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Nuclear uncertainty study of the s-process in massive stars based on Monte-Carlo simulations

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The s-process in massive stars, the weak s-process, is origin of the solar s-process nuclei up to $A = 90$ as well as other heavier nuclei, e.g., Ba, in very metal-poor stars. The s-process still has a significant uncertainty of nuclear reactions, although we has used several theoretical abundance prediction for the comparisons with several observations. The present study is aimed at evaluating the reliability of the current theoretical s-process calculations. Based on different stellar evolution models, we performed Monte-Carlo simulations of the s-process with randomly varying neutron-captures rates. We found that the uncertainty propagates through the weak s-process nuclei up to Sr for a solar metallically star. On the other hand, a rotating metal-poor star shows different response to final abundances, which heavier s-process elements, i.e., Ba, have significant variation. In conclusion, the remaining uncertainty of neutron-capture reactions is still possible to change the results of s-process calculations. This uncertainty even can be caused in qualitative difference in the production of heavy s-process nuclei in a metal-poor stars.

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1. Introduction

The slow neutron capture process, the s-process, is one of the major nucleosynthesis processes, producing heavy elements beyond iron via neutron captures and β-decays. The s-process has nucleosynthesis paths along the β-decay stable isotopes and progresses on long time scales ($\gg 1$ yr) during the nuclear burning of stellar evolution. Massive stars, for which the zero age main sequence mass exceeds 10 $M_\odot$, are an astronomical site for the s-process, as well as low mass asymptotic giant branch (AGB) stars (for a review, see [1]). The s-process in massive stars, the so-called weak s-process, generally takes place during the core-He and the shell-C burning phases. The neutron source is provided by the reaction $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ and the weak s-process produces mainly isotopes up to the mass number of $A \sim 90$.

At solar metallicity, rotation-induced mixing has a moderate effect on s-process production. At very low metallicities, however, rotation-induced mixing has a much stronger effect. Indeed, it leads to mixing between the helium-burning core and the hydrogen-burning shell. This first mixes primary ^{12}C and ^{16}O into the H-burning shell, which produces ^{14}N via the CNO cycle. Later on, the ^{14}N is mixed back into the He-burning core, at which point it immediately converts into ^{22}Ne via $^{14}\mathrm{N}(\alpha, \mathrm{n})\,^{18}\mathrm{F}(\mathrm{e}^+ \nu_\mathrm{e})\;^{18}\mathrm{O}(\alpha, \gamma)\,^{22}\mathrm{Ne}$. At the end of He-core burning, $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ releases large amounts of neutrons and drastically changes the s-process production [2]. Due to a high neutron number density, this non-standard weak s-process possibly produces heavy nuclei up to $A \sim 200$.

There are studies about the uncertainty of nuclear physics on the weak s-process, however, most of previous works on this issue were mostly performed with focuses on individual reaction rates. In this study, we focus on the physical uncertainty of the neutron capture rates relevant to the s-process in massive stars both at solar and very low metallicities, based on comprehensive simulations in a Monte-Carlo framework. Our comprehensive approach can shed light on the sensitivity of week s-process due to remaining nuclear physics properties, i.e., the neutron capture on heavy nuclei and beta-decay.

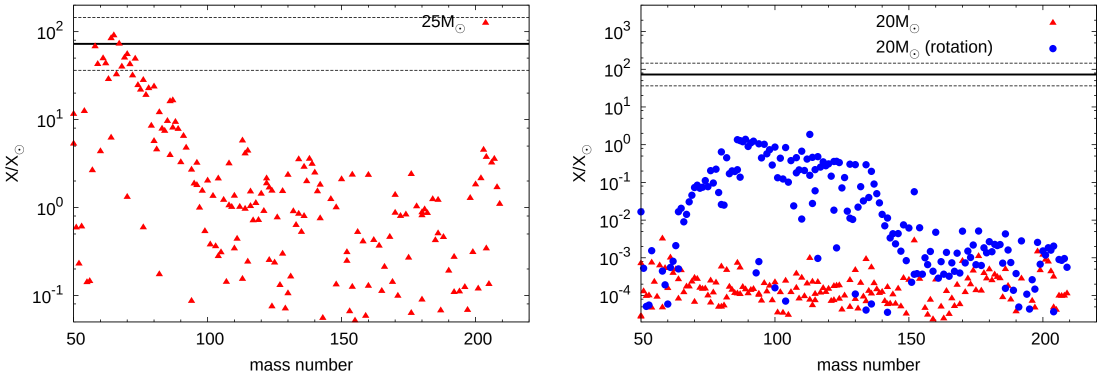

Figure 1: Results of s-process nucleosynthesis in massive stars. Production factor relative to the solar abundance are shown for a $25M_\odot$ star with solar metallicity (left) and a rotating and non-rotating $20M_\odot$ star of low metallicity, $Z = 10^{-5}$, (right), respectively. The region of the horizontal lines corresponds the range of ^{16}O within the factor of 2.

