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# Universality of the $p$-process

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The solar abundances provide a concept of universality that the abundance ratios of the $p$-nucleus to the $s$-nucleus with the same atomic number are almost constant with the wide region for materials produced by individual stellar nucleosynthesis episode. We study this universality using $\gamma$-process calculations with core-collapse supernova explosions under various conditions. The calculated results show that the $\gamma$-process under the various conditions can occur but the ratios are almost constant with the wide region independent of the conditions. The shift of $\gamma$-process layers, weak $s$-process and the $\beta$-decay after the $\gamma$-process contribute to the manifestation of the universality.

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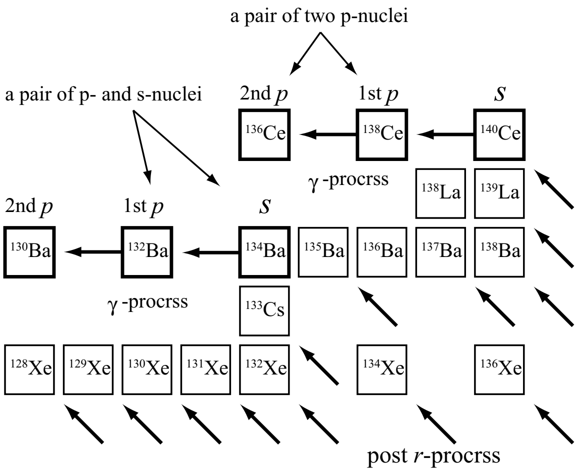


**Figure 1:** A partial nuclear chart around Xe and Ba isotopes.

## 1. Introduction

The solar system abundance is a crucial record of nucleosynthesis episodes since the solar system was formed from interstellar media originated from many different stellar nucleosynthesis episodes in the Galaxy. The stellar conditions such as the mass, metallicity and explosion energy are different and thus the abundance distribution of the solar system should be different with that of individual nucleosynthesis episode. However, recent astronomical observations for some very metal-deficient stars reported an epoch-making discovery of the "universal" abundance distribution for the atomic number $Z > 56$, which are consistent with the abundance distribution of the *r*-process nuclides in the solar system [1, 2].

We here focus attention to 35 *p*-process isotopes (*p*-nuclei), which locate in the neutron-deficient side from the $\beta$-stability line and have small isotope abundances (typically $0.1 \sim 1$ %) [3]. As the origin of the *p*-nuclei, Arnould proposed the *p*-process in pre-supernova phases [4], and Woosley and Howard proposed the $\gamma$-process in supernovae (SNe) [5]. In these pioneering work, the *p*-nuclei are synthesized mainly by photodisintegration reactions from pre-existing nuclei. Nevertheless, the origin of the *p*-nuclei has been discussed during about 50 years and many nucleosynthesis processes have been proposed [6, 7, 8, 9, 10, 11, 12, 13]. In our previous paper [14], we reported two empirical scaling laws in the solar system abundances, which are a piece of evidence that the most probable origin of the 27 *p*-nuclei is $\gamma$-process in SNe. These scalings lead to a novel concept of "the universality of the $\gamma$-process" [14, 15]. The understanding of the mechanism of the universality is crucial for the $\gamma$-process and the Galactic chemical evolution (GCE) of the *p*- and *s*-nuclei. We here present the analyses of the solar abundances and results of $\gamma$-process calculations under various astrophysical conditions.

