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Evidence for p-process nucleosynthesis recorded at the Solar System abundances

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Abstract. Analyzing the Solar System abundance, we have found two universal scaling laws concerning the p- and s-nuclei with the same atomic number. They are evidence of the p-nucleus origin that has been discussed for long years. The first scaling is the correlation of the isotope abundances between a p-nucleus and an s-nucleus that is two neutron heavier than the p-nucleus. The abundance ratios of the s-nucleus to the p-nucleus are almost constant in a wide range of atomic numbers. This scaling indicates that the p-nucleus is dominantly produced from the s-nucleus by (γ, n) reactions in huge photon bath in supernova explosions. The second scaling indicates that the isotope abundance ratio between two p-nuclei with the same atomic number is almost unity. These two scalings are a new useful method to verify nucleosynthesis models for the p-process. We have calculated these ratios by a p-process nucleosynthesis based on a typical core-collapse supernova explosion model. The results are consistent with the scaling in the solar abundances. In addition, the scalings provide new concepts: a universality of the p-process, a rate meter for the s-process and a new nuclear cosmochronometer.

PACS. 26.30.+k Nucleosynthesis in novae, supernovae and other explosive environments – 98.80.Ft Origin, formation, and abundances of the elements – 91.65.Dt Isotopic composition/chemistry

1 Introduction

Light elements such as H, He were mainly produced by Big-Bang nucleosynthesis and heavy elements were dominantly synthesized by stellar nucleosynthesis after the formation of the Galaxy. The Solar System was formed from the interstellar medium (ISM), whose composition is provided from stellar nucleosynthesis episodes. The Solar System abundance is, therefore, an important record of stellar nucleosynthesis and the galactic chemical evolution (GCE). About 99% of elements heavier then the iron group were produced by two different neutron-capture reaction chains, *i.e.* the slow neutron-capture process (s-process) along the β-stability line, and the rapid neutron-capture process (r-process) in the neutron-rich side. The Solar System abundance shows specific indication that they have actually happened before the Solar System formation. The first evidence is the pairs of two abundance peaks near the neutron magic numbers $N = 50, 82, 126$. These two peaks correspond to the s- and r-processes [1]. The second evidence for the s-process is an empirical relation, $N \cdot \sigma \sim$ constant, where N and σ are, respectively, the solar abundance and the neutron capture cross-section [2, 3]. However, there are stable isotopes that cannot be synthesized by the neutron capture reactions because they are located in the neutron-deficient side of the β-stability line in the nuclear chart (see fig. 1). These isotopes are called the "p-nuclei". They have the feature that their isotope abundances are very rare (typically 0.1%–1%). The anti-correlation between the photodisintegration reaction rates and the solar abundances for the p-nuclei has been pointed out [4]. Nevertheless, their origin has long been discussed with many possible nuclear reactions, and their astrophysical sites have not been identified uniquely. The proposed nuclear processes are the rapid proton capture reactions in novae and type-I X-ray bursts in neutron stars (rp-process) [5,6], the proton-induced reactions by galactic cosmic rays [7], the photodisintegration reactions in supernova (SN) explosions (γ-process or p-process) [4,8, 9,10,11,12], and the neutrino-induced reactions in SN explosions (ν-process) [13,14]. The origin of the p-nuclei is crucial to our understanding of how the Solar System material formed and evolved. We here report two empirical scaling laws obtained from a careful analysis of the Solar

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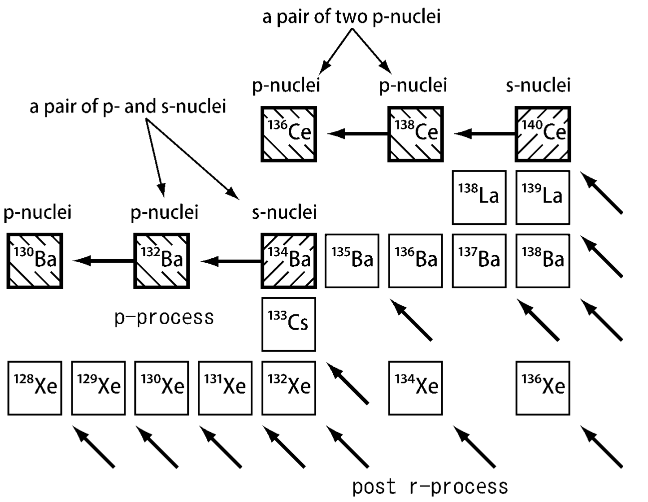

