

FREE-NUCLEON/ALPHA-PARTICLE DISEQUILIBRIUM AND R-PROCESS NUCLEOSYNTHESIS

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We demonstrate that if r-process nucleosynthesis occurs in expansions of matter from high temperature and density in which free nucleons are persistently in disequilibrium with alpha particles, then the resulting abundance distribution can be highly sensitive to the magnitude of strong and electromagnetic reaction cross sections on heavy nuclei. For the particular expansions studied in this work, reactions on nuclei in the atomic number range $Z \approx 40$ and $Z \approx 55$ have the largest effect. These nuclei may be important targets for near-term nuclear cross section experiments.

Keywords: r-Process; Nucleosynthesis; Nuclear Reactions.

1. Introduction

The r-process of nucleosynthesis is responsible for production of roughly half the nuclei heavier than iron^{1,2}. It is generally thought to proceed through a series of increasingly constrained statistical equilibria (e.g., see Ref. 3), in which case the matter needs to be sufficiently neutron rich to make the heavy neutron-rich isotopes. If, however, expansions of matter from high temperature and density occur rapidly enough, the free nucleons and alpha particles are not in equilibrium with each other during the expansion and it becomes possible to make heavy, neutron-rich nuclei even in matter that is slightly proton rich⁴.

When the nucleosynthesis proceeds through a series of constrained equilibria, the final r-process abundance distribution is quite sensitive to the reactions that assemble heavy nuclei from nucleons and alpha particles but not to reactions on heavy nuclei. In sufficiently fast, high-entropy expansions, however, the possibility of a free-nucleon/alpha-particle disequilibrium can make the abundance distribution highly sensitive to reactions on

heavy isotopes. We demonstrate that the magnitude of strong and electromagnetic reaction cross sections on heavy nuclei can govern whether the free nucleons and alphas are in equilibrium. Since these cross sections are generally not known experimentally, they may be important for experimental study in the near future.

2. Alpha-Particle Disequilibrium and Sensitivity to Cross Sections

In order to study the role of reactions on heavy nuclei in fast expansions of high-entropy matter, we ran calculations with the Clemson Nucleosynthesis Code⁵. The network included species from neutrons and protons up to uranium and all relevant strong, electromagnetic, and weak reactions. The matter was taken to be initially slightly neutron rich with a net electron-to-nucleon ratio $Y_e = 0.4975$. The mass density ρ was assumed to evolve with time as

$$\rho(t) = \rho_1 e^{-t/\tau_1} + \rho_2 e^{-t/\tau_2}, \quad (1)$$

where $\rho_1 = 2.265 \times 10^6 \text{ g/cm}^3$, $\tau_1 = 0.7$ milliseconds, $\rho_2 = 1.195 \times 10^3 \text{ g/cm}^3$, and $\tau_2 = 100$ milliseconds. The initial temperature was $T_9 = T/10^9 \text{ K} = 10$, which translates to a photon-to-nucleon ratio of 15. This photon-to-nucleon ratio was taken to be a constant during the expansion so that $\rho \propto T^3$. It is useful to note that a photon-to-nucleon of 15 corresponds to an entropy per nucleon of about 150.

The first calculation used standard reaction rates on heavy nuclei⁶. In order to study the effect of the catalyzing effect of the reactions on heavy nuclei, we also ran an identical calculation to the first but this time with all strong and electromagnetic reactions on nuclei with atomic number $Z \geq 20$ increased by a factor of two at all temperatures. In order to ensure that the nuclear populations achieved the correct equilibrium, the code automatically increased the corresponding reverse reaction rates by a factor of two as well.

