r-Process Nucleosynthesis without Excess Neutrons

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Matter expanding sufficiently rapidly and at high enough entropy per nucleon can enter a heavy-element synthesis regime heretofore unexplored. In this extreme regime, more similar to nucleosynthesis in the early universe than to that typical in stellar explosive environments, there is a persistent disequilibrium between free nucleons and abundant alpha particles, which allows heavy *r*-process nucleus production 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.

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Despite years of study, a complete 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 nuclei form. If excess neutrons remain after heavy nuclide production, each nucleus serves as a "seed" nucleus for subsequent neutron capture, which thereby produces 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 time scale. 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, typically requiring an electron-to-nucleon ratio $Y_e \approx 0.1$–0.2. For reference, in charge-neutral matter, Y_e is the fraction of all nucleons that are protons. While ejection of neutronized matter from supernova cores (e.g., [3]) or from colliding neutron stars (e.g., [4]) 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 protoneutron stars, seed nucleus production is less efficient, and the *r* process may occur for larger Y_e. Recent general-relativistic models show that winds from compact nascent neutron stars can expand on several millisecond time scales [5,6]. Such rapid winds achieve high neutron-to-seed ratios and thereby successfully produce the heaviest *r*-process nuclei for only moderately neutron-rich material ($Y_e \approx 0.4$–0.45) [5,7].

The purpose of this Letter 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 implications for the site of the *r* process, the variability of *r*-process yields, and constraints on neutrino physics drawn from nucleosynthesis.

To explore this issue, calculations were made with the Clemson nucleosynthesis code [8], recently updated to use the NACRE [9] and NON-SMOKER [10] 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

$$\rho(t) = \rho_1 \exp(-t/\tau) + \rho_2\left(\frac{\Delta}{\Delta + t}\right)^2, \qquad (1)$$

where $\rho_1 + \rho_2$ is the density at time $t = 0$ and Δ 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 roughly models a radial outflow at a constant mass loss rate (such as might occur in neutrino-driven winds). Matter initially expands exponentially [the first term in Eq. (1)] so that the radial coordinate r increases exponentially on a time scale $\tau_{\rm dyn} = 3\tau$ (since $\rho \propto r^{-3}$) but then evolves to an outflow with constant velocity [the second term in Eq. (1)] so that the $\tau_{\rm dyn}$ increases linearly with t. This means that for certain initial radial

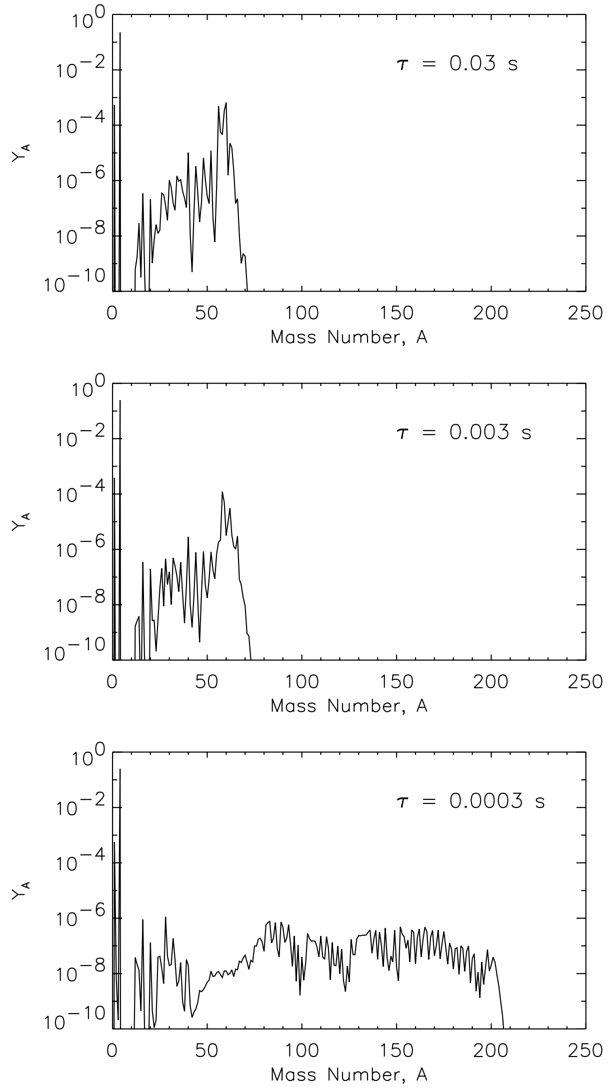

FIG. 1. Final abundances per nucleon versus mass number A for increasingly rapid expansions.