Fig. 1. Partial nuclear chart around the Xe and Ba isotopes. The nuclei located on the β-stability line are mainly synthesized by the s- and r-processes. In contrast, p-nuclei such as ^{130,132}Ba and ^{136,138}Ce are synthesized by the p-process. There are pairs of a p-nucleus and an s-nucleus that are two neutron heavier than the p-nucleus. We find a strong correlation between the solar abundances of these p- and s-nuclei.

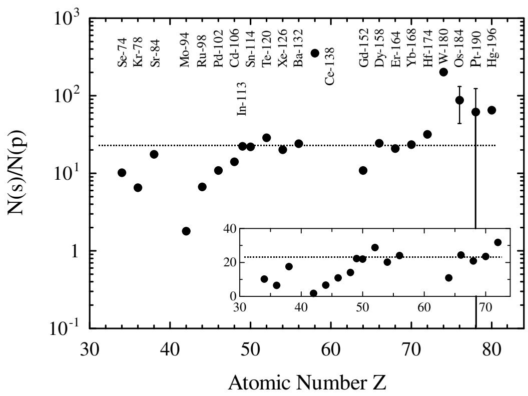

Fig. 2. Abundance ratios of pure s-nucleus to pure p-nucleus, $N(\mathrm{s})/N(\mathrm{p})$, in the Solar System. The p-nucleus is a two-neutron–deficient isotope from an s-nucleus with the same atomic number Z. The ratios are almost constant, $N(\mathrm{s})/N(\mathrm{p}) \approx 23$ in a wide region of atomic numbers. The inset displays the same quantities in the linear scale except for the ^{138}Ce and ^{180}W pairs which show large deviations from the scaling value ≈ 23. Deviations from the scaling and the uncertainty of the Os and Pt isotopes are discussed in the text.

System abundance [12], and discuss new concepts of "the universality of the p-process" and the rate meter for the s-process. We also calculate the p-process nucleosynthesis using a typical type-II SN model.

2 Analyzing the solar abundances and discovery of the first scaling

There are thirty-five p-nuclei in nature. Most p-nuclei are even-even nuclei consisting of even protons and even neutrons. There are 22 pairs of a p-nucleus and an almost pure s-nucleus that are two neutron heavier than the p-nucleus. The pure s-nuclei are dominantly synthesized by the s-process and shielded by stable isobars against the β^--decay after the freezeout of the r-process. Figure 1 shows a partial nuclear chart in the Xe-Ba region. 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 β-decay.

We here discuss the isotope abundance ratios of these two isotopes. Taking the abundance ratio of the s-nucleus to the p-nucleus, $N(\mathrm{s})/N(\mathrm{p})$, where $N(\mathrm{s})$ and $N(\mathrm{p})$ means the solar abundances of the s- and p-nucleus, respectively, we find a clear correlation between them (see fig. 2). The ratios are almost constant and constrained at a constant value of $N(\mathrm{s})/N(\mathrm{p}) \approx 23$ in a wide region of atomic numbers except for the deviations. The reason for the deviations will be discussed later. This scaling has never been recognized in the literature quantitatively.