Figure 1 shows the final abundances in the two calculations as a function of nuclear mass number A . Remarkably, when the reaction cross sections on isotopes of Calcium and heavier are increased by a factor of two, lighter nuclei are produced. The calculation with standard rates produces a robust third r-process peak ($A \approx 195$) while the calculation with the increased cross sections only produces a second r-process peak ($A \approx 130$). The reason for difference this is that described in Ref. 4. Early in these fast, high-entropy expansions, the alpha particles fall out of equilibrium with the free

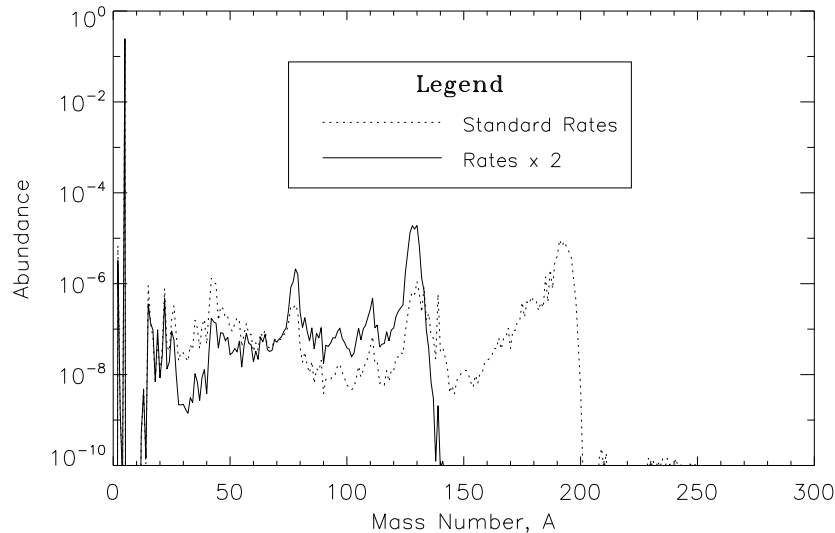


Fig. 1. The final abundances for the calculation with standard rates and the calculation with strong and electromagnetic reaction cross sections for $Z \geq 20$ increased by a factor of 2.

nucleons. This is because the high entropy leads to deuterium, tritium, and ^3He abundances that are too low to carry flow to ^4He as rapidly as the equilibrium demands. Later in the expansion, however, the alpha particles that are present assemble into heavier nuclei via three-body reactions, such as the triple- α reaction. If enough of these heavy nuclei form, reaction cycles such as $^{56}\text{Ni}(n, \gamma)^{57}\text{Ni}(n, \gamma)^{58}\text{Ni}(p, \gamma)^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$ and their reverses can assemble ^4He from free neutrons and protons and restore the free-nucleon/alpha-particle equilibrium. If the equilibrium catalyzing reaction cycles are not efficient, however, the disequilibrium between free nucleons and alphas persists.

For the expansions considered here, the catalyzing nuclear reactions are not fast enough to restore the free-nucleon/alpha-particle equilibrium. However, when we increase the cross sections on Calcium and heavier isotopes, the reactions are faster and do restore the equilibrium. This is evident in Figure 2. The quantity $R_\alpha/R_n^2 R_p^2$ measures how well the free neutrons and protons are in equilibrium with the alpha particles⁷. From Figure 2, it is clear that the free-nucleon/alpha-particle equilibrium fails in the expansion

