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# Constraining nucleosythesis in neutrino-driven winds using the impact of $(\alpha, \mathbf{xn})$ reaction rates

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**Abstract.** The lighter heavy elements of the first r-process peak, between strontium and silver, can be synthesized in the moderately neutron-rich neutrino–driven ejecta of either core–collapse supernovae or neutron star mergers via the weak r–process. This nucleosynthesis scenario exhibits uncertainties from the absence of experimental data from $(\alpha, xn)$ reactions on neutron–rich nuclei, which are currently based on statistical model estimates. We have performed a new impact study to identify the most important $(\alpha, xn)$ reactions that can affect the production of the lighter heavy elements under different astrophysical conditions using new, constrained $(\alpha, xn)$ reaction rates based on the Atomki-V2 $\alpha$OMP. Our results show how when reducing the nuclear physics uncertainties, we can use abundance ratios to constrain the astrophysical conditions/environment. This can be achieved in the near future, when the key $(\alpha, xn)$ reaction rates will be measured experimentally in radioactive beam facilities.

## 1 Introduction

The astrophysical *r*-process can produce around half of the elements heavier than iron in explosive environments, such as the merging of a binary neutron star system [1]. Spectroscopic observations of galactic halo metal-poor stars show a large scatter in the light heavy elements of the first *r*-process peak, between strontium and silver (Z= 38-47), compared to a rather

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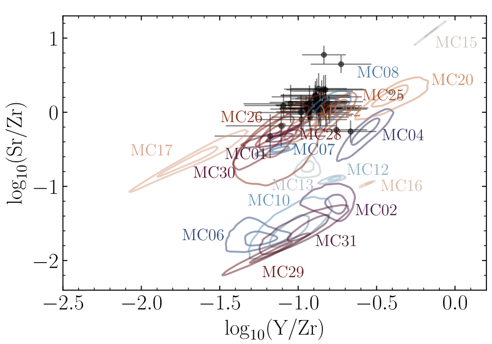
robust production of the lanthanides [2]. For this reason, many other processes have been suggested to produce the lighter heavy elements.

A possible scenario is nucleosynthesis in neutrino-driven outflows of core-collapse supernovae or neutron star mergers, via the weak *r*-process (also known as $\alpha$-process) [3]. This nucleosynthesis process operates for $T \approx 2{-}5$ GK and creates heavy elements mainly through $\alpha$- and proton-induced reactions on neutron-rich nuclei. Refs. [4, 5] have demonstrated that the main nuclear physics uncertainty in weak *r*-process nucleosynthesis is caused by the $(\alpha, n)$ reaction rates, and more specifically from the $\alpha$-nucleus potential ($\alpha$OMP), since these rates are calculated through the statistical Hauser-Feshbach model.

## 2 Impact study of the $(\alpha, xn)$ reaction rates

We recently performed an impact study of the $(\alpha, xn)$ reaction rates to the weak *r*-process [6], employing the Atomki-V2 $\alpha$OMP [7]. We explored the phase space of the astrophysical conditions, based on Ref. [8] and used a Monte Carlo technique to systematically vary the $(\alpha, xn)$ reaction rates.

Instead of finding the impact on *elemental* abundances, as Ref. [9], we explored the impact on *abundance ratios*, which can be better constrained through observations. Figure 1 shows results of the predicted abundance ratios of Sr/Y and Y/Zr for various astrophysical conditions. We also show the recent observations by Lombardo *et al.* [10], which includes 52 giant metal-poor stars ([Fe/H] $< -1.5$), using high resolution spectra from the UVES instrument of the Very Large Telescope (VLT).




