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Following Fission Products in Explosive Astrophysical Environments

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Abstract. The astrophysical process by which the heaviest elements are formed in the universe is known as the rapid neutron capture process, or *r* process, of nucleosynthesis. The *r* process is characterized by the neutron capture and β^- decay of short-lived, neutron-rich atomic nuclei; in suitably extreme environments, nuclear fission can also play a major role in determining the ensuing nucleosynthesis. In this work, we present the application of our recently-developed *nucleosynthesis tracing framework* to precisely quantify the impact that neutron-induced and β^--delayed fission processes have in *r*-process environments that produce fissioning nuclei.

1 Introduction

The rapid neutron capture (*r*) process of nucleosynthesis is thought to be the astrophysical process by which the heaviest elements are formed in the universe. While the general mechanism has been proposed since the 1950s [1], a complete understanding of its mysteries has, to date, remained elusive. Considerable challenges exist across a range of disciplines relevant to the *r* process, including in observational astronomy, computational astrophysics, and computational and experimental nuclear physics [2].

While significant progress is underway in each of these fields to further our understanding of the *r* process (see, e.g., [3] for a recent review), this work focuses specifically on the problem of modeling and analyzing the competing processes that occur during nucleosynthesis. In astrophysical environments conducive to nucleosynthesis, a system of atomic nuclei may undergo any number of nuclear transmutation processes; through these processes, the abundance of each nuclear species evolves over time. The *r* process is an especially complex example of nucleosynthesis which involves thousands of nuclear species connected by tens of thousands of transmuation processes. Nevertheless, numerical techniques exist to effectively model how the nuclear abundances evolve over time in astrophysical *r*-process environments [4–9], and a great deal has been learned about the *r* process through their use.

However, *r*-process nucleosynthesis (and nucleosynthesis in general) is a fundamentally dynamical and non-linear problem. Because of this, it is extremely difficult to establish the relationship between a particular nucleus or transmutation process to the nucleosynthetic system as a whole. Approximate statements may be made, for example, by analyzing how fast or how often the transmutation process occurs, as in [10–12], but these approaches lack consideration for how the process actually *alters* any nucleosynthesis that takes place after it occurs.

In this work, we present recent results that attempt to address this challenge. In Sect. 2, we introduce our recently-developed *nucleosynthesis tracing framework* which allows for a precise and quantitative description of the role nuclear transmutation processes have in nucleosynthetic systems. In Sect. 3, we demonstrate several immediate applications of this framework to characterize how fission products participate in a fission-cycling *r* process.

2 Nucleosynthesis Tracing

We have developed a nucleosynthesis tracing framework that extends the function of conventional nuclear reaction networks to enable a quantitative description of individual nuclear reaction, decay, and fission transmutation processes, or collections thereof, as they participate in the broader context of nucleosynthetic events. We begin by identifying all nuclei in a calculation as belonging to either a *traced* or *untraced* population. At the beginning of each calculation, all nuclei are assigned to the untraced population. Additionally, we allow each of the reaction, decay, and fission processes occurring during nucleosynthesis to be one of three types, based on how the products of each are assigned to the traced and untraced populations. In particular, the products of each process may be

- mapped exclusively to the traced population,
- mapped to preserve the identity of the reactant(s), or
- mapped exclusively to the untraced population,

as illustrated schematically in figure 1. By carefully assigning each process to one of these three types, one may effectively model all subsequent nucleosynthesis in which fission products participate, among other exciting applications. For a more thorough description of the tracing framework, as well as some comments on its implementation in the nuclear reaction network code Portable Routines for Integrated nucleoSynthesis Modeling (PRISM), see [13].

