Evidence for Nucleosynthesis in the Supernova γ Process: Universal Scaling for p Nuclei

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Analyzing the solar system abundance, we find two universal scaling laws concerning the p and s nuclei. They indicate that the γ process in supernova (SN) explosions is the most probable origin of the p nuclei that has been discussed with many possible nuclear reactions and sites in about 50 years. In addition, the scalings lead to new concepts: a universality of the γ process and a new nuclear cosmochronometer. We carry out γ-process nucleosynthesis calculations for typical core-collapse SN explosion models, and the results satisfy the observed scalings.

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The solar system abundance ratio is an important record of stellar nucleosynthesis and the chemical evolution of the Galaxy. Stable elements heavier than iron in the solar system are classified into three groups in the nuclear chart, as (1) the main nuclei located near the β-stability line, (2) the isolated neutron-rich nuclei, and (3) the neutron-deficient nuclei. The first and second groups are inferred to be synthesized via 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 indications that they actually happened before the formation of the solar system. The first evidence is the two abundance peaks near the neutron magic number corresponding to the s and r processes [1]. The second evidence for the s process is an empirical relation, $N\sigma \sim$ const, where N and σ are the solar abundance and the neutron-capture cross section [2,3]. The third nuclei are called the "p nuclei," which are located in the neutron-deficient side and have very rare isotope abundance ratios (about 0.1%–1%). The anticorrelation 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) [4,8–10], and the neutrino-induced reactions in SN explosions (ν process) [11–13]. The origin of the p nuclei is crucial to our understanding of how the solar system material formed and evolved. The first purpose of this Letter is to report empirical laws, obtained from a careful analysis of the solar system abundance, which indicate that the origin of the p nuclei is the SN γ process. The second purpose is to show our theoretical SN nucleosynthesis calculations and to propose two new concepts: universality on p nuclei in the SN γ process and a nuclear cosmochronometer for the γ process.

First we discuss the features of the p nuclei in the solar system abundance. There are 22 p nuclei associated with almost pure s nuclei that have two more neutrons than the p nuclei. The pure s nuclei are dominantly synthesized by the s process and shielded by stable isobars against the β^- decay after the freeze-out of the r process. A typical example is found in hafnium isotopes: ^{174}Hf is a pure p nucleus and ^{176}Hf is a pure s nucleus shielded by ^{176}Yb against the r process, while ^{175}Hf between them is unstable. Taking the abundance ratios of the s nucleus to the p nucleus, $N(s)/N(p)$, where N is each isotope abundance, we find a clear correlation between them (see Fig. 1). The ratios concentrate at a constant value of $N(s)/N(p) \approx 23$ in a wide region of the atomic number. Large deviations for Ce and W can be explained by an exceptional contribution from the r process because they are not shielded completely. Small deviations for Cd and Gd originate from a weak branch of the s process which contaminates the p nuclei. Mo and Ru are known to have different origins from other p nuclei in the previous studies [14,15]. 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 [16]. The measurement of their abundances with a high precision is desired. Except for these deviations, the scaling rule $N(s)/N(p) \approx$ const holds for a very wide region of the atomic number, which has never been recognized in literature quantitatively.

Furthermore, we find another scaling rule between two pure p nuclei with the same atomic number. Nine nuclear species have two pure p nuclei, in which the second p nucleus is two neutron deficient to the first p nucleus. The abundance ratios, $N(\text{1st } p)/N(\text{2nd } p)$, are shown in Fig. 2.

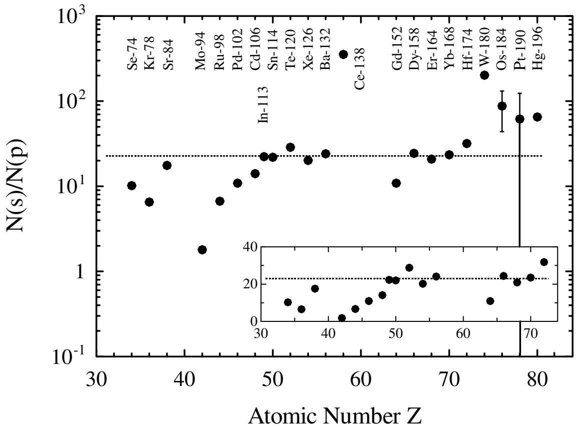

FIG. 1. Abundance ratios of pure s nucleus to pure p nucleus, $N(s)/N(p)$, in the solar system. The p nucleus is two neutron-deficient isotope from the s nucleus with the same atomic number Z. The ratios are almost constant about $N(s)/N(p) \approx 23$ in a wide region of the atomic number. The inset displays the same quantities in the linear scale except for ^{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.