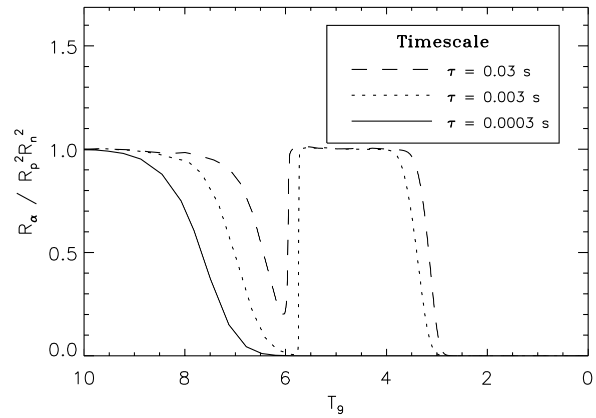

FIG. 2. Equilibrium of neutrons, protons, and alpha particles during the three expansions of Fig. 1.

coordinates (e.g., $r < 30$ km for the $\tau = 0.0003$ s expansion below), the maximum outflow speed is always less than c. At each time step, the temperature was determined from the composition, entropy, and density by iteration, as described in Ref. [11].

As Fig. 1 shows, expansions with $\tau = 0.03$ or 0.003 s 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. The $\tau = 0.0003$ s expansion, however, forms considerably heavier nuclei. While the resulting abundance pattern does not match the solar system r-process abundance distribution in detail, many heavy r-process nuclei are present.

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 Fig. 2, which shows the quantity $R_\alpha/R_p^2R_n^2$ 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. $R_i/R_p^{Z_i}R_n^{N_i}$ is unity if the free nucleons are in equilibrium with species i and less than unity if species i is underabundant relative to equilibrium [12]. 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 $R_\alpha/R_p^2R_n^2$ stays near unity throughout much of the expansion (cf. Fig. 8 of Ref. [12]). 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 production of heavy nuclei. As Fig. 4 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

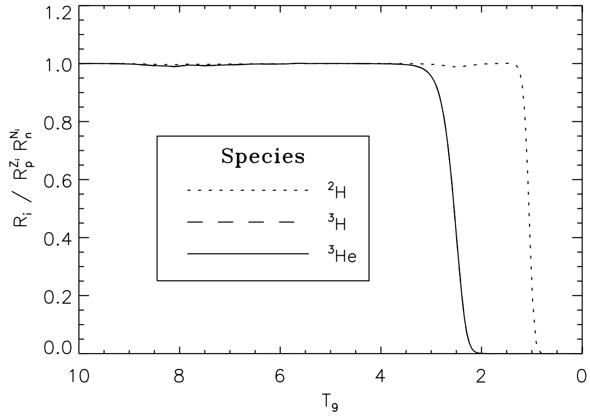

FIG. 3. The equilibrium among the neutrons, protons, ^{2}H, ^{3}H, and ^{3}He for $\tau = 0.0003$ s. The ^{3}H curve lies beneath the ^{3}He curve.

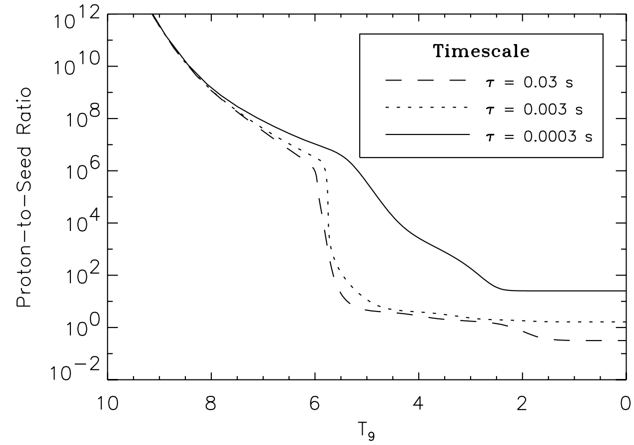

FIG. 5. The proton-to-seed ratio versus temperature for the three calculations of Fig. 1.