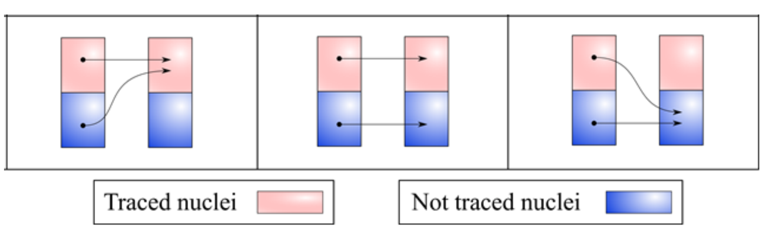

Figure 1. Schematic overview of the nucleosynthesis tracing framework. All nuclei belong to either a traced population (top red boxes) or an untraced population (bottom blue boxes). Every nuclear reaction, decay, and fission channel is cast into one of three types based on how it maps its products into the traced and untraced populations. The first type maps product(s) exclusively to the traced population (left panel). The second type preserves the traced and untraced populations between the reactant(s) and product(s) (center panel). The last type maps product(s) exclusively to the untraced population (right panel).

3 Results

We present several immediate applications of the nucleosynthesis tracing framework described in Sect. 2 to describe the interplay between nuclear fission and r-process nucleosynthesis. We begin with astrophysical conditions taken from a hydrodynamical simulation of material ejected during a neutron star merger [14]. For these conditions, fission is an especially active process, such that nearly all nuclei have participated in fission at least once during nucleosynthesis. All relevant reaction, decay, and fission rates, as well as β-delayed neutron emission probabilities, are the same as used in [11]. Fission yields are taken from calculations based on the finite-range liquid-drop model [15].

3.1 Neutron-induced Fission Products

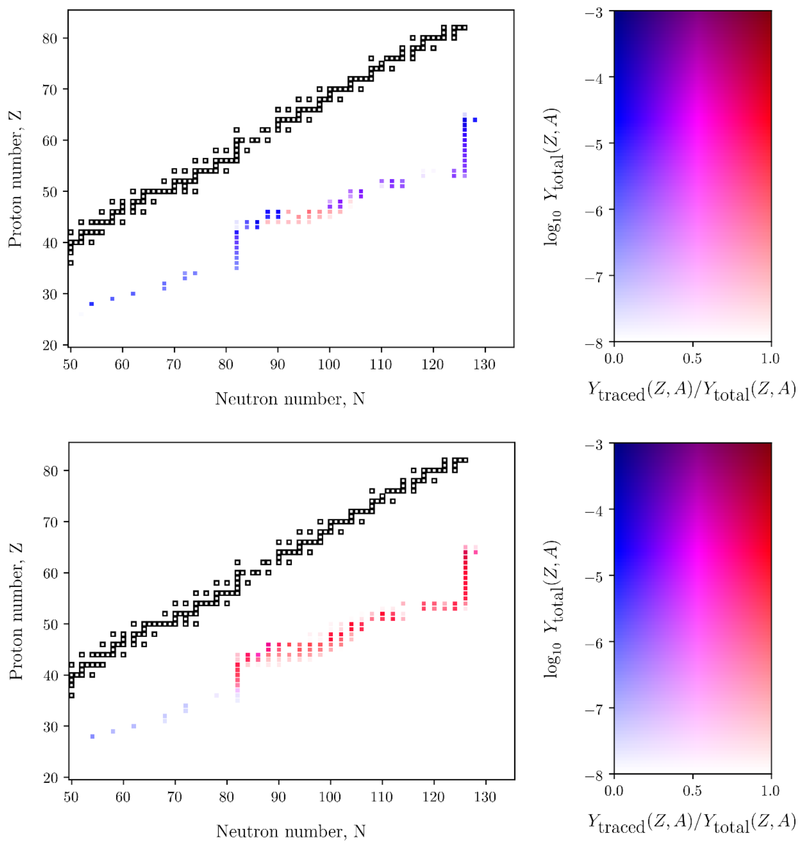

Figure 2. Neutron-induced fission product contributions to nuclear abundances at the onset of fission during nucleosynthesis (top panel) and after an additional $\sim$ 0.2 seconds of nucleosynthesis has taken place (bottom panel). Total abundances (Y_{total}) of each nucleus is given by the luminosity of the colored squares, and their hue encodes the relative fraction of traced nuclei to the total ($Y_{\mathrm{traced}}/Y_{\mathrm{total}}$). In the top panel, nuclei with mass number $A \sim 130$ are beginning to be dominated by fission product contributions. In the bottom panel, effectively all nuclei with $A > 120$ have been involved with neutron-induced fission.