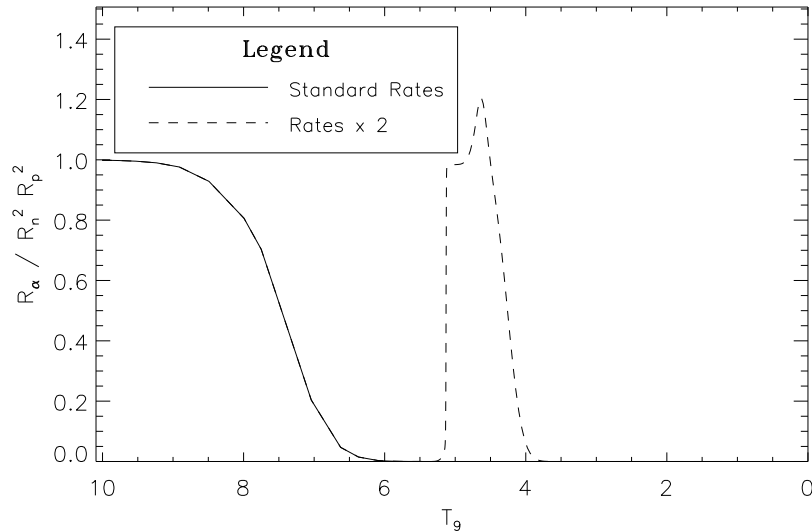


Fig. 2. The quantity measuring equilibrium between free nucleons and alpha particles as a function of temperature for the calculation with standard rates and the calculation with strong and electromagnetic reaction cross sections for $Z \geq 20$ increased by a factor of 2.

with standard rates near temperature $T_9 \approx 8$ and is never restored. By contrast, in the expansion with the increased cross sections on heavy nuclei, the equilibrium is restored near $T_9 = 5.2$.

It is important to note that, for the high-entropy expansions we consider in this work, the free-nucleon/alpha-particle equilibrium favors ${}^4\text{He}$ over free nucleons as the temperature drops below $T_9 \approx 6$. A disequilibrium between the free nucleons and alpha particles thus leads to a much higher abundance of free neutrons and protons than would prevail if the equilibrium were present. The consequence is that the few heavy nuclei that do form by three-body reactions (namely, the triple- α reaction) capture many neutrons and protons and are thus much heavier than they would be if the free-nucleon/alpha-particle equilibrium were present. If the equilibrium is restored, however, the abundance of free nucleons that keeps the nuclei at high mass is depleted and, thus, the heavy nucleus abundance distribution collapses back down towards the iron-group isotopes. Figure 3 shows the number of free protons per heavy nucleus during the two expansions. It

