yield (e.g., [4]), the present results should nevertheless encourage further study of supernova models with rapid ejection of high-entropy but nearly symmetric ($Y_e \approx 0.5$) matter. Additional nucleosynthesis calculations are also needed to explore conditions required for a disequilibrium between free nucleons and alpha particles and the resulting r-process abundances. The presence or absence of such a disequilibrium can cause the final r-process abundances to be quite sensitive to the expansion parameters, especially for slightly neutron-rich matter. For example, an expansion with $s/k_B = 150$, $\tau = 0.0007$ s, and $Y_e = 0.4975$ predominantly forms third-peak nuclei (mass number $A \approx 195$) because of the persistent disequilibrium between nucleons and alpha particles while a calculation with $s/k_B = 150$, $\tau = 0.0008$ s, and $Y_e = 0.4975$ makes a strong second r-process peak ($A \approx 130$) but few heavier nuclei because the nucleon-alpha particle equilibrium is restored [16]. Such sensitivity could result in variability of r-process yields from nucleosynthesis event to event and provide a natural explanation for the two r-process component scenario often invoked to explain the abundances of extinct short-lived
r-process radioactivities in meteorites (e.g., [17]). It should also be clear that since heavy r-process nuclei can form even in matter with $Y_e > 0.5$, constraints on the properties of neutrinos, as inferred from r-process yields (e.g., [18]), must be made with caution.

The above considerations clarify the fundamental difference between “normal” explosive nucleosynthesis in stars and nucleosynthesis in the early universe. In “normal” explosive stellar nucleosynthesis, conditions are not too extreme, and the free nucleons typically remain in equilibrium with the $^{4}\text{He}$ nuclei to relatively low temperature. This leaves few free protons or neutrons available for subsequent modification of the abundances, unless the material is significantly neutron or proton rich. By contrast, in the early universe, $^{4}\text{He}$ would dominate the equilibrium abundances at $T_9 \approx 3$ and lock up all free neutrons, resulting in a $^{4}\text{He}$ mass fraction greater than 30% [16]. The extremely high entropy, however, keeps the abundance of $^2\text{H}$, $^3\text{H}$, and $^3\text{He}$ low, thereby preventing $^4\text{He}$ from attaining its high equilibrium value. Synthesis of $^4\text{He}$ occurs only several minutes later when the temperature drops below $T_9 \approx 1$. At this point, the equilibrium between the nucleons and $^2\text{H}$ breaks and non-equilibrium nuclear flows build up $^4\text{He}$. Because the neutrons remain free due to the lack of equilibrium between free nucleons and $^4\text{He}$, their abundance declines by beta decay over the several minutes period from $T_9 = 3$ to $T_9 \approx 1$, thereby leading to a $^4\text{He}$ mass fraction of approximately 25%.

Further modeling will establish whether the solar system’s r-process isotopes formed in a disequilibrium between the free nucleons and alpha particles. Regardless of the outcome of such modeling, however, a certain irony attends the fact that the synthesis of heavy r-process nuclei can be in its fundamental aspect more similar to the formation of nature’s lightest isotopes in the early universe than to production of heavier isotopes such as $^{56}\text{Fe}$ in less extreme explosive processes.

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FIG. 1: Final abundances per nucleon versus mass number $A$ for increasingly rapid expansions.
FIG. 2: Equilibrium of neutrons, protons, and alpha particles during the three expansions of Fig. [4].

FIG. 3: The equilibrium among the neutrons, protons, $^2$H, $^3$H, and $^3$He for $\tau = 0.0003$ s. The $^3$H curve lies beneath the $^3$He curve.
FIG. 4: The abundance of heavy nuclei versus temperature for the three calculations of FIG. 4.

FIG. 5: The proton-to-seed ratio versus temperature for the three calculations of FIG. 5.
FIG. 6: The neutron-to-seed ratio versus temperature for the three calculations of FIG. 1.

FIG. 7: The final abundances per nucleon as a function of nuclear mass number for the calculation with $Y_e = 0.505$, $s/k_B = 200$, and $\tau = 0.0003\,s$. 