As a first example, we perform a nucleosynthesis calculation in which all neutron-induced fission products are mapped into the traced population. In this way, we quantify the relative fraction of each nuclear abundance that has a history involving a neutron-induced fission event, at each timestep in the calculation. In figure 2, we plot this fraction at two points in time during nucleosynthesis. In the top panel, we consider the approximate onset of neutron-induced fission, in which nuclei in the neighborhood of $A \sim 130$ begin to become populated with the products of fissioning $A > 250$ nuclei. These fission products will capture additional neutrons and proceed along the r-process pathway to form heavier nuclei. After an additional 0.2 seconds of nucleosynthesis has elapsed, sufficient neutron-induced fission has taken place that effectively all heavy nuclei have a history involving neutron-induced fission, as shown in the bottom panel of figure 2.

3.2 Fission Products of Individual Nuclei

We may further refine the approach taken in Sect. 3.1 to study the fission products of individual nuclides fissioning by distinct fission channels. In figure 3, we present such an analysis applied to the neutron-induced fission of Plutonium 295 and the β^--delayed fission of Berkelium 268. Plutonium 295 is produced along with many other very neutron-rich actinides at early stages of the r process, when the abundance of free neutrons is high. Therefore, its fission products undergo substantial reprocessing by subsequent neutron capture, photodissociation, and β^--decay processes. As such, these fission product yields bear minimal resemblance to their distribution at the conclusion of nucleosynthesis; the fission product yield distribution is 'washed away' by other reaction and decay processes.

This contrasts with the β^--delayed fission of Berkelium 268. This nucleus fissions at a relatively late stage of the r process, as neutron capture is winding down. Thus its fission products are predominantly restricted to β^- decays which mostly preserve their isotopic distribution, as shown in figure 3. In this case, the fission product yields are critical for determining their contribution to final nucleosynthetic yields.

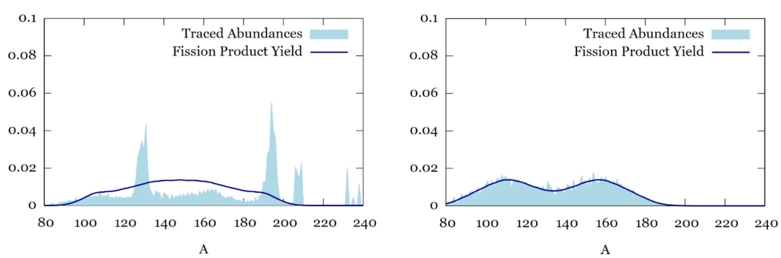

Figure 3. Comparison of mass distribution of fission products immediately after fission occurs (blue line) and after they participate in all subsequent r process nucleosynthesis (light-blue filled curve). The left panel corresponds to the neutron-induced fission of Plutonium 295; this nucleus fissions relatively early during nucleosynthesis, so its fission products undergo a significant amount of subsequent nucleosynthesis. The right panel corresponds to the β^--delayed fission of Berkelium 268; in this case, fission occurs at a much later time during nucleosynthesis, and the products' contribution to nucleosynthesis is closely tied to its product yield distribution.

4 Conclusions

Nuclear fission may play an important role during the formation of the heaviest elements via the astrophysical r process [16]; through the use of our nucleosynthesis tracing framework, we can drastically improve our ability to quantitatively describe this role. In this work, we have demonstrated some of the analyses that this technique enables. In particular, we show that it is possible to follow fission products generated during the *r* process throughout any follow-up nucleosynthesis in which they participate; this approach can be applied to the fission of all nuclei via a particular channel, as in Sec. 3.1, or even for the fission of individual nuclei, as in Sec. 3.2.

5 Acknowledgements

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