The first scaling shows a strong correlation between p- and s-nuclei with the same atomic number, which indicates that the origin of the p-nuclei is strongly correlated with the s-nuclei. This is consistent with the previous theoretical calculations that the p-nuclei are produced by the p-process (or γ-process) in SN explosions [15,16,17]: namely, the pre-existing nuclei in massive stars are affected by the s-process during the pre-supernova evolutionary stage and the p-nuclei are subsequently produced from them by photodisintegration reactions such as (γ, n) reactions in a huge photon bath at extremely high temperatures in SN explosions. The previous calculations indicated that the p-nuclei are produced via two paths, direct (γ, n) reactions and the EC/β^+-decay from the neutron-deficient unstable nuclei which are first transmuted by successive photodisintegration reactions (γ, n), (γ, p), (γ, α) from heavier elements. The first scaling suggests that the former reactions are likely to play a more important role than the latter reactions. The charged particle reactions in the rp-process [5,6] and proton-induced reactions by cosmic rays [7] change the proton number of seed nuclei. In the ν-process, the charged current interaction that has a contribution larger than the neutral current interaction also changes the proton number [18,19]. Therefore, the scaling does not emerge from the dominant charged particle processes or the ν-process. The first scaling is, thus, a piece of evidence that the p-process is the most promising origin of the p-nuclei.

We finally discuss the reason for the deviations. The two large deviations for Ce and W can be explained by an exceptional contribution from the r-process because they are not shielded against β-decay. The heavy isotopes ^{140}Ce and ^{182}W are dominantly synthesized by the r-process. This fact indicates that the p-nuclei are not synthesized from the seed nuclei of the r-process mass distribution. In addition the effect of the neutron magic number $N = 82$ should contribute to the deviation for Ce. The small deviations for Cd, Sn and Gd may originate from a weak

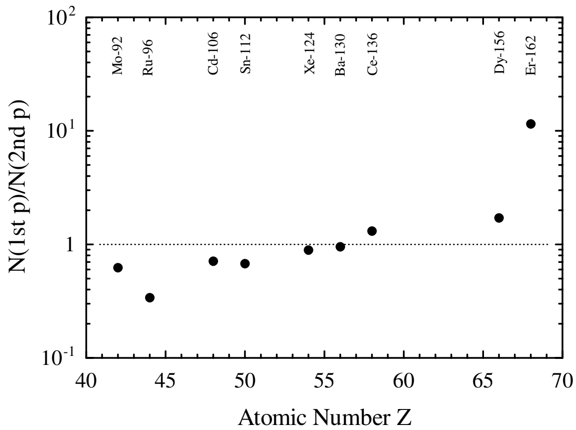

Fig. 3. Abundance ratios of two pure p-nuclei, $N(\text{1st p})/N(\text{2nd p})$. The first and second p-nuclei are, respectively, two- and four-neutron–deficient isotopes from an s-nucleus with the same atomic number.

branch of the s-process which contaminates the p-nuclei. The deviations of Mo and Ru are consistent with the underproduction of these isotopes in the previous calculations [15,16]. Their origin may be different with the other even-even p-nuclei. The deviations in the heavy-mass region may originate from the large uncertainties of the solar abundances. The uncertainties for ^{184}Os and ^{190}Pt are about 50% and 100%, respectively [20]. The measurement of their abundances with a high precision is desired.

3 Discovery of the second scaling

We find another scaling law between two p-nuclei with the same proton number. Nine elements have two p-nuclei. We define that the second p-nucleus is two neutron lighter than the first p-nucleus. For example, ^{132}Xe is the first p-nucleus and ^{130}Xe is the second p-nucleus (see fig. 1). Taking the abundance ratio, $N(\text{1st p})/N(\text{2nd p})$, we also find a strong correlation between these isotope abundances (see fig. 3). The ratios are almost constant in a wide range of atomic numbers and they are almost unity, *i.e.* $N(\text{1st p})/N(\text{2nd p}) \approx 1$. This second scaling is useful to constrain the astrophysical condition of the p-process. There is a deviation for Er. It can be explained by a contamination from the β^--decay of ^{163}Dy under stellar s-process conditions [21,22].

4 Proposal of a novel concept of the universality of the p-process

The universality of nucleosynthesis processes is an important concept for understanding stellar nucleosynthesis. The Solar System was formed from the ISM originated from many nucleosynthesis episodes in stars in the Galaxy. The nucleosynthesis environments such as mass, metallicity and explosion energy are different and hence the produced abundance distribution may be different. The abundance distribution in the Solar System material is, thus, equal to the average of the stellar nucleosynthesis processes. However, astronomical observations for very metal-deficient stars have reported the "universal" abundance distribution for $Z > 56$ [23,24], which is in agreement with the abundance distribution of the r-process nuclides in the Solar System. These facts suggest a uniform site and/or uniform conditions for the synthesis of the r-process nuclei. Otsuki *et al.* could succeed in explaining the universality of the r-process by a neutrino-energized wind model [25].