## 2. Analyses of the solar system abundances

First we present analyses of the observed solar abundances [16]. There are 22 *p*-nuclei associated with almost pure *s*-nuclei that have two more neutrons than the *p*-nuclei. The pure *s*-nuclei

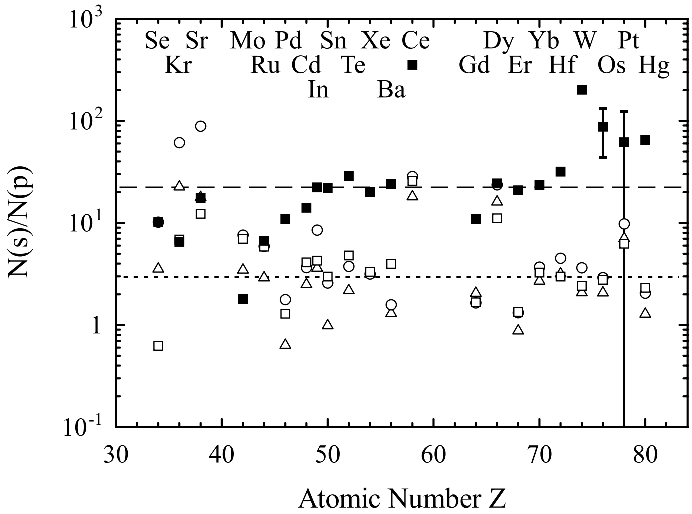


**Figure 2:** The abundance ratios of the *s*-nuclei to *p*-nuclei with the same atomic number, N(s)/N(p). The filled squares are the solar abundances. The open squares are the calculated results in a metal deficient model with $Z$ = 0.05 $Z_\odot$, $M$ = 25 $M_\odot$ and $E$ = $10^{51}$ erg. The open circles are those in a heavier progenitor mass model with $Z = Z_\odot$, $M$ = 40 $M_\odot$ and $E$ = $10^{51}$ erg. The open triangles are those in a high energy explosion model with $Z = Z_\odot$, $M$ = 25 $M_\odot$ and $E = 20 \times 10^{51}$ erg.

are dominantly synthesized by the *s*-process and shielded by stable isobars against $\beta$-decay after the *r*-process. As shown in Fig. 1, a typical example is found in Ba isotopes: $^{132}$Ba is a p-nucleus and $^{134}$Ba is a pure s-nucleus shielded by an isobar $^{134}$Xe against the $\beta$-decay. We here discuss the isotope abundance ratios of these two isotopes. Taking the abundance ratios of the *s*-nucleus to the *p*-nucleus in the pair, $N_\odot$(s)/$N_\odot$(p), where $N_\odot$(s) and $N_\odot$(p) are the solar abundances of the *s*- and *p*-nucleus, respectively, we find an empirical scaling law that the ratios are almost constant in a wide range of the atomic number, $N_\odot(s)/N_\odot(p) \approx 23$, except for deviations (see Fig. 2). Two large deviations of Ce and W originate from the contamination of the *r*-process. Deviations of Mo and Ru support a previous suggestion that their origin may be different with the other *p*-nuclei. We also find the second empirical scaling law between two *p*-nuclei with the same atomic number. Nine elements have two *p*-nuclei. The first and second *p*-nuclei are two and four neutron deficient from the *s*-nucleus, respectively (see Fig. 1). The ratios, $N_\odot$(1st p)/$N_\odot$(2nd p), are almost constant with the wide region.

The first scaling shows a strong correlation between *p*- and *s*-nuclei with the same atomic number, which indicates that the origin of most *p*-nuclei is strongly correlated with the *s*-nuclei. This is consistent with the *p*-process (or $\gamma$-process) in SN explosions [5, 7, 10]. The *p*-nuclei are produced from heavy isotopes by photodisintegration reactions such as ($\gamma$,n) reactions in SN explosions. In contrast, the other proposed models change the proton number as well as the neutron number of the pre-existing seeds. Therefore, the first scaling is a piece of evidence that the $\gamma$-process in SNe is the most promising origin of the 27 *p*-nuclei.

The *p*-nuclei were produced in different stellar environments and thus the mass distribution of synthesized nuclei may depend on the astrophysical conditions. Nevertheless, the scaling is found in the solar system. This fact leads to a novel concept, "the universality of the $\gamma$-process", that the scaling, the N(s)/N(p) ratios are almost constant in the wide region, holds for materials produced by individual $\gamma$-process.

