Origin of the main r-process elements

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Abstract. The r-process is supposed to be a primary process which assembles heavy nuclei from a photo-dissociated nucleon gas. Hence, the reaction flow through light elements can be important as a constraint on the conditions for the r-process. We have studied the impact of di-neutron capture and the neutron-capture of light (Z<10) elements on r-process nucleosynthesis in three different environments: neutrino-driven winds in Type II supernovae; the prompt explosion of low mass supernovae; and neutron star mergers. Although the effect of di-neutron capture is not significant for the neutrino-driven wind model or low-mass supernovae, it becomes significant in the neutron-star merger model. The neutron-capture of light elements, which has been studied extensively for neutrino-driven wind models, also impacts the other two models. We show that it may be possible to identify the astrophysical site for the main r-process if the nuclear physics uncertainties in current r-process calculations could be reduced.

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INTRODUCTION

In spite of decades of study, the astrophysical site for the main r-process component is still unknown. There are three dominant candidates: neutrino-driven winds in Type II supernovae; the prompt explosion of low-mass supernovae; and neutron star mergers. The conditions for the r-process nucleosynthesis, such as the temperature and density profile, are significantly different in each of these candidate environments. although there have been many theoretical nucleosynthesis studies aimed at testing the viability of those models none of them has reached a definitive conclusion. This uncertainty is due in part to the difficulty of modeling of such explosive events.

On the other hand, many new determinations of r-process elemental abundances have been reported, in part due to the availability of a new generation observational facilities. Specifically, studies of r-process abundances in metal-poor halo stars have been made because they provide clues to the origin of r-process elements and the evolution of the early Galaxy. One of the most interesting results is the robustness of r-process abundance distributions(e.g., [1]). The r-process abundance distribution for elements heavier than Ba in a dozen studied metal-poor halo stars show the same pattern. Furthermore, this abundance pattern is in good agreement with the solar r-process abundance pattern. This fact suggests that the r-process for elements heavier than Ba are always generated in same pattern from the time of Galaxy formation to the

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present epoch. Hence, the r-process is metallicity independent. This means that the r-process is a primary nucleosynthesis process (i.e. seed elements for the r-process are generated when the r-process occurs). In a primary r-process, light element reactions for seed production are as important as the r-process itself, especially for testing the reliability of theoretical models. This is because light-element reactions often consume neutrons and affect the neutron-to-seed ratio at the beginning of the r-process.

The importance of the neutron-capture reactions of light elements in neutrino-driven wind models was pointed out by Terasawa et al. [2]. Although the neutron capture reaction rates of such light elements have large uncertainties, those reactions can have a large impact on the final calculated abundances. We have studied the importance of those reactions for the other two r-process models using same reaction rates.

The reaction flow of ^{4}He(2n, γ)^{6}He(α,n)^{9}Be has been neglected in previous r-process calculations because the ^{4}He(2n,γ)^{6}He reaction rate is very small and this reaction flow has been thought to be insignificant. The study in Bartlett et al. [3], however, shows that di-neutron capture can increase the ^{4}He(2n,γ)^{6}He reaction rate by orders of magnitude. We performed r-process nucleosynthesis calculations to see if this reaction flow has any impact on the final r-process abundances.

MODELS

Our nucleosynthesis code is based on the dynamical network described in Meyer [4], which has been extended by Terasawa and Orito [2][6]. This code calculates dynamically the r-process and its seed production simultaneously. We terminated our calculation when the neutron abundance Y_n became less than 10^{-15}, by which point the abundance distribution is no longer affected by neutron capture. We adopted a primitive fission recycling model, which assumes that all elements with A=260 immediately break into two symmetric nuclei. For each of the models considered, we have calculated the nucleosynthesis yields with three networks: 1) without the neutron capture of light elements nor the di-neutron capture of ^{4}He; 2) with the neutron capture of light elements but without di-neutron capture; and 3) with both the neutron capture of light elements and di-neutron capture.

We have assumed simple schematic parameterizations for each of the environments as described below. We chose parameter set for each environment such that the ratio of the actinide-to-third peak elements in the final abundances was consistent with observed abundances in metal-poor stars.