The $N(\text{s})/N(\text{p})$ ratios for the Solar System abundance are subject to galactic chemical evolution. The p-nuclei and s-nuclei were produced in different stellar environments. Thus, the mass distribution of synthesized nuclei may depend on astrophysical conditions. Nevertheless, the observed $N(\text{s})/N(\text{p})$ ratios in the Solar System are almost constant in a wide region of atomic numbers. The observed ratios do not depend on the proton number. This leads to a novel concept, "the universality of the p-process", that the $N(\text{s})/N(\text{p})$ ratios produced by individual p-process are constant in a wide range. We would like to stress that this universality indicates a uniform astrophysical condition or a nucleosynthesis process that does not depend on astrophysical conditions. The universality is, thus, essential for understanding the nucleosynthesis site of p-nuclei.

5 Proposal of a novel concept of rate meter for the s-process

The universality of the SN p-process is an important concept for understanding the chemical evolution of the Galaxy as well as the p-process nucleosynthesis. Figure 4 shows a schematic chart for the GCE. First, we would like to stress that the s-nuclei in the Solar System were mainly produced by the s-process in the low-mass AGB stars [3]. In contrast, p-nuclei are synthesized by the p-process in SNe. The astrophysical sites for the p- and s-processes are different. However, the isotope abundance ratios of the p- and s-nuclei have a strong correlation. This fact indicates that the average $N(\text{s})/N(\text{p})$ ratios in the first scaling are proportional to the abundance synthesized by individual s-process and to the frequency of the formation of the AGB stars. Second, the s-process nucleosynthesis depends highly on the metallicity which increases along the evolution of the Galaxy [26,27]. These two facts concerning s-nuclei and the universality of p-nuclei indicate that the $N(\text{s})/N(\text{p})$ ratios should depend on time.

Astronomical observations of the time variation of these ratios for various metallicity stars should constrain the galactic chemical evolution of s-nuclei and also provide new information on the metallicity dependence of the s-process nucleosynthesis [28]. The recent progress in spectroscopic studies of extremely metal-poor stars has enabled successfully isotope separation of several heavy elements [29,30]. It is of particular interest to observe the ancient metal-poor stars whose material had been affected by a single or a few SN p-processes. Since the primitive

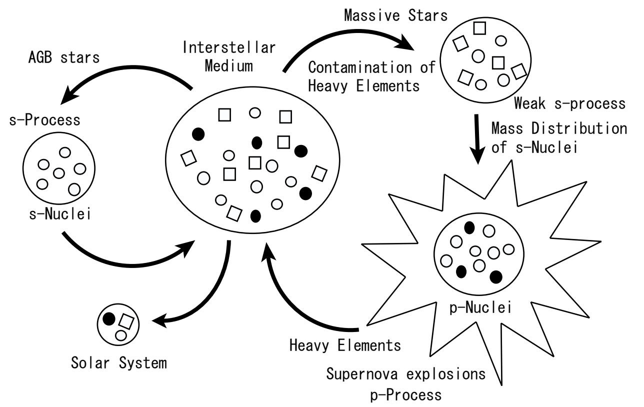

Fig. 4. A schematic chart for the galactic chemical evolution for p- and s-nuclei. The s-nuclei in the ISM are dominantly produced in the main s-process in the AGB stars. The massive stars have contamination of heavy elements from the ISM. The heavy elements are irradiated by neutrons in the weak s-process before SN explosions and the abundance distribution of the heavy elements is changed to that of the s-process. p-nuclei are synthesized in the SN p-process. The s-process depends strongly on metallicity. The $N(\mathrm{s})/N(\mathrm{p})$ ratio is proportional to the frequency of the s-process events and is time dependent.

