Role of light exotic nuclei in abundance evolution in explosive nucleosynthesis

J. Barman* and R. Chatterjee†
Department of Physics, Indian Institute of Technology, Roorkee - 247667, INDIA

Introduction

Most of the heavy elements are produced via r-process nucleosynthesis. In Ref. [1], it has been observed that light nuclei play an important role in the production of heavy elements via explosive nucleosynthesis in a neutrino-driven wind associated to core collapse supernova. To understand the final abundances evolved through such nucleosynthesis processes, one needs to study the proper nuclear physics inputs. Nuclei far from the valley of stability, and often near the drip lines, exhibit exotic behaviour challenging our current understanding of nuclear structure. One such exotic feature is a halo structure found in nuclei such as ^{19}C, which possesses extended matter density tails. Another captivating advancement in this arena pertains to the existence of bubble nuclei such as ^{20}N, exhibiting a marked depression in their central densities and a biconcave spheroid shape. Coulomb dissociation method with finite range distorted wave Born approximation (FRDWBA) theory is extensively used to study these exotic nuclei. We investigate how improved calculations accounting for exotic features, such as nuclear halos and bubbles, affect radiative capture rates associated with light nuclei. Without proper structural inputs, reliance on statistical estimates with uncertainties in the reaction rates becomes a significant constraint. This work focuses on the impact of radiative capture rates and photodisintegration constants with exotic structures in determining abundance evolution in a nuclear network of selected neutron-rich C-N-O isotopes.

Formalism

A reaction network is described by the following set of differential equations (with Y_i as the abundance of nucleus 'i'),

$$\frac{dY_i}{dt} = \left(\sum_{j,k} \rho N_A Y_j Y_k \langle \sigma v \rangle_{jk\to i} + \sum_l \lambda_{\beta,l\to i} Y_l + \sum_m \lambda_{\gamma,m\to i} Y_m \right) - \left(\sum_n \rho N_A Y_n Y_i \langle \sigma v \rangle_{ni} + \sum_o \lambda_{\beta,i\to o} Y_i + \sum_p \lambda_{\gamma,i\to p} Y_i \right).$$

In the equation, the terms in the first parentheses represent the production of nucleus i, encompassing nuclear reactions between j and k, β-decays from nucleus l and photodisintegration of nucleus m to i. The terms in the second parentheses represent the processes leading to the destruction of nucleus i.