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 coexist with a huge overabundance of free neutrons and protons down to low temperature. This is shown in Figs. 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. It is worth remarking that the persistent disequilibrium between nucleons and the alpha particles means the $\tau = 0.0003$ s expansion is similar to early-universe nucleosynthesis, which is also characterized by a lack of equilibrium between free nucleons and alpha particles. More details of the three expansions, including movies and comparisons to early-universe nucleosynthesis, are available in the electronic addendum to this paper [13].

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, Fig. 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.

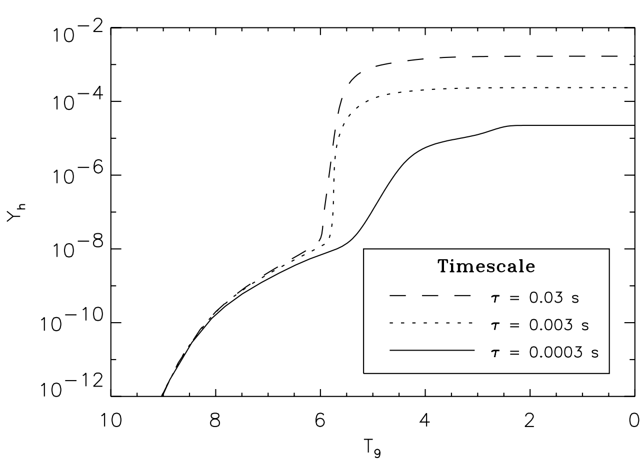

FIG. 4. The abundance of heavy nuclei versus temperature for the three calculations of Fig. 1.

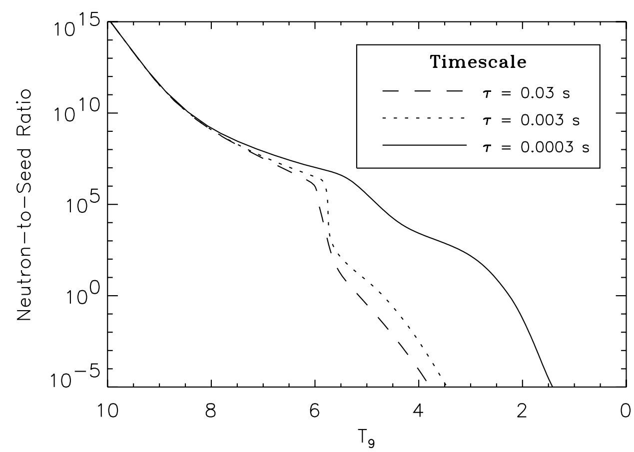

FIG. 6. The neutron-to-seed ratio versus temperature for the three calculations of Fig. 1.

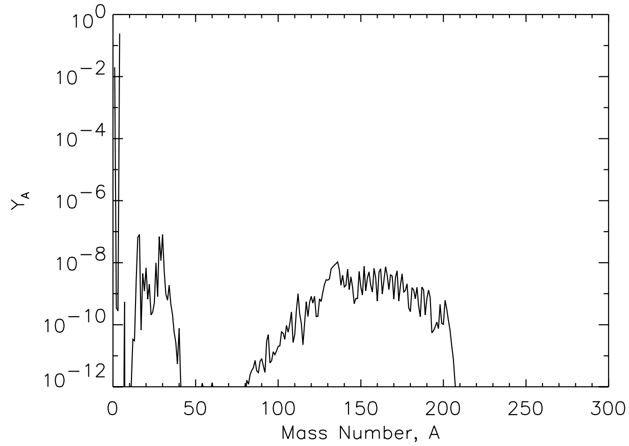

FIG. 7. The final abundances per nucleon as a function of nuclear mass number for the calculation with $Y_e = 0.505$, $s/k_B = 200$, and $\tau = 0.0003$ s.

Although the expansion time scales and/or entropies needed for an r process without excess neutrons are considerably more extreme than current models yield (e.g., [5,6]), the present results should nevertheless encourage further study of models of astrophysical settings 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 disequilibrium can also result for slower expansions but higher entropies—for example, a calculation with $Y_e = 0.5$, $s/k = 250$, and $\tau = 0.002$ s gives results similar to the $\tau = 0.0003$ s expansion in Fig. 1. Interestingly, 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 [13]. 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 scenarios often invoked to explain the abundances of extinct short-lived r-process radioactivities in meteorites (e.g., [14]). 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., [15]), must be made with caution.

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