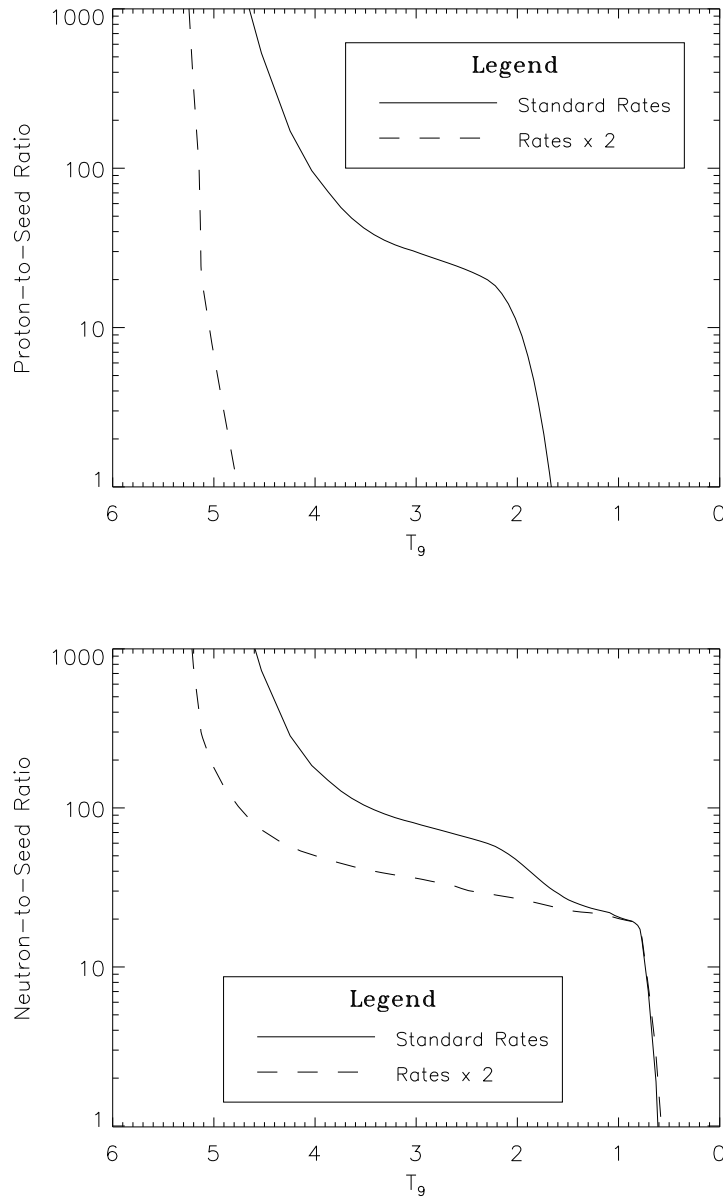


Fig. 3. The number of protons (upper panel) and neutrons (lower panel) per heavy nucleus as a function of temperature for the calculation with standard rates and the calculation with strong and electromagnetic reaction cross sections for $Z \geq 20$ increased by a factor of 2.

is clear that for the expansion with enhanced nuclear cross sections, there are many fewer protons after the free-nucleon/alpha-particle equilibrium is restored. The seed abundance distribution for the r-process phase of the expansion is thus lower in mass than in the expansion with the standard rates. Figure 3 shows that there are also fewer neutrons per nucleus available for the subsequent r-process phase. The result is that the expansion with the enhanced reaction cross sections makes lower-mass nuclei on average than the expansion with the standard rates, as seen in Figure 1.

Since an increase of the strong and electromagnetic reaction cross sections is better able to catalyze the free-nucleon/alpha-particle equilibrium, a decrease of those cross sections should hinder the catalysis and produce heavier nuclei. This is evident in Figure 4. The smaller cross sections leads to a heavier seed distribution and more free particles for the subsequent r-process phase.

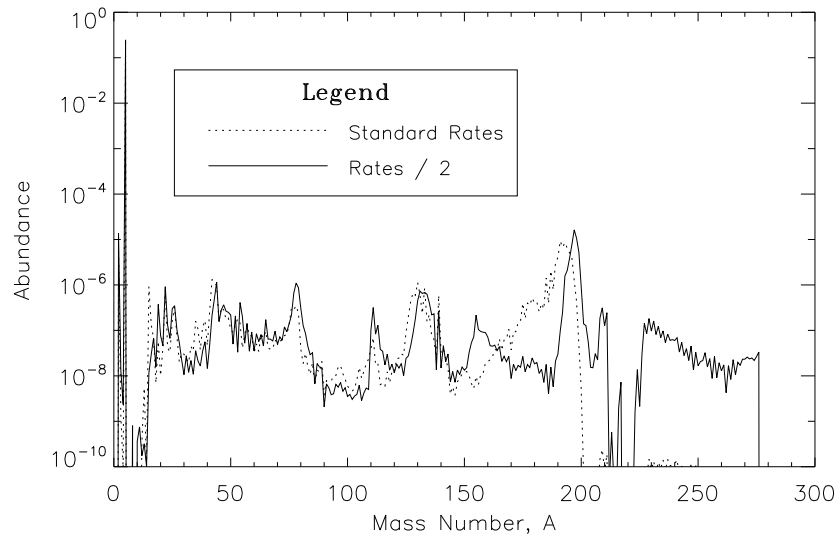


Fig. 4. The final abundances for the calculation with standard rates and the calculation with strong and electromagnetic reaction cross sections for $Z \geq 20$ decreased by a factor of 2.

3. Nuclei of Importance

As Figures 1-4 show, the magnitude of the cross sections for strong and electromagnetic reactions on heavy nuclei can affect the final r-process yields by determining the efficiency of the catalysis of the free-nucleon/alpha-particle equilibrium. In order to get a better sense of which nuclei are important as catalysts for the conditions studied here, we ran identical calculations but with different values of the cutoff atomic number Z_c , that is, the atomic number including and above which we increased the cross sections of strong and electromagnetic reactions by a factor of two. The results of this survey are shown in Figure 5.

