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Sensitivity to neutron captures and β-decays of the enhanced s-process in rotating massive stars at low metallicities

N Nishimura[1], **R Hirschi**[1,2] **and T Rauscher**[3,4]
[1]Astrophysics, Faculty of Natural Sciences, Keele University, Keele ST5 5BG, UK
[2]WPI Kavli IPMU, The University of Tokyo, Kashiwa 277–8583, Japan
[3]Centre for Astrophysics Research, University of Hertfordshire, Hatfield AL10 9AB, UK
[4]Department of Physics, University of Basel, 4052 Basel, Switzerland

E-mail: `n.nishimura@keele.ac.uk`

Abstract. The s-process in massive stars, producing nuclei up to $A \approx 90$, has a different behaviour at low metallicity if stellar rotation is significant. This *enhanced s-process* is distinct from the s-process in massive stars around solar metallicity, and details of the nucleosynthesis are poorly known. We investigated nuclear physics uncertainties in the enhanced s-process in metal-poor stars within a Monte-Carlo framework. We applied temperature-dependent uncertainties of reaction rates, distinguishing contributions from the ground state and from excited states. We found that the final abundance of several isotopes shows uncertainties larger than a factor of 2, mostly due to the neutron capture uncertainties. A few nuclei around branching points are affected by uncertainties in the β-decay.

1. Enhancement of weak s-process by stellar rotation

The s-process in massive stars ($\gtrsim 10M_{\odot}$) is called "weak s-process", because the major products are limited to lighter s-process elements up to $A \approx 90$ (heavier elements up to Pb and Bi are produced in low mass AGB stars, called *main s-process*, see [1] for a review). It takes place during the He-core and C-shell burning, and the main neutron source is an α-capture reaction ^{22}Ne(α, n)^{25}Mg following the reaction sequence $^{14}\mathrm{N}(\alpha,\gamma)^{15}\mathrm{F}(\beta^{-})^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$. For very metal-poor stars, the behaviour of this weak s-process drastically changes due to rotation, and heavy nuclei with $A \approx 138$, including Ba, are produced (see [2, 3]; Frischknecht et al., 2015, in preparation). Rotation-induced mixing between the helium-burning and hydrogen-burning convective zones increases the abundance of primary ^{14}N (and thus of ^{22}Ne). This increases the neutron captures and enhances the weak s-process (hereafter, we call it *enhanced s-process*, "e.s-process").

The evolution of the e.s-process pattern is shown in Figure 1. This is based on a simplified evolutionary track from a $25M_{\odot}$ model, effectively accounting for rotation-induced mixing by increasing the primary ^{14}N, as introduced in a previous study [4]. The abundance pattern at $T = 219$ MK is similar to the weak s-process producing isotopes up to $A = 90$. As temperature increases ($T = 236$ MK), the distribution goes to the higher A region and finally reaches $A \approx 140$. The final abundances show production in the range $90 \leq A \leq 140$.

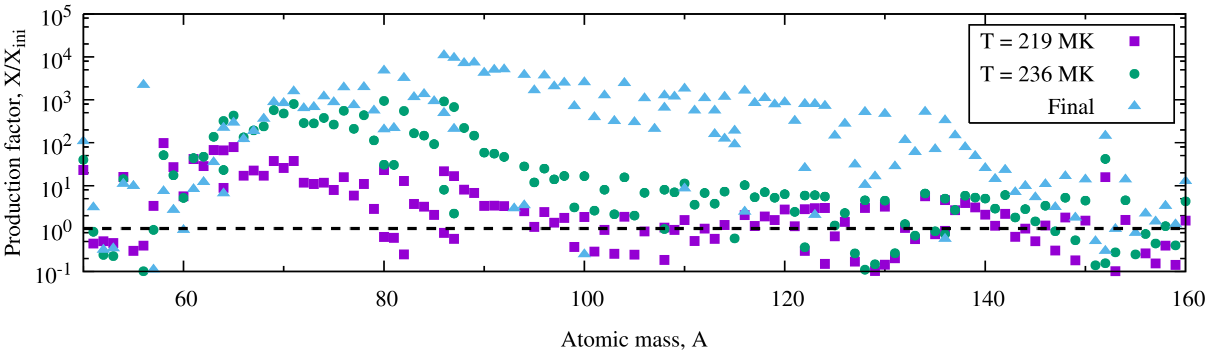

Figure 1. Evolution of abundances by the e.s-process by the production factors.

2. Uncertainty of reaction rates and Monte-Carlo simulation

Nucleosynthesis in the e.s-process is quantitatively different from the standard weak s-process. The impact of reactions relevant to stellar burning (α-captures) of lighter nuclei has been studied before, but with a focus on neutron-source and -poison reactions [4]. However, the impacts of uncertainties in (n,γ) and β-decay on the path of the e.s-process are poorly known. We investigated, therefore, the role of nuclear physics input on the path of the e.s-process. For this purpose, we performed Monte-Carlo (MC) simulations focusing on (n,γ) and β-decay reactions. We use a MC framework with a general reaction network which is applicable to a variety of nucleosynthesis processes [5, 6].

