Online tools for nucleosynthesis studies

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Abstract. The nucleosynthesis of the elements between iron and uranium involves many different astrophysical scenarios covering wide ranges of temperatures and densities. Thousands of nuclei and ten thousands of reaction rates have to be included in the corresponding simulations. We investigate the impact of single rates on the predicted abundance distributions with post-processing nucleosynthesis simulations. We present online tools, which allow the investigation of sensitivities and integrated mass fluxes in different astrophysical scenarios.

1. Introduction

1.1. Neutron capture processes

The heavy elements from iron to uranium are mainly produced by the rapid and slow neutron capture processes, r- and s-process. In stars, the \textit{s-process} takes place in helium and carbon burning phases with neutron number densities between $10^8$ and $10^{10}$ cm\textsuperscript{-3} [1]. The reaction path closely follows the valley of stability since neutron capture time scales of typically ten years are much slower than most of the \textit{β}-decay time scales of the involved nuclei. Three components contribute to the \textit{s-process}: the weak, main and strong components. The main differences lie in the neutron-to-seed ratio, the temperature, as well as the neutron densities [2].

The main and the \textbf{strong components of the \textit{s-process}} take place in low-mass Asymptotic Giant Branch (AGB) stars and produce the nuclei with mass numbers above \(A \approx 90\) [3]. The low-mass AGB star (1.5 to 3 \(M_\odot\)) consists of a C/O core surrounded by alternately burning He and H shells, which are separated by a thin He-rich layer. The H envelope is fully convective. He is produced during the H shell burning, accumulating He-rich material on top of the He intershell. The temperature rises and triggers He burning, which generates the flash and the following thermal pulse (TP) [4]. The intershell becomes convective, the envelope expands and the H burning can be temporarily extinguished [5]. These flashes reoccur until the AGB envelope is entirely lost by mass loss. The number of TPs depends on the initial mass of the star, the mass loss description, the opacities etc. [6]. After each TP, if the H burning shell is inactive, the so-called third dredge-up (TDU) occurs and mixes H into the He intershell [7, 2]. The available protons are captured by \(^{12}\text{C}\) producing \(^{13}\text{N}\), which \textit{β}-decays to \(^{13}\text{C}\), forming the
\(^{13}\text{C}\) pocket \([8]\). The s-process starts when neutrons are released by the \(^{13}\text{C}(\alpha,\text{n})^{16}\text{O}\) reaction. A second neutron source \(^{22}\text{Ne}(\alpha,\text{n})^{25}\text{Mg}\) is partially activated after subsequent thermal pulses when the temperature exceeds \(2.5 \times 10^8\) K \([6]\).

The weak component of the s-process takes place in massive stars with \(M_{\text{star}} > 8\) \(M_\odot\). The time-integrated neutron flux is lower compared to the main component producing nuclei with mass numbers \(A \leq 90\). The reaction \(^{22}\text{Ne}(\alpha,\text{n})^{25}\text{Mg}\) provides neutrons during convective He burning at temperatures of about \(3 \times 10^8\) K and during convective shell C burning at about \(10^9\) K. The star explodes as a core-collapse supernova (ccSN) at the end of its evolution and enriches the interstellar medium \([2, 9, 10, 11]\).

In addition to the s- and r-processes an intermediate neutron capture process with neutron number densities around \(10^{15}\) cm\(^{-3}\) has been proposed, the i-process \([12]\). Very late thermal pulses in post-AGB stars are a possible astrophysical site \([13]\). When the He burning convective zone brings some hydrogen from the H-rich layers outward, protons can be captured by \(^{12}\text{C}\). The produced \(^{13}\text{N}\) decays to \(^{13}\text{C}\) which reaches the bottom of the convective He-burning layers. Neutrons are produced via \(^{13}\text{C}(\alpha,\text{n})\) at high temperatures resulting in neutron densities typical for the i-process \([14, 15]\).

