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The s-process nucleosynthesis: impact of the uncertainties in the nuclear physics determined by Monte Carlo variations

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Abstract. We investigated the impact of uncertainties in neutron-capture and weak reactions (on heavy elements) on the s-process nucleosynthesis in low-mass stars and massive stars using a Monte-Carlo based approach. We performed extensive nuclear reaction network calculations that include newly evaluated temperature-dependent upper and lower limits for the individual reaction rates. We found β-decay rate uncertainties affect only a few nuclei near s-process branchings, whereas most of the uncertainty in the final abundances is caused by uncertainties in the neutron capture rates. We suggest a list of uncertain rates as candidates for improved measurement by future experiments.

1. Introduction

The s-process nucleosynthesis is a source of heavy elements beyond iron in the universe, taking place in stellar burning environments. There are two astronomical conditions and corresponding classes of the s-process (for a review, see Käppeler et al., 2011) and references therein). The s-process occurs in (i) thermal pulses of low mass AGB stars producing heavy nuclei up to Pb and Bi, called the *main* s-process; (ii) He-core and C-shell burning phases of massive stars representing the lighter components (up to $A \approx 90$), categorised as the *weak* s-process.

In both cases, the primary mechanism is to produce heavier elements due to the neutron capture and β-decay close to valley of stability from seed Fe nuclei over a long-term stellar evolution period. Neutron source reactions for the s-process are α-captures on different nuclei, where ^{13}C$(\alpha, n)^{16}$O and ^{22}Ne$(\alpha, n)^{25}$Mg are main reactions for the main and weak s-processes, respectively. The impact of these key fusion reactions has already been studied (Käppeler et al., 2011). The remaining prob-

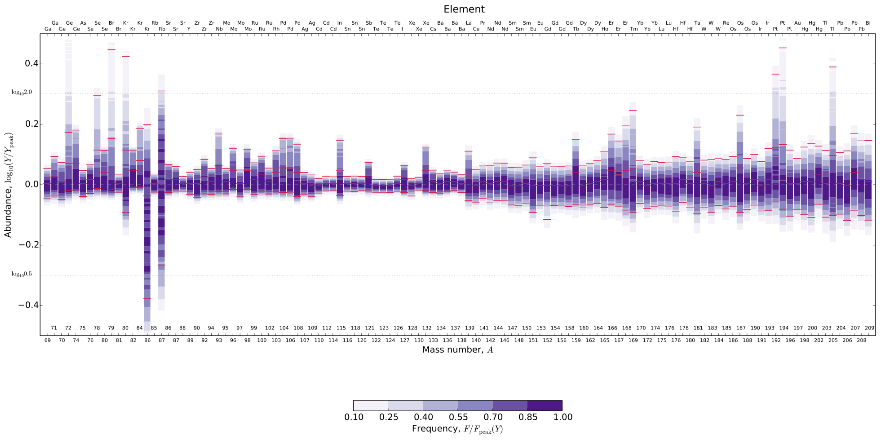

Fig. 1. The results of the MC for the main s-process. Uncertainty range is shown for each isotope with the shading and red lines, which indicate 5% and 95% of the distribution. Note that the final abundance is normalised by the value at the peak of the distribution.

lem is the effects of uncertainty of (n,γ) and β-decay reactions on the final products. As many of these reactions are involved in the s-process, the uncertainty is not as simple as the cases of neutron source/poison reactions. More systematic studies based on the Monte-Carlo (MC) and statistical analysis (Iliadis et al., 2015; Rauscher et al., 2016) are necessary for such problems.

In this study, we investigate the impact of uncertainty due to nuclear physics on the s-process using the MC-based nuclear reaction network. Adopting simplified stellar models that reproduce typical s-process patterns, we apply realistic temperature-dependent uncertainty of nuclear reaction and decay rates to nucleosynthesis calculation. Based on an MC method, we evaluate uncertainty of nucleosynthesis yields.

2. Methods

We use simplified stellar evolution models at the solar metallicity based on 1D evolution calculation. We follow nucleosynthesis evolution along temporal history of the temperature and density from the initial abundances. The thermal evolution is treated as the time evolution for a "trajectory" as a single fluid component. We adopt $3M_\odot$ AGB star model calculated by the MESA code (Paxton et al., 2011) and $25M_\odot$ massive star evolution model (Hirschi et al., 2004; Hirschi et al., 2008). We confirmed that these trajectories reproduce a typical abundance pattern for the main and weak s-process, respectively.

We consider that reaction rates have a temperature-dependent uncertainty due to the relative contributions by the ground state and excited states for experimental based cross sections. Following the prescription in Rauscher et al. (2011) and Rauscher (2012), experimental uncertainties are used for the ground state contributions to (n,γ) rates, whereas a factor 2 is used for excited state uncertainties (for details, see Rauscher, 2012). As theoretical calculated rates may have large uncertainty, we simply apply a constant value 2.