1. Neutrino-driven wind in core-collapse supernovae

The proto-neutron stars born in Type II supernovae, release their energy via neutrinos during their Kelvin-Helmholtz cooling phase. Those neutrinos heat up material on the surface and eject them into a high entropy bubble above the neutron star. This is the so-called neutrino-driven wind (e.g., [7][8]). Since the energy of anti-electron neutrinos is higher than electron neutrinos, the wind material becomes slightly neutron-rich. If the entropy is high enough, it becomes a suitable environment for the main r-process. Although this is a popular model, there are several problems in this model. For example, it is still controversial at to whether such high entropy is actually realized in the wind (e.g., [8] and reference there in). In addition, Meyer et al. [14] pointed out that neutrino interactions with nuclei during the r-process increases the electron fraction. Higher entropy and/or shorter timescale may thus be necessary to realize suitable conditions for the r-process in this model when neutrino effects are considered.

We assume an exponential adiabatic expansion model for the neutrino-driven wind. This model is often invoked in parametric studies of high-entropy environments such as neutrino-driven winds. In this model, the density and temperature profiles are given as;

$$T_9 = 9.0 \exp(-t/t_{\rm exp}) + 0.6 \tag{1}$$

$$\rho = 3.3 \times 10^5 T_9^3 / S, \tag{2}$$

where T_9 is the temperature in units of 10^9, $t_{\rm exp}$ is the expansion timescale, ρ is the baryon matter density in g/cm^{-3}, and S is the entropy per baryon. We chose a parameter set of S=300, $t_{\rm exp}$=0.05 sec, and Y_e=0.45 for this study as it provides a reasonable reproduction of the solar r-process abundance curve with a single profile.

2. Prompt explosions of low-mass supernovae

Low mass core-collapse SNe ($8-12M_\odot$) are another candidate. If such low-mass supernovae explode, they would occur via a prompt explosion. During such prompt explosions, relatively low entropy (∼15k), and a low electron fraction ($Y_e \sim 0.2$) can be realized (e.g.,[9][10]). These are also ideal conditions for the r-process. The main objection to this model is the explosion mechanism itself. It is still unclear as to whether such light supernovae actually explode. This is exacerbated by the fact that, there is no convincing observational evidence of the remnants of such explosions.

For these calculations, we have assumed that the material expands exponentially, $\rho \propto \exp(-t/t_{exp})$. Here, t_{exp} is the expansion timescale. Corresponding temperatures are obtained from the equation of state of Timmes et al. [11]. As used in previous studies, we adopted the entropy to be S=15, and Y_e=0.2. We calculated the case with $t_{\rm exp}$=0.05 sec for $T_9 > 1.0$ and $t_{\rm exp}$=0.3 sec when the temperature drops below $T_9 < 1.0$. We also did calculations with different timescales. These, however, did not change the conclusions discussed here.

3. Neutron star mergers Another neutron-rich environment could be realized in neutron star mergers (e.g., [12]). In this model the entropy is very low, but the electron fraction is also very low. It is the most neutron-rich environment among the three models considered here. Although theoretical calculations show reasonable yields, this model encounters some difficulties in explaining the chemical enrichment history of the Galaxy [13].

For the other two models, the heating from nucleosynthesis can be shown to be negligible. However, in the neutron star merger model, heating from beta-decays and fission can significantly affect the temperature profiles. Since the current version of our network code does not take heating from nucleosynthesis into account, we have assumed a constant temperature T_9=1.0. In other r-process calculations in the neutron star merger model, the temperature varies between 0.2 to 1.2 $\times 10^9$ K during the r-process [12]. Hence, a constant temperature is a reasonable assumption for our purposes of testing the impact of new nuclear reaction flows. Initial conditions for this model are from Tables 1 and 2 in [5]. Here, we assume that the material expands on a free fall timescale (α=1.0) and the electron fraction is initially set to Y_e=0.15.

DISCUSSION

Neutron capture on light elements is effective for all of the models considered here. Since neutrons are consumed by the formation of lightr elements, the final actinide abundances are reduced in the neutrino-driven wind and low-mass supernova models. Especially in the case of low mass supernovae, these reactions make the ratio of actinide elements to the third peak elements much smaller. Even if we increase the entropy to 50, we cannot reproduce the higher actinide abundances which have been observed in metal-poor stars. If we believe all of the reaction rates which were involved in the present calculations, low mass supernovae model should be discarded. Although their reaction rates have large uncertainties, neutron-capture of light elements seems to have a large impact on all three models. It is indeed a high priority to obtain more reliable neutron-capture reaction rates for the relevant light elements.

On the other hand, the effect of the new reaction flow ^{4}He(n^2,γ)^{6}He(α, n)^{9}Be is not significant in the neutrino driven wind models or low-mass supernovae. For the neutron star merger model, the effects of both reactions appear at $A < 130$, but are not significant for the production of heavy element abundances. This is because the environment is so neutron rich that fission recycling obscures the effects of all processes that occurred at an earlier stage of nucleosynthesis.