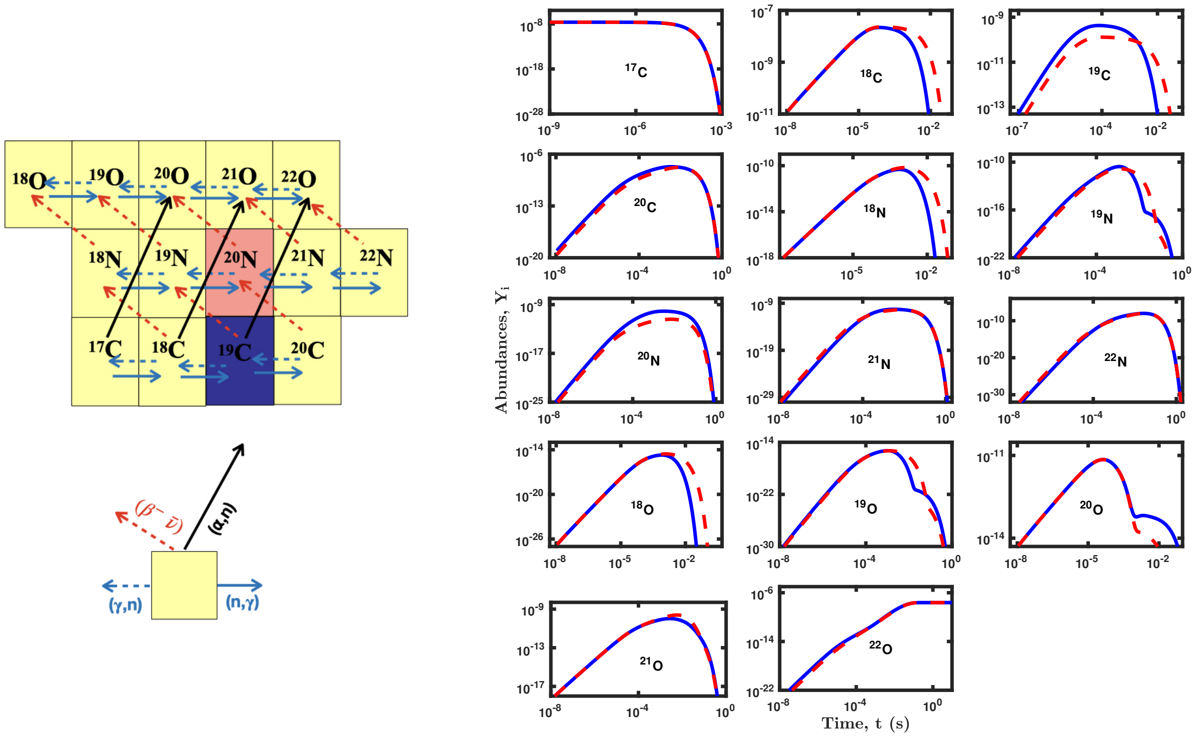
Results and discussions

In this work, we consider a variety of nuclear physics inputs sourced from FRDWBA calculations of particle-induced reaction rates and photodisintegration constants, rates from the JINA-REACLIB database, and statistical model estimates from TALYS. Following Refs. [2, 3], we have recalculated the radiative capture rates and photodisintegration constants for ^{19}C and ^{20}N with one nucleon separation energy of 0.53 and 2.16 MeV, respectively, with FRDWBA theory. Notably, ^{19}C has halo structure with a spin parity configuration of $^{18}\mathrm{C}(0^+) \otimes 1s_{1/2}\nu$ [2], and ^{20}N has a bubble structure [3].

- **Set 1:** $^{18}\mathrm{C}(n,\gamma)^{19}\mathrm{C}$, $^{19}\mathrm{N}(n,\gamma)^{20}\mathrm{N}$, $^{19}\mathrm{C}(\gamma,n)^{18}\mathrm{C}$, $^{20}\mathrm{N}(\gamma,n)^{19}\mathrm{N}$ rates are calculated with FRDWBA theory, $^{20}\mathrm{N}(n,\gamma)^{21}\mathrm{N}$ taken from [4], β^- decay constants from NNDC and all other rates are taken from TALYS and JINA-REACLIB.

---

*Electronic address: j_barman@ph.iitr.ac.in
†Electronic address: rchatterjee@ph.iitr.ac.in



(a)

(b)

FIG. 1: (a) A schematic of our network. The solid blue arrows, dashed blue, dashed-red and solid black arrows indicate e (n, γ) radiative capture reactions, (γ, n) photo-disintegration decays, β^- decays, and (α, n) reactions, respectively. (b) Time evolution of the nuclei in the network. solid blue line represents set 1 with FRDWBA inputs. Red dotted line represents set 2 with statistical inputs.

Set 2: Particle-induced reaction rates and photodisintegration constants are extracted from JINA-REACLIB database for the available data, β^- decay constants from NNDC and the rest of the rates and constants are estimated with TALYS.

Constructing the above two sets of nuclear physics inputs, we have calculated the time evolution of abundances of nuclei at a typical temperature of $T_9 = 0.62$ (just before freeze-out) in a neutrino driven wind scenario for our C-N-O network. This corresponds to time, $t = 0.57$ s and mass density, $\rho = 5.4 \times 10^2$ g cm^{-3} [1]. Initial abundance for ^{17}C is taken from the final abundances of r-process calculation (fig. 3 of ref. [1]). The initial abundances for all other nuclei are taken to be zero. This consideration is reasonable because the reactions are not initiated yet, in the network that we consider.

One notices that there is a marked difference between abundances with set 1 and set 2 inputs. Thus, incorporating exotic structures for ^{19}C and ^{20}N makes a noticeable difference.The neutron capture reactions dominate over the α- capture, (α, n) reactions for $T_9 = 0.62$. This ensures that the reactions flow towards the drip line by capturing neutrons followed by β^- decays. Calculating this with a more extensive network is preferred, accounting for various astrophysical scenarios like compact binary star mergers. However, even within this limited network with simplified conditions, we observe the broad characteristics of a complete network as described in ref. [1], along with variations in abundance evolution when incorporating exotic structures.

Acknowledgments

The MoE, India, for the SPARC/2018-2019/P309/SL grant and the Prime Minister's Research Fellowship (PMRF-192002-1693).

References

[1] M. Terasawa *et al.*, ApJ **562**, 470 (2001).
[2] M. Dan *et al.*, Phys. Rev. C **99**, 035801 (2019).
[3] V. Choudhary *et al.*, arXiv.2302.06986 (2023).
[4] M. Röder *et al.*, Phys. Rev. C **93**, 065807 (2016).