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# Sensitivity study for *s* process nucleosynthesis in AGB stars

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ABSTRACT

In this paper we present a large-scale sensitivity study of reaction rates in the main component of the *s* process. The aim of this study is to identify all rates, which have a global effect on the *s* process abundance distribution and the three most important rates for the production of each isotope. We have performed a sensitivity study on the radiative $^{13}$C-pocket and on the convective thermal pulse, sites of the *s* process in AGB stars. We identified 22 rates, which have the highest impact on the *s*-process abundances in AGB stars.

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## Contents

## 1. Introduction

In the solar system about half of the elements heavier than iron are produced by the slow neutron capture process, or *s* process [1]. The *s* process is a sequence of neutron capture reactions on stable nuclei until an unstable isotope is produced, which usually decays via a $\beta^-$ decay to the element with the next higher proton number. This chain of neutron captures and beta decays will continue along the valley of stability up to $^{209}$Bi [2]. The signature of the *s* process contribution to the solar abundances suggests a main, a weak and a strong component. While the main component is responsible for the atomic mass region from 90 to 209, the weak component contributes to the mass region between 60 and 90. Finally, the strong component is required for the production of lead. The main and strong component is made by low mass stars with $1 \leq M/M_\odot \leq 3$ at different metallicities, whereas the weak component is related to massive stars with $M \geq 8M_\odot$ ($M_\odot$ stands for the solar mass) [3]. According to our current understanding of the main *s* process component, two alternating stellar burnings create environments with neutron densities of $10^{6-7}$ cm$^{-3}$ and $10^{11-12}$ cm$^{-3}$. The corresponding neutron sources are the $^{13}$C($\alpha$, n) $^{16}$O and the $^{22}$Ne($\alpha$, n)$^{25}$Mg reaction. These reactions are activated in low-mass Asymptotic Giant Branch stars (AGB stars) [4]. AGB stars are characterized by alternating hydrogen shell burning and helium shell burning after the formation of a degenerate carbon–oxygen core.

In this paper, we provide a complete sensitivity study for the final, most important pulse and the preceding $^{13}$C-pocket computed for the stellar model of a $3M_\odot$ star with metallicity $Z = 0.02$.

## 2. *s*-process

The production site for the main *s* process component is located in thermally pulsing AGB stars, which is an advanced burning phase of low mass stars, where the core consists of degenerate oxygen and carbon and the helium inter-shell and the hydrogen envelope burn alternately.

During the AGB evolution phase, the *s* process is mainly activated in the radiative $^{13}$C-pocket by the $^{13}$C($\alpha$, n)$^{16}$O reaction. After a thermal pulse (TP, [5]), the shell H burning is not efficient and H-rich material from the envelope is mixed down in the He intershell region by the so called Third Dredge Up (TDU, [6]). Convective boundary mixing (CBM) processes leave a decreasing abundance profile of protons below the bottom of the TDU. Protons are then captured by the He burning product $^{12}$C and converted to $^{13}$C via the channel $^{12}$C(p, $\gamma$)$^{13}$N($\beta^+$)$^{13}$C. Therefore, a $^{13}$C-rich radiative layer is formed, where the $^{13}$C($\alpha$, n)$^{16}$O reaction is activated before the occurrence of the next convective TP, at temperatures around 0.1 GK and with neutron densities between $10^6$ and $10^7$ cm$^{-3}$. In particular, the $^{13}$C-pocket is the region where $^{13}$C is more abundant than the neutron poison $^{14}$N (for recent reviews, see [7,8]).

A smaller contribution to the *s* process economy is given by the partial activation of the $^{22}$Ne($\alpha$, n)$^{25}$Mg reaction, during the convective TP. The neutron source $^{22}$Ne produces only a few per cent of all the neutrons made by the $^{13}$C($\alpha$, n)$^{16}$O in the $^{13}$C-pocket, but it is activated at higher temperatures resulting in a higher neutron density (around $10^{10}$ cm$^{-3}$). This affects the *s*-process abundance distribution for several isotopes along the *s*-process path (e.g. [9,4]). The most sensitive isotopes to the $^{22}$Ne($\alpha$, n)$^{25}$Mg contribution are located at the branch points.

### 2.1. Branch points

Branch points are unstable nuclei along the *s*-process path with a life time comparable to the neutron capture time. The average neutron capture time for the *s* process depends on the isotope's (n, $\gamma$) cross section and the neutron density. It is around 10 years during the $^{13}$C phase. If the *s*-process path reaches such a nucleus, the path will split into two branches, with some of the mass flow following the $\beta$ decay and the rest of the mass flow following the neutron capture branch. The branching itself is very sensitive to the neutron capture time, hence the neutron density and the (n, $\gamma$) cross section. With increased neutron density, the neutron capture will become more likely and the beta decay less frequent and vice versa.

## 3. Nuclear network

### 3.1. MACS

For exact simulations it is essential to know the precise probability that a given reaction will take place. Taking into account the Maxwell–Boltzmann-distribution of the neutrons in stars, the cross sections can be calculated by

$$\langle\sigma\rangle := \frac{\langle\sigma v\rangle}{v_T} = \frac{1}{v_T}\frac{\int \sigma v \Phi(v) \mathrm{d}\, v}{\int \Phi(v) \mathrm{d}\, v} \tag{1}$$

where $\langle\sigma\rangle$ is the Maxwellian-averaged cross section (MACS). $\langle\sigma v\rangle$ is the integrated cross section $\sigma$ over the velocity distribution $\Phi(v)$ and

$$v_T = (2kT/m)^{1/2} \tag{2}$$

with $m$ the reduced mass of the reaction partners.