Exploring the uncertainties of (α, xn) reactions for the weak r-process

Athanasios Psaltis[1,*], *Almudena* Arcones[1,2], *Melina L.* Avila[3], *Maximillian* Jacobi[1], *Zach* Meisel[4], *Peter* Mohr[5], *Fernando* Montes[6,7], and *Wei Jia* Ong[8]

[1]Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstr. 2, Darmstadt 64289, Germany
[2]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, Darmstadt 64291, Germany
[3]Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[4]Institute of Nuclear & Particle Physics, Department of Physics & Astronomy, Ohio University, Athens, OH, 45701 USA
[5]Institute for Nuclear Research (ATOMKI), H-4001 Debrecen, Bem tér 18/c, Hungary
[6]National Superconducting Cyclotron Laboratory, East Lansing, MI, 48824, USA
[7]Joint Institute for Nuclear Astrophysics – Center for the Evolution of the Elements, Michigan State University, East Lansing, Michigan 48824, USA
[8]Nuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore CA USA 94550

Abstract. "Light" heavy elements ($Z = 38 - 47$) can be synthesized in the neutrino–driven ejecta of core–collapse supernovae via the weak *r*–process. This nucleosynthesis scenario exhibits uncertainties from the absence of experimental data from (α, n) reactions on neutron–rich nuclei, and are mostly based on statistical model calculations. We present preliminary results from a recent sensitivity study, using the Atomki–V2 α-nucleus potential to identify the most important (α, n) reactions that can affect the production of "light" heavy elements between strontium and silver under different astrophysical conditions. We also discuss the planning of studies to experimentally determine (α, xn) reaction rates using the MUSIC detector at Argonne National Laboratory and the SECAR recoil separator at FRIB.

1 Introduction

The origin of the heavy elements in the cosmos is one of the most stimulating questions in modern physics. Half of them can be produced via the *r*–process in extreme astrophysical environments with a high neutron density, such as neutron star mergers (NSMs) or magneto-rotational supernovae explosions (MR-SNe), but there are still many open questions regarding which site has the dominant contribution in the Galactic *r*–process abundances [1]. Observations of metal–poor stars have shown a scatter in the "light" region between strontium and silver ($Z = 38 - 47$), which has sparked discussions for an additional nucleosynthesis process [2–4].

One promising nucleosynthesis scenario is the weak *r*–process (also known as α–process), which occurs in the neutron–rich, neutrino–driven wind ejecta of core–collapse

*e-mail: psaltis@theorie.ikp.physik.tu-darmstadt.de

supernovae [5, 6]. Nucleosynthesis in the weak r–process starts from Nuclear Statistical Equilibrium (NSE) with $Y_e = 0.40 - 0.49$[1]. As the ejecta expand and cool down, the plasma temperature decreases, and when it reaches $T \approx 5$ GK, an α–rich freeze–out occurs. α and proton captures – mainly (α, n), (p, n) and (α, γ) reactions – lead the reaction flow to heavier masses until the temperature falls to $T \approx 2$ GK. Refs. [7–9] have demonstrated that the main reaction channel which dominates this nucleosynthesis scenario is the (α, xn) reactions on unstable, neutron–rich nuclei. Nevertheless, the (α, xn) reaction rates that are used in nucleosynthesis studies rely on statistical model predictions, since few experimental cross sections are available. The most important input of such models is the α optical model potential (αOMP), which can produce differences in the calculated reaction rate of up to two orders of magnitude in the relevant temperature region [7, 8] (see Figure 1 for an example of the ^{93}Sr$(\alpha, xn)^{96}$Zr reaction).