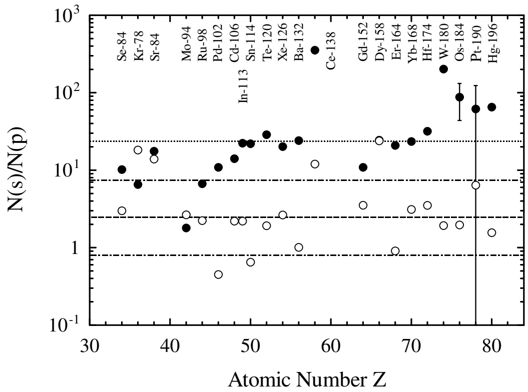

Fig. 5. Comparison of the calculated and observed abundance ratios, $N(\mathrm{s})/N(\mathrm{p})$. The filled and open circles mean the observed ratio in the Solar System and the calculated ratios. The uppermost dotted line is $N(\mathrm{s})/N(\mathrm{p}) = 23$. The dashed line displays the average value of the calculated $N(\mathrm{s})/N(\mathrm{p})$ ratios in the SN p-process model, and the two dot-dashed lines above and below this line are those multiplied by factor of 3 and 1/3, respectively.

gas is made of products of the Big-Bang nucleosynthesis or an explosive nucleosynthesis in the first generation population-III SNe, it does not contain any heavy s-nuclei. The abundance distribution of p-nuclei in metal-poor stars is, thus, expected to be very different from the solar abundance distribution, and the detection of p-nuclei by spectroscopically separating isotope abundances in these stars would be an urgent subject in future studies.

6 Supernova model calculations

For the photodisintegration-reaction p-process sites, some astrophysical sites have been proposed. They are 1) O/Ne layers in core collapse SNe [8,4], 2) He deflagration in C/O white dwarfs [9], 3) accretion disks around neutron stars or black holes [11,31]. Since one of the most probable site is the O/Ne layer in type-II SNe, we carry out nucleosynthesis calculations of the p-process in SNe [32]. The purpose of the calculations is to verify the robustness of the scalings in the Solar System abundance and to demonstrate the dependence of the calculated ratios, $N(\mathrm{s})/N(\mathrm{p})$ and $N(\text{1st p})/N(\text{2nd p})$, on astrophysical conditions. We use solar metallicity ($Z = Z_\odot$) progenitor models with 25 solar masses ($25M_\odot$) which exploded with an explosion energy of 10^{51} ergs. The s-processed abundances for the initial chemical composition are adopted. The calculated $N(\mathrm{s})/N(\mathrm{p})$ ratios are shown in fig. 5 by open circles. It is shown that they are almost constant in a wide region of atomic numbers, although the calculated ratios are lower than the observed values. This result is consistent with the observed scaling. The observed ratios in the light-mass region show a slight enhancement of p-nuclei, which may originate from progressively increasing roles of

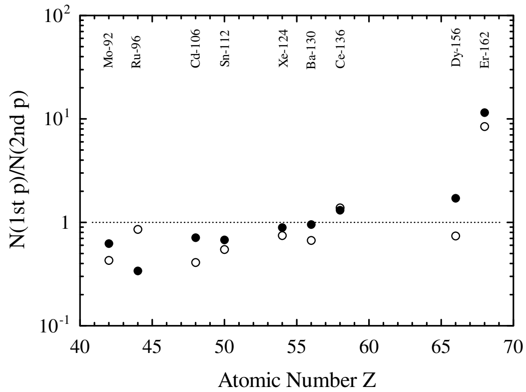

Fig. 6. Abundance ratios of two pure p-nuclei, $N(\text{1st p})/N(\text{2nd p})$. The first and second p-nuclei are, respectively, two- and four-neutron–deficient isotopes from an s-nucleus with the same atomic number Z. The filled circles stand for the observed ratios in the Solar System. The open circles stand for the calculated ratios.