The input of nuclear physics uncertainty (i.e., of reaction rates) is crucial for studying impacts on the nucleosynthesis yields. In the present study, we assumed that reaction rates have a temperature-dependent uncertainty because the relative contributions by the ground state (g.s.) and excited states to the rate change with temperature and experimental cross sections, if available at all, only constrain g.s. contributions. Following the prescription in [7, 8], experimental uncertainties are used for the g.s. contributions to (n,γ) rates, whereas a factor 2 is used for excited state uncertainties. We simply apply a constant value 2 for theoretical rates. A similar approach is used for β-decay rates, based on partition functions to determine the importance of excited states. The uncertainty at lower temperatures ($T < 10^7$ K) corresponds to the one of measured decays, while the uncertainty becomes larger as the temperature increases (for details, see [8]). A uniform random distribution between the upper and lower limit of the

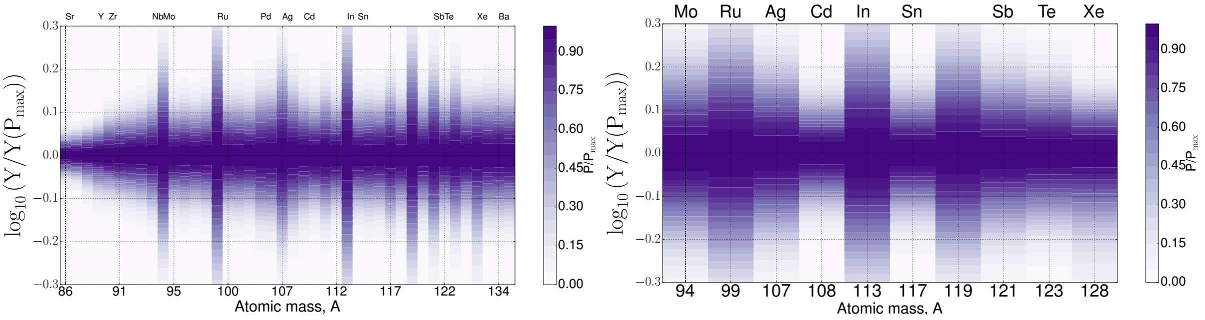

Figure 2. Uncertainties in final isotope production when all reactions are varied for stable isotopes that e.s-process produces (left) and selected isotopes with larger uncertainty (right). For each isotope, the normalized probability density distribution $Y/Y(P_{\mathrm{max}})$ is shown.

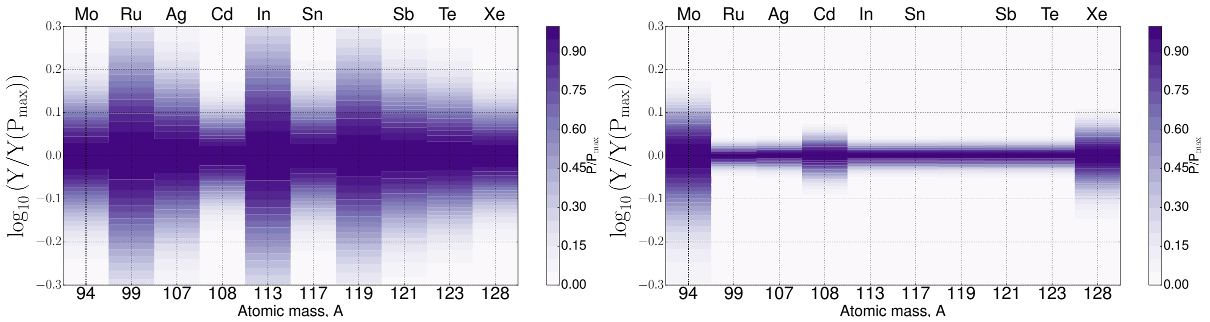

Figure 3. Same as Figure 2, where only (n,γ) (left) and only β-decay (right) are varied.

reaction rate at a given temperature was used for the MC variation factors.

Figure 2 shows the resulting production uncertainty for the cases where we varied all (n,γ) reactions and β-decays. We chose to show abundance uncertainties for stable s-process isotopes with $86 \leq A \leq 136$ in the left panel, which cover the main products of the e.s-process. We plot isotopes showing the largest uncertainties in the right panel. The colour distribution corresponds to the normalized probability density distribution of the uncertainty in the final abundance. Values of 0.114 and 0.301 for the probability density distribution correspond to 30 % and a factor of 2 uncertainty, respectively.

Some isotopes show larger uncertainties, while most others are within the ±30 % range. In order to identify the role of the reactions for the final uncertainty, we varied neutron captures and β-decays separately. Figure 3 shows the results for the isotopes with the largest uncertainties, the left and right panels correspond to variation of all (n,γ) and all β-decays, respectively.

The results clearly indicate that (n,γ) reactions have a dominant impact on the nucleosynthesis uncertainty and that β-decays have a limited importance: (i) the uncertainties in (n,γ) leads to a general 30 % uncertainty in the final abundances, several isotopes having a higher value up to a factor of 2; (ii) β-decays only affect a few isotopes around the branching points at $A \approx 94$, 108, and 128.

3. Conclusion

In this study, we evaluated the impact on e.s-process nucleosynthesis of nuclear physics uncertainties using MC calculations. The method can identify the importance of reactions and we found that (n,γ) reactions dominate the total uncertainty, with a few important contributions from β-decays around branching points. Our method is a robust way to identify key reaction rates to support further investigations in nuclear astrophysics regarding the e.s-process.

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