1.2. p-process

About 35 proton-rich isotopes heavier than iron cannot be produced by neutron-capture reactions since they are bypassed by s- and r-process paths \([16]\). The origin of the p-nuclei is, to date, little understood and many possible production sites are under discussion \([17]\). The widely accepted model of the γ-process assumes that the p-nuclei are produced in sequences of photodisintegration reactions starting at r- and s-process nuclei as seed. The necessary temperatures are 2.0 to 3.5 \(\times 10^9\) K, which implies explosive conditions. Neutron-, proton- and \(\alpha\)-dissociation reactions on more neutron-rich nuclei drive the masses towards the proton-rich side of the valley of stability, reaching the p-nuclei directly or via β-decays of unstable nuclei. The explosive burning in the shock-heated Ne/O shell of a core-collapse supernova was identified as a possible production site \([18, 19, 20, 21]\).

2. Post-processing network

Post-processing nucleosynthesis (PPN) studies were carried out within the Nucleosynthesis Grid (NuGrid) research platform \([22]\). NuGrid offers a software framework for nucleosynthesis simulations in astrophysical environments \([23, 24]\). Temperature and density profiles (so-called “trajectories”) are obtained from simulations of stellar evolution that include only reactions relevant for the energy production. PPN processes the trajectories and calculates the stellar yields with a large network including up to 5,000 isotopes and 60,000 reactions. Different nuclear data sets can be chosen as input for the reaction network.

3. Sensitivity studies

The impact of nuclear reaction rates on the final abundance of the isotopes was determined by sensitivity studies for different s-process scenarios and an i-process scenario. In each nucleosynthesis simulation one reaction rate was changed compared to the default rates. The sensitivity was calculated as the ratio of the relative change in abundance \(\Delta N_j/N_j\) of isotope \(j\) and the relative change of the rate \(\Delta r_i/r_i\) \([15, 25]\):

\[
s_{ij} = \frac{\Delta N_j/N_j}{\Delta r_i/r_i}
\]
4. Nucleosynthesis fluxes during a core-collapse supernova
The post-processing nucleosynthesis simulations for the $\gamma$-process used a stellar progenitor with an initial mass of 25 $M_\odot$ and metallicity $Z = 0.02$ [26]. The nucleosynthesis was calculated by using classic ccSN trajectories [27].

Nucleosynthesis fluxes show the main reaction paths for a certain time range in the simulation. The fluxes give important information about the relevance of a reaction for the isotopic abundances. The flux leading to the product nucleus via a certain reaction is defined by [24]

$$f_{\text{Reaction}} = \frac{\Delta Y_{\text{Product,Reaction}}}{\Delta t}.$$ 

The reaction rate and the abundance of the parent species determine the flux [23]. Relative nucleosynthesis fluxes for a single isotope represent the relative net abundance yield in the simulation. They also illustrate the most relevant reaction paths for the nucleus.

5. Online tools
We provide the results of the sensitivity studies via the web interface http://exp-astro.physik.uni-frankfurt.de/sensitivities/. The user may choose the scenario (“i-process”, “C-shell”, “C13 pocket”, “Thermal pulse”, “weak s process”; the trajectories are described in detail on the webpage) and the reaction of interest. The results are shown color-coded for a part of the chart of nuclei (Figure 1). Other parameters may be displayed in addition to the sensitivities. The results are shown in different color schemes and layouts according to the chosen parameter (“Sensitivity”, “Decay”, “(n,g) MACS”, “Abundance”, “Halflife” or “custom”).

We show the integrated nucleosynthesis fluxes of the classic ccSN model via the web interface http://exp-astro.physik.uni-frankfurt.de/fluxes/. The pictures show the relative time-integrated production and destruction fluxes (Figure 2). The sum of all production fluxes is normalized to 100% for each isotope, and the destruction fluxes are scaled with the same factor.

6. Outlook
The online tools are under development. Our goal is to provide sensitivity studies for a large variety of astrophysical scenarios, and nucleosynthesis flux studies to investigate in detail the production and destruction of isotopes in different stellar conditions.
Relative time-integrated fluxes producing (blue) and destroying (red) the p-isotope $^{94}$Mo in the post-processing nucleosynthesis simulation of the 25 $M_{\odot}$ ccSN model. The sum of all production fluxes is normalized to 100%, and the destruction fluxes are scaled with the same factor. Fluxes smaller than 1% are not shown.

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