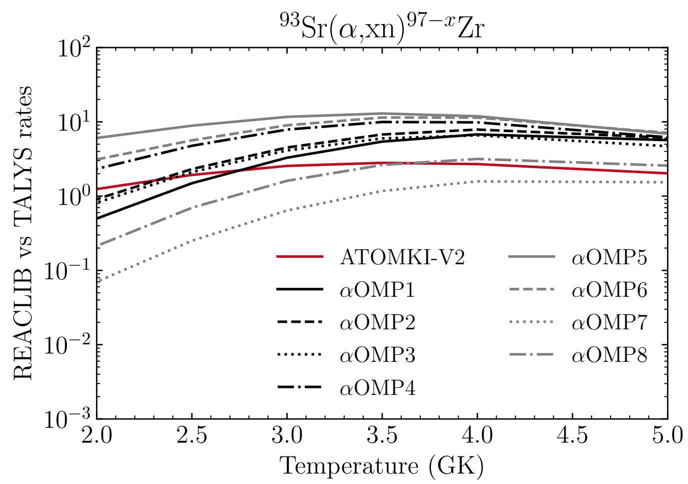

Figure 1. Comparison of the REACLIB ^{93}Sr$(\alpha, xn)^{97-x}$Zr reaction rate to the `TALYSv1.95` predictions using the 8 different α Optical Model potentials (αOMP) available in the code, including the Atomki–V2 potential [10] for the astrophysical window of the weak r–process.

Bliss *et al.* [11] recently studied the the effect of the (α, n) reaction rate uncertainty on the production of "light heavy" elements under different astrophysical conditions using Monte Carlo techniques. They used (α, xn) reaction rates calculated with the default αOMP of the reaction code `TALYS` and assumed uncertainties of a factor of 10. A list of (α, xn) reactions which produce the largest abundance differences was also identified.

2 The impact of new (α, n) reaction rates with an improved αOMP

Recently Mohr *et al.* [12] published a compilation of α–induced reaction rates for elements between iron and bismuth using the `TALYS` code and the Atomki–V2 αOMP [10, 13]. Recent experiments of (α, n) reactions on stable nuclei [14, 15] have shown agreement with the Atomki–V2 predictions to within a factor of two and thus provide reliability in the use of the αOMP when used on (α, n) reactions on unstable nuclei.

[1]The Y_e is defined as $Y_e = n_p(n_p + n_n)^{-1}$, where n_p and n_n are the number densities of protons and neutrons, respectively.

We have performed a Monte Carlo sensitivity study using the (α, xn) reaction rates from Ref. [12] following the methodology of Ref. [11]. The reaction rate uncertainties are lower compared to Ref. [11], since the rates based on the Atomki–V2 αOMP generally agree to within a factor of 2 to experimental data [14, 15]. Figure 2 shows some preliminary results of the predicted abundance ratios of Sr/Y and Y/Zr for a single astrophysical condition of the neutrino–driven wind. Production uncertainties have been greatly reduced and are now at the same order as the observational ones.

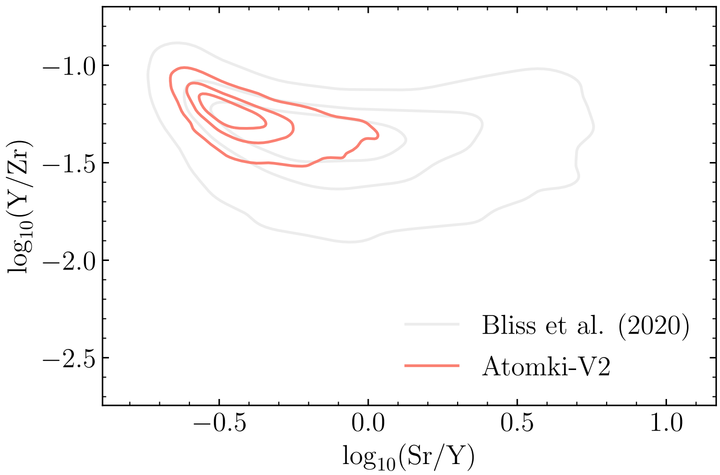

Figure 2. Kernel Density Estimate (KDE) of the Sr/Y and Y/Zr elemental ratios for the Monte Carlo study of Bliss *et al.* [11] using `TALYS v1.6` (α, n) reaction rates and the present work using rates based on the Atomki–V2 αOMP [12]. The contours show the 3σ uncertainties for each calculation. The conditions of the trajectory used are: $Y_e = 0.4$, entropy $s = 56\ k_B$/nucl. and expansion time $\tau = 63.8$ ms. Typical observational uncertainties are $\sim 0.1 - 0.2$ dex [2].