(γ, p) and (γ, α) reactions with decreasing atomic number and/or the production from heavier nuclei at high temperature. The calculated ratios are smaller than the observed ones by several factors because s-nuclei in the Solar System mainly originate from the AGB stars [3]. In contrast the relation $N(\text{1st p})/N(\text{2nd p}) \approx 1$ can be directly compared with the theoretical calculations of the SN p-process, and thus the second scaling can be used for strongly constraining the SN p-process models. We present the calculated $N(\text{1st p})/N(\text{2nd p})$ ratios in fig. 6. The calculated ratios (open circles) are consistent with the observed ratios (filled circles).

We further perform the p-process nucleosynthesis calculations for the 15 and 40 $M_\odot$ progenitors to study the progenitor mass dependence. The abundance patterns of the two ratios do not change drastically from those in the 25 $M_\odot$ models. This result indicates that the two ratios are almost independent of the progenitor mass of the massive stars. We calculate the p-process in the different metallicity ($Z = 0.05\ Z_\odot$) models with the same progenitor mass. The calculated result shows that the ratios are almost constant and independent of the metallicity. These results support the proposed universality of the p-process. The calculated results in the previous p-process studies were shown to compare directly with the Solar System abundance of p-nuclei [15,16,17], not in the form of $N(\mathrm{s})/N(\mathrm{p})$ or $N(\mathrm{1st\ p})/N(\mathrm{2nd\ p})$. The p-process calculations for different models constructed with different explosion energies or the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate showed similar abundance distributions [15,16]. These results also support the universality of the p-process. Although these results indicate that p-nuclei in the Solar System are mainly produced by the p-process in type-II SNe, other astrophysical sites such as deflagrating white dwarf stars [9] and supernova-driven supercritical accretion disks [11,31] may also contribute to p-nuclei. Overproduction factors of p-process nuclei in realistic models of exploding stars were often a factor of a few below what is needed to explain the solar abundances. This may signal the p-process in some other environments as another producer of p-nuclei. We presume that such p-processes should also reproduce the two scalings.

7 Proposal of a new nuclear cosmochronometer

Long-lived radioactive nuclei are used as nuclear cosmochronometers, which are useful for an investigation of the nucleosynthesis process history along the GCE before the Solar System formation. The radioactive nuclei of cosmological significance are very rare and only six chronometers with half-lives in the range of the cosmic age 1–100 Gyr were known. They are ^{40}K [1] and ^{87}Rb [33] for the s-process or explosive nucleosynthesis in SNe, ^{176}Lu [34,35] for the s-process, and ^{187}Re [33,36,37], ^{232}Th and ^{238}U [1,38] for the r-process. Historically, a new cosmochronometer with suitable half-life has not been proposed for the last thirty years. Recently, the two elements U and Th were detected for the first time [38] in a very metal-poor star. The actinide nuclei in very metal-poor stars were perhaps created in a single r-process of a SN explosion.

The universal scaling also plays a critical role in constructing a chronometer that can be applied to the analysis of pre-solar grains in primitive meteorites which had been affected strongly by a single or a few nucleosynthesis episodes. We here propose a new cosmochronometer ^{176}Lu (half-life 37.8 Gyr)-^{176}Hf-^{174}Hf of the p-process in the SN explosion. Although the ^{146}Sm and ^{92}Nb have already been proposed as possible chronometers of the p-process [39,40], their half-lives are shorter than the age of the Solar System. Therefore, our proposed chronometer becomes a unique p-process chronometer which has a suitable time scale of the order of the cosmic age ~ 10 Gyr.

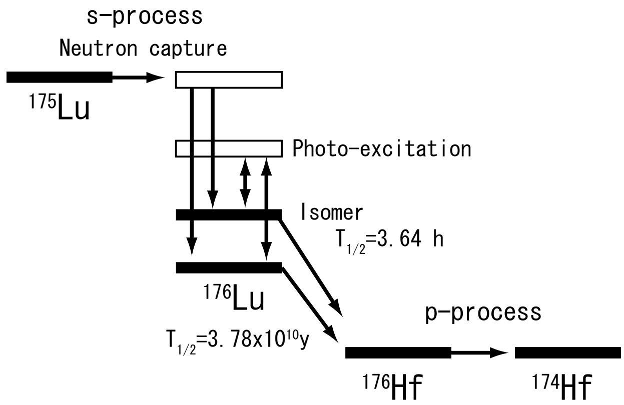

Fig. 7. ^{176}Lu-^{176}Hf-^{174}Hf chronometer. The ground state of ^{176}Lu decays to ^{176}Hf with a half-life of 3.78×10^{10} y. Although ^{176}Hf is produced by different nucleosynthesis paths, the first scaling indicates that the initial abundance of ^{176}Hf at the freezeout of the SN p-process can be calculated from the present abundance of ^{174}Hf.