Fission recycling plays a role in all models, but it is most effective for the neutron-star merger models. Note, that there is no significant difference for elements heavier than the second r-process peak in the neutron-star merger model. If we compare snapshots of each calculations, there are large differences at the early stage of nucleosynthesis. But those differences are obscureded by fission recycling. This effect of fission recycling could be a hint to explain the apparent robustness of the r-process. Since our fission model is very primitive, more realistic, systematic studies of fission are needed for further discussion.

The final computed abundances for the three different environments considered here are compared in Fig. 2. They are scaled to agree at the third r-process peak. The most obvious difference appears between the first and second peak. Unfortunately, our results are based upon a single trajectory in density and temperature. In a realistic calculation one must sum over different trajectories ejected at different times. These trajectories can also affect on this region. In addition, contributions from the weak r-process can also affect the same region. Other differences appear at the third peak. Although yields from the neutron-star merger model is distinguishable from the others, the yield from different types of supernovae are similar in this region. However, neutrino-nucleus interactions (e.g., [15]) have not been included for this calculation. If neutrino-nucleus interactions have a large impact on the final abundances, This may be detectable by observations. If so, we could use this detection to identify the origin of the main r-process. There are still large uncertainties from nuclear physics. We need to reduce those uncertainties if we are ever to identify the origin of the main r-process via a comparison between observed

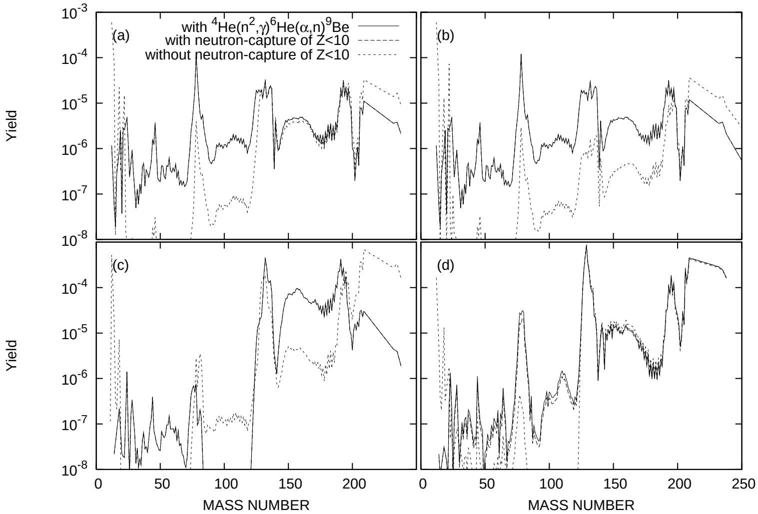

FIGURE 1. Calculated final abundances in the models of (a)neutrino-driven winds, (b) neutrino-driven winds without fission, (c)low-mass supernovae, and (d)neutron star mergers. For each models, the case with di-neutron capture (solid lines), without it (dashed lines), and without any ^{6} He reactions (dotted lines).

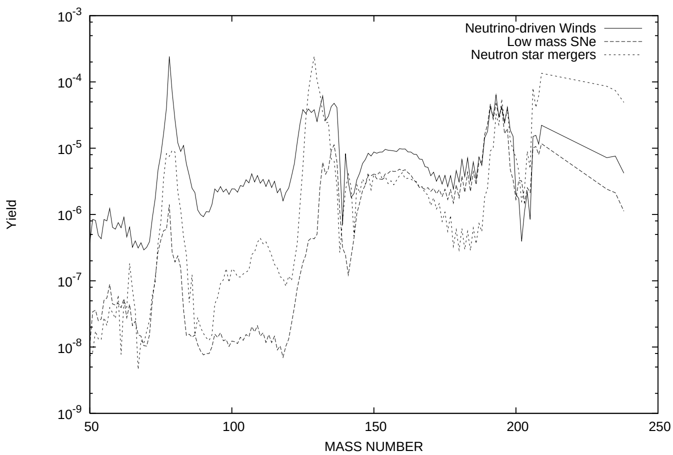

FIGURE 2. Comparison of final abundances of r-process calculations in three different environments, neutrino-driven winds (solid line), low mass supernovae (dashed lines), neutron star mergers (dotted lines).

abundance distributions and theoretical calculations.

Our results suggest that the light element reactions play important roles for nucleosynthesis in the main r-process. We need to pay attention to those light elements when we discuss the viability of environments based upon theoretical calculations.

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