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Using (α, xn) reaction rates and abundance ratios to constrain the weak r-process

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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 (α, 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 (α, xn) reactions that can affect the production of the lighter heavy elements under different astrophysical conditions and using new, constrained (α, xn) reaction rates based on the Atomki-V2 αOMP. We have identified a list of relevant reactions that affect elemental abundance ratios that can be compared to abundances from metal-poor stars. Our results show how when reducing the nuclear physics uncertainties, we can use abundance ratios to constrain the astrophysical conditions/environment. This will be possible with the planned experiments to measure key (α, xn) reaction rates using the SECAR recoil separator at FRIB that will also be briefly discussed.

1. Introduction

Observations of elemental abundances in halo metal-poor stars ([Fe/H][1] < -1.5) are extremely important to understand the astrophysical r-process [1], since these objects contain the nucleosynthesis signatures of the first such events in the Galaxy. Comparing the abundances of metal-poor stars to the solar r-process residuals, shows a remarkable agreement in the lanthanide region (Z= 58-71), suggesting a robust r-process for these elements [2]. Nevertheless, in the lighter mass region around the first r-process peak (Z= 38-47), observations show a large scatter, which suggests that one or more additional processes are responsible for their production [3].

One proposed mechanism to synthesize these lighter heavy elements is the weak r-process (also known as α-process) [4], which occurs in moderately neutron-rich, neutrino-driven ejecta of explosive environments, such as core-collapse supernovae or neutron star mergers. It operates at temperatures of $T \approx 2 - 5$ GK and synthesizes heavy elements mainly via a series of α and proton captures on neutron-rich nuclei. The weak r-process carries many uncertainties, which stem from both the astrophysical conditions of the ejecta, such as the neutron-richness (Y_e), and the underlying nuclear physics uncertainties. In the following, we shall focus on the latter.

2. The impact of (α, xn) reaction rates to the weak r-process

It is well established that the main nuclear physics uncertainty of the weak r-process originates from the (α, xn) rates, which is the dominant reaction channel [5]. In particular, the reaction rates used for weak r-process nucleosynthesis studies are based on the Hauser-Feshbach statistical model, since almost no experimental data are available for the nuclei of interest. These model estimates can differ by up to two orders of magnitude in the relevant temperature region, and this uncertainty propagates in the predicted final abundances. The most important ingredient of the statistical model that enters in these calculations is the α-nucleus potential (αOMP) [6, 7].

Recently, Mohr *et al.* [8], published a compilation of α-induced reaction rates based on the Atomki-v2 αOMP [9] which shows a robustness when compared with experimental data [10, 11]. We performed an impact study of the (α, xn) reaction rates to the weak r-process [12] using the data from Ref. [8] and following a similar methodology with Ref. [13]. We explored the relevant phase space of the weak r-process, using thermodynamical trajectories from Bliss *et al.* [14] and identified a list of (α, xn) reactions that affect the final elemental abundances and elemental abundance ratios, which are shown in Table 1. In addition, we compared our simulation results with observations of metal-poor stars that show an overabundance of first r-process peak elements. In Figure 1 we show our results for the Sr/Zr and Y/Zr ratios, with the addition of two peculiar stars from the sample of Lombardo *et al.* [15], BS 16085-0050 and HE 2247-4113, which also show an overabundance of Sr, Y and Zr.

3. Measure the important (α, xn) reactions in the lab

To reduce the nuclear physics uncertainties of the weak r-process, we need experimental measurements of the key (α, xn) reactions, as shown in Table 1. Since most of these reactions involve unstable, neutron-rich isotopes, studies in inverse kinematics are necessary. SECAR is a recoil mass separator designed to study low-energy reactions relevant for astrophysics in inverse kinematics with stable and radioactive beams up to mass $A \sim 65$ at the new FRIB facility [16]. Due to its relatively large recoil acceptance, SECAR is able to measure (α, xn) reaction cross sections. The setup to study (α, xn) reactions at SECAR includes a helium jet gas target (JENSA) [17] and neutron–tagging from neutron detectors surrounding the target. The reaction products can be detected at the focal plane using a pair of MCP position sensitive

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[1] In the bracket notation $[\mathrm{X/Y}] = \log\left(\frac{\mathrm{N(X)}}{\mathrm{N(Y)}}\right)_\star - \log\left(\frac{\mathrm{N(X)}}{\mathrm{N(Y)}}\right)_\odot$, where the symbols $\star, \odot$ represent the stellar and solar values, respectively.

	Y_e	s (k_B/nuc)	τ (ms)		Y_e	s (k_B/nuc)	τ (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

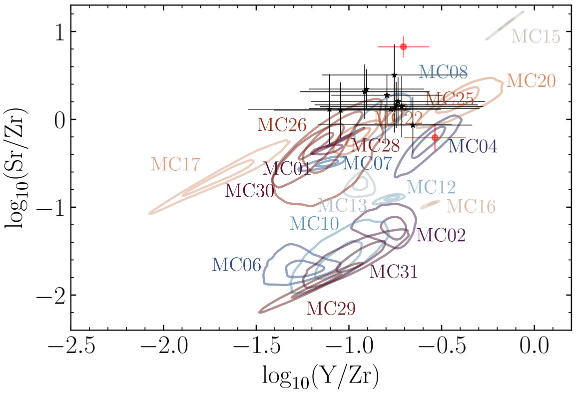

Figure 1. Two-dimensional Kernel Density Estimates (KDEs) of the Sr/Y and Y/Zr elemental ratios from Ref. [12] with the addition of two stars from the sample of Ref. [15] in red. The contours show the 1 and 2σ uncertainties for each calculation. See the text for details.

Table 1. Target nuclei whose (α, xn) reactions affect key elemental abundance ratios for $38 \leq Z \leq 47$ [12].

Group #	Target nuclei	Notes
1	^{84}Se, $^{87-89}$Kr, ^{93}Sr	Affect many elemental ratios under many astrophysical conditions
2	^{86}Br, ^{86,90}Kr, $^{87-89}$Rb, ^{91,92,94}Sr, ^{94}Y	Affect few elemental ratios under many astrophysical conditions
3	^{85}Se, ^{85}Br	Affect many elemental ratios under few astrophysical conditions
4	^{63}Co, ^{67}Cu, ^{79,81}Ga, ^{76}Zn, ^{80,82}Ge, ^{83}As ^{87,90,91}Rb, $^{88-90}$Sr, ^{95,96}Y, $^{96-98}$Zr	Affect few elemental ratios under few astrophysical conditions

detectors, which provides a time–of–flight signal and an ionization chamber combined with a silicon detector, which provide time and energy recoil information. SECAR is currently under commissioning and the technique to measure (α, xn) reactions is under development. Due to the unique capabilities of FRIB in terms of neutron–rich beams, the important ^{84}Se(α, n) and ^{87}Kr(α, n) reactions could be studied using SECAR in the near future.

4. Summary & Discussion

The (α, xn) reaction rates of neutron-rich isotopes at $T \approx 2 - 5$ GK are the most important nuclear physics uncertainty for the weak r-process in neutrino-driven ejecta. In a recent impact study, we identified key rates that need to be measured experimentally using current and the future radioactive ion beam facilities. By reducing the nuclear physics uncertainty, we will be able to constrain the astrophysical conditions of the weak r-process, by comparing our calculations to observations of halo metal-poor stars that contain the nucleosynthesis signatures of the first such events. Future observations of metal-poor stars, and experimental studies of the key (α, xn) reactions, will help us better understand the production of the lighter heavy elements in the Cosmos.

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