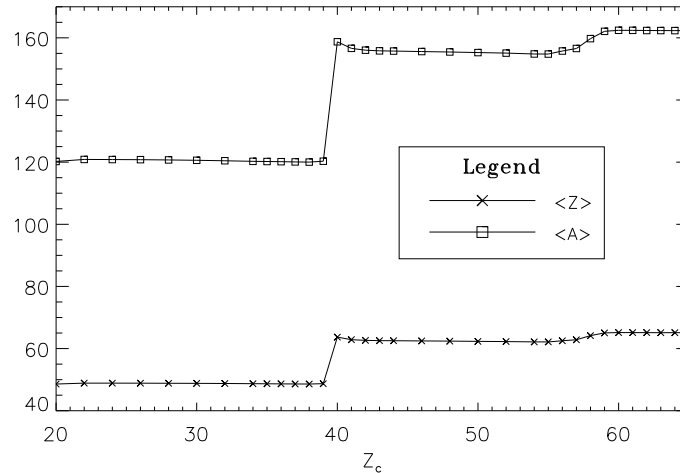


Fig. 5. The resulting average atomic number and mass number of the heavy nuclei when the strong and electromagnetic reaction cross sections for $Z \geq Z_c$ are increased by a factor of 2.

Figure 5 shows the average atomic charge $\langle Z \rangle$ and average atomic mass $\langle A \rangle$ of the heavy nuclei in the final abundance distribution as a function of the cutoff Z . There is a sharp jump when Z_c shifts from 39 to 40 and then declines slightly for higher Z_c before rising again. This suggests that nuclei in the atomic number range $Z = 38 - 42$, and particularly with $Z = 39$, are the important catalysts for restoring the free-nucleon/alpha-particle equilibrium. It is also evident that cross sections on nuclei in the

range $Z \approx 55$ also have an effect on the final abundance distribution.

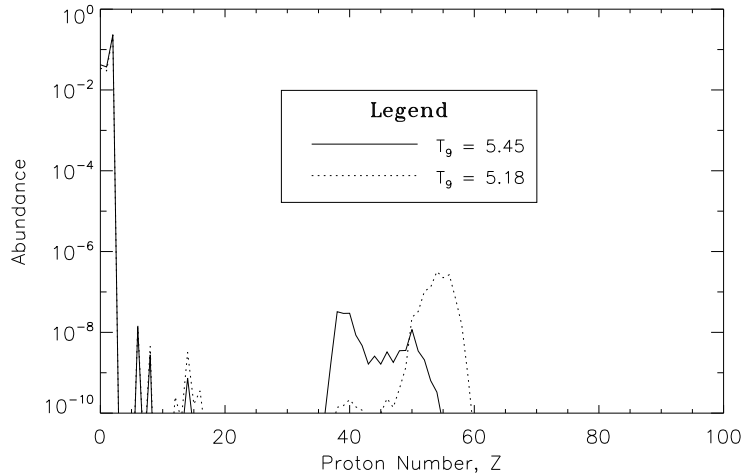


Fig. 6. The elemental abundances at $T_9 = 5.45$ and $T_9 = 5.18$ in the calculation with standard rates.

Figure 6 shows why cross sections on nuclei in the $Z \approx 40$ and $Z \approx 55$ range are important. In the expansion with standard rates, the heavy-element abundance distribution for $T_9 = 5.45$ is dominated by $Z \approx 40$ nuclei. Reactions on these nuclei then are the ones that catalyze the free-nucleon/alpha-particle equilibrium. As the temperature drops, the abundance distribution shifts to even higher charge. At $T_9 = 5.18$ nuclei with $Z \approx 55$ dominate the abundances and, consequently, reactions on these species catalyze the assembly of ${}^4\text{He}$ and deplete the free nucleon abundance.