A ^{176}Lu-^{176}Hf pair was previously proposed as an s-process chronometer [34], since ^{176}Lu is a pure s-nucleus. The daughter nucleus ^{176}Hf is also a pure s-nucleus and is located outside the main path of the s-process. An isomeric state in ^{176}Lu decays to ^{176}Hf with a short half-life of 3.64 hours. The experiments using stellar-energy neutrons have been carried out and the branching ratio between the ground state and the isomer in ^{176}Lu was measured. It was, however, pointed out that the solar abundances of ^{176}Lu cannot be explained by a classical s-process model [35]. The isomer is populated through intermediate states with high excitation energy by (γ,γ') reactions at high temperature, $T \sim 10^8$ K (see fig. 7). The decay rate of ^{176}Lu depends strongly on the temperature and the initial abundance at the end of a nucleosynthesis episode cannot be predicted by theoretical calculations. The system ^{176}Lu-^{176}Hf is considered to be useless as a chronometer, although it is a good thermometer [35].

The p-process chronometer of ^{176}Lu-^{176}Hf-^{174}Hf has the advantage that the initial abundance of ^{176}Hf can be calculated from the present abundance of ^{174}Hf by applying the first scaling if the pre-solar grain is affected strongly by a single SN event. The first scaling indicates that the abundance of ^{174}Hf is proportional to ^{176}Hf, although ^{176}Hf is produced through different nucleosynthesis paths. Our proposed chronometer of the p-process is, therefore, free from the uncertainty of the initial abundance. The time passing after the SN p-process can be calculated by

$$T = -\frac{T_{1/2}(^{176}\mathrm{Lu})}{\ln 2} \times \ln\left(\frac{N(^{176}\mathrm{Lu})}{N(^{176}\mathrm{Lu})+(N(^{176}\mathrm{Hf})-R_i(\mathrm{Hf})\times N(^{174}\mathrm{Hf}))}\right), \quad (1)$$

where, $N(^{A}Z)$ means the isotope abundance, and R stands for the $N(\mathrm{s})/N(\mathrm{p})$ ratio in the scaling in meteorites, which should be systematically measured or predicted by p-process calculations. Heavy elements such as Sr, Zr, Mo and Ba in a primitive material such as the pre-solar grains have already been successfully separated into isotopes including p-nuclei, whose origin is considered to be the ejecta of core collapse SN explosions [41,42]. Although the pre-solar grains would be likely to condense ^{176}Hf and ^{176}Lu from other regions of the star, the chemical composition of the grains enhanced by the products of the O/Ne layer may be found. The separation of the three isotopes, ^{174,176}Hf and ^{176}Lu, in the pre-solar grains is highly desirable.

8 Conclusion

In summary, we have presented two universal scaling laws concerning p- and s-nuclei in the Solar System abundance. They provide four novel concepts: a piece of evidence that the SN p-process is the most probable origin of p-nuclei, a universality that the abundance ratios $N(\mathrm{s})/N(\mathrm{p})$ of products by individual SN p-process are almost constant in a wide region of atomic numbers, a rate meter that the $N(\mathrm{s})/N(\mathrm{p})$ value is proportional to the frequency of the AGB s-process events, and a new nuclear cosmochronometer for the p-process. The scalings are useful for identifying the astrophysical sites of p-nuclei and limiting the contribution from other nuclear processes. We carry out typical type-II SN p-process calculations and the results support the universality of the p-process. Therefore our proposals provide new insights into the chemical evolution of the Galaxy as well as the SN p-process.

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