| | $Y_e$ | s ($k_B$/nuc) | $\tau$ (ms) | | $Y_e$ | s ($k_B$/nuc) | $\tau$ (ms) |
|---|---|---|---|---|---|---|---|
| MC02 | 0.45 | 113 | 11.9 | MC16 | 0.49 | 126 | 15.4 |
| MC04 | 0.44 | 66 | 19.2 | MC17 | 0.46 | 132 | 12.4 |
| MC06 | 0.40 | 56 | 63.8 | MC20 | 0.41 | 42 | 59.3 |
| MC07 | 0.47 | 96 | 11.6 | MC22 | 0.40 | 40 | 46.7 |
| MC08 | 0.43 | 78 | 35.0 | MC25 | 0.46 | 96 | 20.9 |
| MC10 | 0.40 | 54 | 31.0 | MC26 | 0.40 | 84 | 36.2 |
| MC12 | 0.48 | 85 | 9.7 | MC28 | 0.46 | 113 | 11.9 |
| MC13 | 0.43 | 64 | 35.9 | MC29 | 0.41 | 66 | 41.4 |
| MC15 | 0.48 | 103 | 20.4 | MC31 | 0.43 | 71 | 11.4 |

**Figure 1.** Two-dimensional Kernel Density Estimates (KDEs) of the Sr/Y and Y/Zr elemental ratios from Ref. [6] with the addition of stars from the sample of Ref. [10]. In the right, the main properties of each model (electron fraction $Y_e$, entropy per nucleon $s$ and expansion timescale $\tau$) are presented. The contours show the 1 and $2\sigma$ uncertainties for each calculation. See the text for details.

Based on the analysis above, we have identified 35 $(\alpha, xn)$ reactions which affect the production of the lighter heavy elements in the weak *r*-process (see Ref. [6] for the complete list). In the following, we discuss experimental plans to measure these important reactions at radioactive ion beam facilities.

## 3 Experimental Plans

Measuring the relevant $(\alpha, xn)$ reaction rates will help us better constrain the relevant astrophysical conditions that produce the lighter heavy elements between strontium and silver via the weak *r*-process. There is an intense interest in the nuclear astrophysics community regarding these reactions, and many measurements already have either been proposed or recently been performed in various stable and radioactive ion beam facilities worldwide, such as in ATOMKI, Argonne, FRIB and TRIUMF. In the following, we shall briefly discuss a recently approved proposal by the ATLAS PAC at Argonne to perform the first measurement of the $^{93}\mathrm{Sr}(\alpha, n)^{96}\mathrm{Zr}$ reaction using MUSIC. This reaction has been shown to affect many elemental ratios under many astrophysical conditions in the impact study of Ref. [6].

The MUSIC (Multi-Sampling Ionization Chamber) detector [11] is a a highly-efficient, self-normalizing active-target system that is capable of measuring cross sections of reactions relevant for astrophysics. It is sensitive to the energy losses of the particles that travel through the gas (in our case helium) and has the ability to measure excitation functions using a single beam energy. For the proposed experiment, the $^{93}$Sr radioactive beam will be provided by the nuCARIBU neutron-induced fission source.

Recently, MUSIC successfully measured the $^{100}\mathrm{Mo}(\alpha, xn)$ reaction, which demonstrated its capability for $(\alpha, xn)$ reaction cross sections up to $A = 100$ [12]. The detector can also be transported to other facilities, such as FRIB, to study important reactions that were identified in our impact study [6].

## 4 Summary & Discussion

Explaining the origin of the lighter heavy elements between strontium and silver is an exciting open question in nuclear astrophysics. Nucleosynthesis in neutrino-driven ejecta through the weak $r$-process provides a possible solution, but there are still uncertainties, both in the astrophysical conditions and the underlying nuclear physics input.

We recently performed an impact study of the $(\alpha, xn)$ reaction rates to the weak $r$-process using the Atomki-V2 $\alpha$OMP and identified key reactions that affect the abundance ratios that are observed in metal-poor stars. Future experimental and observational efforts will help to further reduce the relevant reaction rate uncertainties and shed light to the production of the lighter heavy elements in the Cosmos.

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