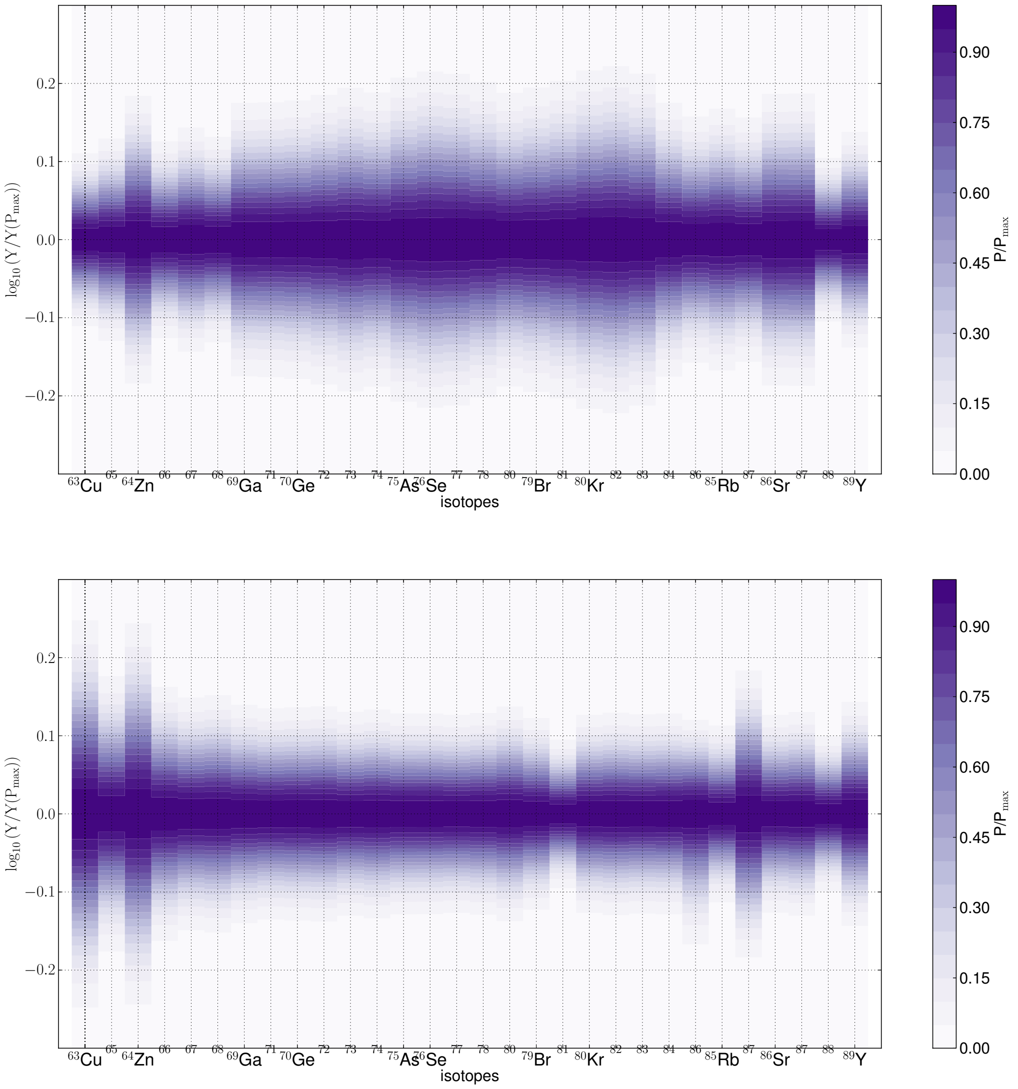

Figure 2: The probability density of selected s-process nuclei for a Monte-Carlo calculation. $25M_\odot$ non-rotating star with solar metallicity (upper), $20M_\odot$ rotating, metal poor star (lower).

2. The s-process and Monte-Carlo Simulations

Based on stellar evolution calculations in spherical symmetry (multi-zones in 1D), we developed a representative thermodynamic evolution via a single zone “trajectory”, which contains the time evolution of density and temperature. We tested that the s-process production using the single zone trajectories is comparable to full stellar model calculations. Here, we consider the single trajectory of a $25M_\odot$ solar metallicity star ($Z = Z_\odot$) and of a $20M_\odot$ metal poor star ($Z = 10^{-5}$), which are based on the stellar evolution calculations presented in [3] and [4], respectively.

In the metal poor star, the effect of rotation-induced mixing is included in the single zone

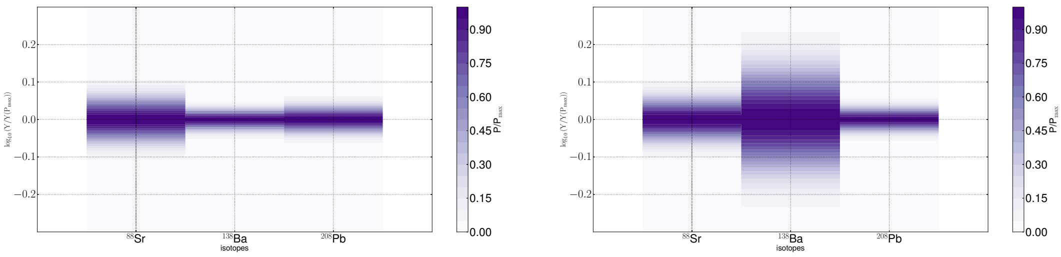

Figure 3: The probability density of the s-process peak nuclei, ^{88}Sr, ^{138}Ba, and ^{208}Pb. $25M_\odot$ non-rotating star with solar metallicity (left), $20M_\odot$ rotating, metal poor star (right).