When the reaction cross sections on nuclei with $Z \geq 20$ are increased by a factor of 2, the reactions on $Z \approx 40$ nuclei restore the free-nucleon/alpha-particle equilibrium. The abundance distribution never reaches the $Z \approx 55$ nuclei. Rather it returns to a quasi-statistical equilibrium dominated by iron-group isotopes. When the reaction cross sections on nuclei with $Z \geq 55$ are increased by a factor of 2, the abundance distribution is able to shift past $Z \approx 40$ up to $Z \approx 55$. The catalyzing reactions on those species do form ${}^4\text{He}$ but not enough to restore the full free-nucleon/alpha-particle equilibrium.

The seed distribution is a little lower in mass and the abundance of free neutrons is a little less than in the calculation with standard rates. This is the cause of the slight rise in the average nuclear mass and atomic number in Figure 5 when Z_c is above $Z \approx 57$. The reader is invited to study this further by viewing the movies at <http://nucleo.ces.clemson.edu/home/movies>.

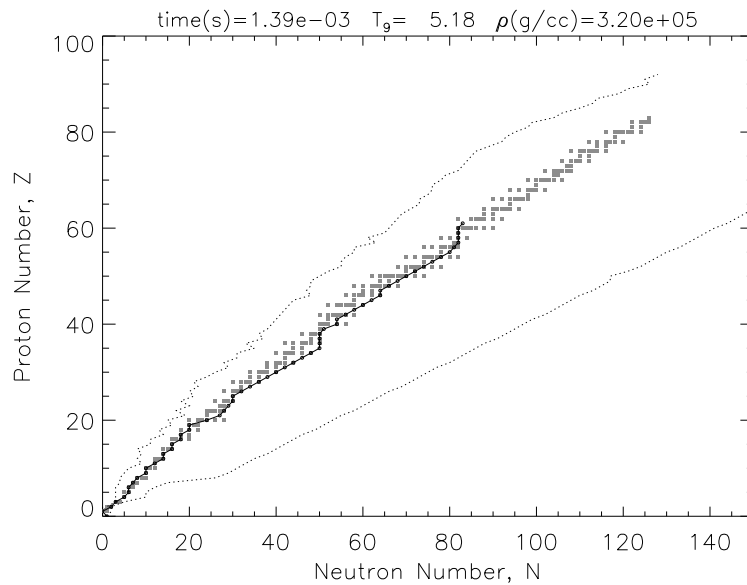


Fig. 7. The r-process “path”, that is, the locus of most abundant isotopes for each element, for $T_9 = 5.18$ in the calculation with standard rates. The stable isotopes are the small solid boxes. The limits of the network are also shown.

The specific reaction pathways that are important for catalyzing the free-nucleon/alpha-particle equilibrium are difficult to determine because they involve many nuclei simultaneously. Nevertheless, it is clear that the important isotopes are beta-stable nuclei or near stability. Figure 7 shows the nucleosynthesis “path”, that is, the locus of most abundant isotopes for each element, at $T_9 = 5.18$. It is evident that at this temperature, the most abundant isotopes are near stability. Only at lower temperatures does the path move to more neutron-rich species. This again is best seen in movies at the URL above.

4. Discussion

Recent work suggests that supernovae can indeed achieve conditions in which nucleosynthesis occurs with a persistent free-nucleon/alpha-particle disequilibrium⁸. If indeed this result is further confirmed, experimental studies of strong and electromagnetic reaction cross sections on nuclei in the $Z \approx 40$ and $Z \approx 55$ regions will become important for good estimates of the resulting nuclear yields. Interestingly, the important isotopes will be near beta stability and, hence, can be studied with facilities currently existing or planned for construction in the near future.

Acknowledgments

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