A similar approach is used for β-decay rates, based on partition functions to consider excited state contribution. The uncertainty at lower temperatures ($T < 10^7$ K) corresponds to the ground state value, while the uncertainty becomes larger as the temperature increases. We adopt a factor 10 for the maximum value at a high temperature, although uncertainty is about 2 in stellar burning temperatures.

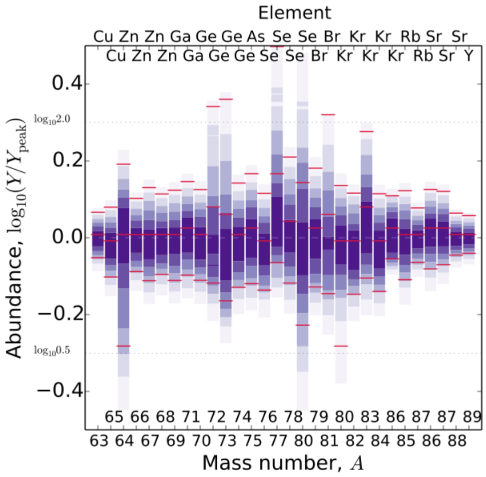

Fig. 2. The same as Fig.1, but the results of weak s-process. Taken from Nishimura et al. (2017).

3. Results of MC calculations

We performed MC simulations with variation of reaction rates. A uniform random distribution between the upper and lower limit of the reaction rate at a given temperature was used for each variation . Fig. 1 shows the resulting production uncertainty of main s-process for the cases where we varied all (n,γ) reactions and β-decays. For the main s-process, we select abundance uncertainties for 116 stable s-process isotopes up to bismuth. Since the number of nuclei produced by the s-process exceeds 200 species, we only select isotopes that contribute a minimum of 10% to the total elemental abundance. The colour distribution corresponds to the normalised probability density distribution of the uncertainty in the final abundance.

Fig. 2 shows the resulting production uncertainty of weak s-process (Nishimura et al., 2017). We select in this case abundance uncertainties for stable s-process isotopes up to ~ 90.

The stored MC data allow us for a more comprehensive analsysis and a fully automated search for key rates. Since the variation factors for each rate are saved in the stored variation, it can be tested whether there is a correlation between the variation of a rate and the resulting change in abundance. The correlation will be larger the fewer reactions contribute to the uncertainty of the abundance of a given isotope. There are various definitions for correlations in the literature. We employ a widely-used correlation coefficient, the Pearson product-moment correlation coefficient (Pearson, 1895).

Review of the available literature suggests that a Pearson product-moment correlation coefficient value above 0.7 indicates a strong correlation. We choose a threshold of 0.65 to account for numerical uncertainties in our calculations. Therefore we define key rates, rates with a value above 0.65 in our MC run.

In Table 1, we compare the correlation coefficient for the key reactions for the main s-process which are also relevant for the weak s-process. Not all of the latter are above the established threshold, but we decide to show them to have a comparison.

There are several differences, but we underline that for example ^{72}Ge(n, γ)^{73}Ge, ^{78}Se(n, γ)^{79}Se and ^{85}Kr(n, γ)^{86}Kr are key rates with very high correlations, therefore a more precise measurements of these rates can provide better nucleosynthesis for both processes.

4. Conclusion

We evaluated the impact on s-process nucleosynthesis in massive stars and low mass AGB stars of nuclear physics uncertainties in neutron capture and weak reactions on heavy elements using MC calculations. Our method is a robust way to identify key reaction rates to support further investigations in nuclear astrophysics regarding the s-process. The method can identify the importance of reactions and we found that ^{72}Ge(n, γ)^{73}Ge, ^{78}Se(n, γ)^{79}Se and ^{85}Kr(n, γ)^{86}Kr are key rates with very high correlations for both weak s-process and main s-process. More detailed analysis are presented in Nishimura et al. (2017) for s-process in massive stars; whereas for the main s-process, they will be shown in our upcoming Cescutti et al. (2017).

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Table 1. First column: key rates determining the production uncertainties for the main s-process, and also important for the weak s-process; second column: isotopes for which the rate is highly correlated in the main s-process production; third column: value of this correlation; fourth column: isotopes for which the rate is correlated in the weak s-process production; fifth column: value of this correlation.

Key rates	Nuclide main s-	$r_{\mathrm{cor},0}$ main s-	Nuclide weak s-	$r_{\mathrm{cor},0}$ weak s-
^{72}Ge(n, γ)^{73}Ge	^{72}Ge	-0.93	^{72}Ge	-0.85
^{74}Ge(n, γ)^{75}Ge	^{74}Ge	-0.97	^{74}Ge	-0.44
^{75}As(n, γ)^{76}As	^{75}As	-0.86	^{75}As	-0.50
^{78}Se(n, γ)^{79}Se	^{78}Se	-0.96	^{78}Se	-0.71
^{84}Kr(n, γ)^{85}Kr	^{84}Kr	-0.99	^{84}Kr	-0.49
^{85}Kr(n, γ)^{86}Kr	^{86}Kr	0.88	^{86}Kr	0.84

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