trajectory by adding 1% of ^{14}N to the initial composition. This primary ^{14}N is then converted into ^{22}Ne during He-burning, which is consistent with more sophisticated evolution calculations [2]. The results of nucleosynthesis calculations using these simplified trajectories are shown in Fig. 1. The abundance pattern of the $25M_\odot$ star ($Z = Z_\odot$) corresponds to the typical weak s-process, which produces mainly nuclei up to $A \sim 90$. On the other hand, the $20M_\odot$ star ($Z = 10^{-5}$) with effective rotation (by adding 1% of ^{14}N to the initial composition), has an abundance distribution that is clearly different from the case of the non-rotating star (the non-rotating star showing no signature of the s-process). The figure also shows how rotation-induced mixing allows the production of elements up to the barium peak ($A \sim 138$).

Monte-Carlo simulations using random factors represent a robust scheme to examine relevant physical uncertainties (see, e.g., [5]). We performed large scale simulations using a Monte-Carlo code[1], based on a general nuclear reaction network [6]. In this study, we focus on neutron capture rates, where the reaction network adopts theoretical rates of REACLIB [7] and experimental rates of KADoNiS[2], as the standard nuclear reaction rate inputs. We vary all (n,γ)-rates for nuclei heavier than iron with the random number distributions within ±20% of the standard value. In this study, we only focus on neutron capture reactions by heavy nuclei, although there are other large uncertainties related to key energy-generating reactions (see e. g. [8]) and neutron source or poison reactions (see [6], [9] and references therein).

3. Results

The results of Monte-Carlo simulations are shown in Fig. 2 for the $25M_\odot$ star ($Z = Z_\odot$) and for the rotating $20M_\odot$ star ($Z = 10^{-5}$). These plots show the probability density distribution of the abundance Y for each isotope, resulting from the random variation of (n, γ) reaction rates within the Monte Carlo framework. The plots shows a sample of s-process nuclei.

In Fig. 2 (top-panel), we can see that, in the solar metallicity case, the uncertainty in the final abundances generally increases from Cu to Kr. This is due to the propagation of the uncertainties of all the (n, γ) reactions along the s-process path. As the weak s-process in massive stars ends at the first peak, the uncertainties become smaller again from Kr to Y. Uncertainties in the final abun-

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[1] “PizBuin Monte-Carlo framework”, T. Rauscher, R. Hirschi, N. Nishimura, and U. Frischknecht (2012–2014).

[2] Web site: www.kadonis.org

dances are generally smaller for the case of $20M_\odot$ of the rotating metal poor star compared with a $25M_\odot$ star. This difference is caused by the stronger neutron flux in the rotating low metallicity model, the abundance pattern of which is shown in Fig. 1. Due to the higher number of neutron captures, the production peak is shifted to the region of $A = 80 - 150$. Note that a few isotopes affected by branchings like ^{63}Cu and ^{64}Zn show a larger uncertainty.

Figure 3 shows the result of the same Monte-Carlo simulations, (already presented in Fig. 2), but only for the s-process peak nuclei, ^{88}Sr, ^{138}Ba, and ^{208}Pb. Heavy nuclei $A > 100$, in principle, are produced by main s-process, while weak s-process produces up to ^{88}Sr and other peaks are underproduced. The physical condition is drastically changed if metal poor stars rotate rapidly. The ^{138}Ba is in the region of most abundant nuclei as shown in Fig. 1. We see in Fig. 3 that the uncertainty in the final abundance of ^{138}Ba due to uncertainties in neutron capture rates is significant at low Z.

The production of Ba in metal-poor stars has been investigated because of the observational importance [10]. However, production of heavy s-process nuclei in massive low-Z stars strongly depends on rotation. The abundance is also influenced by the uncertainty of neutron source or neutron poison reactions (see [6, 9] and references therein). Although uncertainties of s-process abundances at low Z due to the known neutron source and/or neutron poison reactions and rotation are dominant, this study shows that the effects of uncertainties in (n,γ) is also important.

As we have demonstrated in this study, which impacts of (n,γ) rates uncertainties on the s-process production in massive stars, a Monte Carlo framework can provide a robust tool for analysis of uncertainties. Additionally, the framework used in this study is applicable to other nucleosynthesis processes (see, e.g., [11, 12]), in particular, synthesises of heavy elements, in which a large number of nuclear reactions are involved. For such complicated nucleosynthesis processes, important reaction and decay processes exceeds tens thousands and more, which we hardly examine one by one. As also shown in the study of γ-process [11], Monte-Carlo scheme has big advantage to quantify uncertainties in complicated processes.

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