Using these new theoretical reaction rates, we have identified a list of (α, xn) reactions that affect the production of "light heavy" elements in different astrophysical conditions. For this, we used any (α, xn) reaction whose Pearson correlation coefficient between the rate variation and the abundance change of a particular nucleus is $r > |0.2|$ and the change is greater than a factor of 5 from the baseline case. Table 1 shows a summary of our preliminary results. Note that most of the reported target nuclei were also identified in the sensitivity study of Ref. [11].

Table 1. Target nuclei whose (α, xn) reactions affect the elemental abundances of $38 \leq Z \leq 47$.

Group #	Target nuclei	Notes
1	^{84}Se, ^{85}Se	Affect many elemental abundances under many astrophysical conditions
2	^{94}Sr, ^{97}Sr, ^{96}Zr	Affect few elemental abundances under many astrophysical conditions
3	^{100}Zr, ^{76}Zn	Affect many elemental abundances under few astrophysical conditions
4	^{60}Fe, ^{74}Zn, ^{104}Mo	Affect few elemental abundances under few astrophysical conditions

3 Experimental Plans

To better constrain the relevant astrophysical conditions in the weak r–process responsible for the production of elements between strontium and silver, experiments that can provide reaction rates with uncertainties lower than the current theoretical ones are needed. Some experiments, mainly in stable nuclei have recently been performed [14, 15], and few radioactive ion beam experiments are currently ongoing in various facilities worldwide, such as MUSIC at ANL/ATLAS, HABANERO and SECAR at NSCL/FRIB, EMMA at TRIUMF/ISAC–II. In the following we shall briefly discuss a limited set of future plans to experimentally determine (α, xn) reaction rates at temperatures relevant to the weak r–process.

3.1 ^{93}Sr$(\alpha, xn)^{96}$Zr at Argonne with MUSIC

The MUSIC detector is based at the Argonne National Laboratory[2] [16] and is an active–target system that is capable of measuring cross sections of (α, n) and (α, p) reactions relevant for astrophysics. It has a segmented anode which allows for highly efficient measurements of a large range of excitation functions of angle and energy integrated cross sections using single beam energy.

Recently, MUSIC successfully measured the ^{100}Mo(α, n) reaction and an experimental proposal to study the important ^{93}Sr(α, n) reaction rate was also approved by the ATLAS PAC (see also the rate discrepancies from theoretical predictions in Figure 1). The ^{93}Sr beam will be provided by the CARIBU spontaneous fission source [17].

3.2 ^{84,87}Se$(\alpha, n)^{87,90}$Kr at FRIB with SECAR

SECAR at FRIB[18] is a versatile recoil separator designed for radiative capture reactions, than can be used to measure (p, n) and (α, xn) reaction rates due to its relatively large recoil acceptance. The setup to study (α, xn) reaction rates at SECAR include helium from the JENSA gas target [19] and neutron–tagging from neutron detectors surrounding the SECAR target. Reaction products are detected at the final focal plane, where a pair of MCP position sensitive detectors provides a time–of–flight signal and an ionization chamber combined with a silicon detector provide time and energy recoil information. SECAR is currently under commissioning and the technique to measure (α, n) reactions is under development. Due to the unique capabilities of FRIB in terms of neutron–rich beams, the important ^{84,87}Se$(\alpha, n)^{87,90}$Kr reactions could be studied using SECAR in the near future.

4 Summary & Discussion

The origin of the "light heavy" elements is an exciting open question in nuclear astrophysics. The weak r–process is one of the plausible scenarios, however it suffers from uncertainties attributed both to the astrophysical conditions and the (α, xn) reaction rates.

We have performed a Monte Carlo (α, xn) reaction sensitivity study using reaction rates based on the Atomki–V2 αOMP. The reduced uncertainties of the (α, xn) reaction rates using the Atomki–V2 αOMP have reduced the production uncertainty of the "light" heavy elements via the weak r–process. Future experimental studies will help to further reduce the underlying nuclear physics uncertainties and shed light to their production in the universe.

[2]The detector can be transported to other facilities and recently a proposal to measure the ^{85}Se(α, xn) reaction was approved by the FRIB PAC.

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