## 3. $\gamma$-Process calculations in core-collapse supernovae

The universality of the $\gamma$-process is derived from the solar abundances but the reason why the empirical scaling laws and universality appear in the solar abundances has remained an open question. We calculate nucleosynthesis in oxygen-neon layers in core-collapse SN explosions under various astrophysical conditions [17]. Massive stars evolve from main sequence to a core-collapse stage and explode with explosion energy of $10^{51}$ or $20 \times 10^{51}$ ergs [18]. We adopt the solar abundances as the initial composition and calculate the weak *s*-process. We use a solar metallicity $Z = Z_{\odot}$ and also a deficient metallicity $Z = 0.05\ Z_{\odot}$. The progenitor masses are 15, 25 and 40 solar masses ($M_{\odot}$). Figure 2 shows also results in three different models. They are (1) a metal deficient model with $Z = 0.05\ Z_{\odot}$, $M = 25\ M_{\odot}$ and $E = 10^{51}$ erg (squares in Fig. 2), (2) a heavier progenitor mass model with $Z = Z_{\odot}$, $M = 40\ M_{\odot}$ and $E = 10^{51}$ erg (circles), and (3) a high energy explosion model with $Z = Z_{\odot}$, $M = 25\ M_{\odot}$ and $E = 20 \times 10^{51}$ erg (triangles). We would like to stress that these calculated N(s)/N(p) ratios are almost constant in a wide region of $Z > 40$ independent of the astrophysical conditions.

The $\gamma$-process layers shifts in mass coordinate, whose range is dependent on the progenitor mass and the explosion energy to keep an identical peak temperature range 1.7 - 3.5 $10^9\ K$. This shift are previously known [4, 5, 7, 10]. However, the scaling between the *p*- and *s*-nuclei cannot be explained only by the layer shift. The first question we have to ask here is why the solar abundances of the *p*-nuclei are proportional to those of the *s*-nuclei originated dominantly from asymptotic giant branch (AGB) stars. The weak *s*-process produced newly *s*-nuclei in a mass region of $A <$ 90. However, the weak *s*-process has also a crucial role for a heavy mass region of $A > 90$. The mass distribution of the seeds is changed to that of the AGB *s*-process for $A > 90$ after the weak *s*-process. The scaling does not strongly depend on the metallicity because the abundances of the *p*-nuclei are proportional to that of the pre-existing seeds except a mass region of $A < 90$. The second question is why the $\beta$-decay after the freezeout of the $\gamma$-process keep the scaling. The $\beta$-decay may break the scaling since the mass distribution on the neutron-deficient side flow depends on nuclear properties such as particle separation energies as well as astrophysical conditions. We calculate the percentage of the abundance produced by the $\beta$-decay to final abundance of each *p*-nucleus. The percentage depends on the neutron number. The *p*-nuclei in a mass region of 28 $< N <$ 82 are dominantly produced by direct ($\gamma$,n) reactions. We find that the $\beta$-decay after the $\gamma$-process increases only the abundances of the *s*-nuclei for $50 < N < 82$ to manifest the constant values in a wide mass region of $50 < N < 128$.

## 4. Summary

We present two empirical scaling laws observed in the solar system abundances, which are a piece of evidence that the most probable origin of 27 *p*-nuclei is $\gamma$-process in SNe and lead to a concept "universality of the $\gamma$-process". We study the universality of the $\gamma$-process by using $\gamma$-process calculations in core-collapse supernova models. The calculated results indicate that even should the

$\gamma$-process occur under the various conditions, the N(s)/N(p) ratios in each nucleosynthesis episode result in almost constant value of the wide region independent of the SN conditions assumed. The shift of $\gamma$-process layers, weak *s*-process and the $\beta$-decay after the $\gamma$-process contribute to the manifestation of the constant values of the N(s)/N(p) ratios.

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