Again the ratios are found to concentrate at almost constant value with a weak slope as shown by the second scaling, $N(1\text{st } p)/N(2\text{nd } p) \approx 1$, to a very good approximation. A large deviation for Er is attributed to a contamination from β^--decay of ^{163}Dy under stellar s process conditions [17,18].

The first scaling shows a strong correlation between p and s isotopes with the same atomic number indicating that the production mechanism of the p nuclei has the reason. This is consistent with the previous theoretical calculations that the p nuclei are produced by the γ process in SN explosions [14,15,19]: namely, the preexisting nuclei in massive stars are affected by the s process during the presupernova 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 calculations indicated that the p nuclei are produced via two paths, the direct (γ, n) reactions and the 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 role more important 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 [13]. 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 γ process is the most probable origin of the p nuclei.

The $N(s)/N(p)$ ratios for the solar system abundance are subject to the galactic chemical evolution. The solar system formed from the admixed interstellar media originated from many different nucleosynthesis episodes in the Galaxy, and the p nuclei and s nuclei were produced in different stellar environments. Thus the mass distribution of synthesized nuclei may depend on the astrophysical conditions. Nevertheless, the observed $N(s)/N(p)$ ratios in the solar system are almost constant. This leads to a novel concept that the $N(s)/N(p)$ ratios produced by

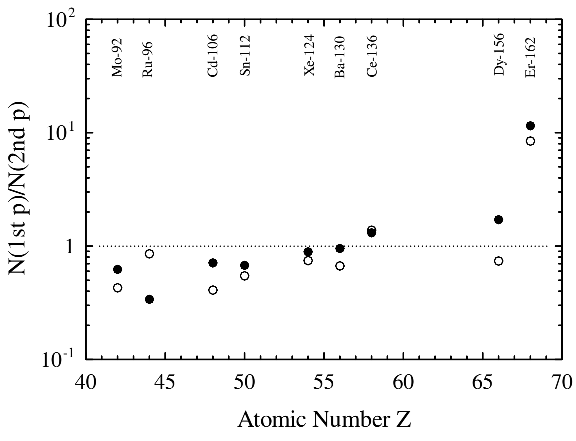

FIG. 2. Abundance ratios of two pure p nuclei, $N(1\text{st } p)/N(2\text{nd } p)$. The first and second p nuclei are, respectively, two and four neutron-deficient isotopes from s nucleus with the same atomic number Z. The filled circles mean the observed ratios in the solar system. The open circles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

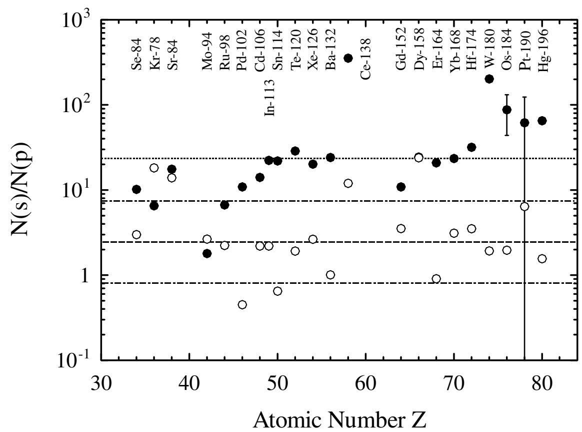

FIG. 3. Comparison of the calculated and observed abundance ratios, $N(s)/N(p)$. The filled and open circles mean the observed ratio in the solar system and the calculated ratios. The uppermost dotted line is $N(s)/N(p) = 23$. The dashed line displays the average value of the calculated $N(s)/N(p)$ ratios in the SN γ-process model, and the two dot-dashed lines above and below this line are those multiplied by factors of 3 and 1/3, respectively.

individual γ processes are universal and almost independent of the astrophysical conditions.

We carry out nucleosynthesis calculations of the γ process in oxygen-neon layers in SN explosions [20]. The purposes of the calculations are to check the robustness of our scaling rules in the solar system abundance and to demonstrate the dependence of the calculated ratios, $N(s)/N(p)$ and $N(1\text{st } p)/N(2\text{nd } p)$, on astrophysical conditions. We use a 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 an initial chemical composition are adopted. The calculated $N(s)/N(p)$ ratios are shown in Fig. 3 by open circles. They show almost constant abundance ratios in a wide region of the atomic number, although the calculated $N(s)/N(p)$ ratios show exceptional deviations. This result is consistent with the observed scaling. The observed ratios in the light mass region show a slight enhancement of the p nuclei, which may originate from progressively increasing roles of (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 the s nuclei in the solar system mainly originate from the asymptotic giant branch (AGB) stars [3]. In contrast, the relation, $N(1\text{st } p)/N(2\text{nd } p) \approx 1$, can be directly compared with the theoretical calculations of the SN γ process, and thus the second scaling rule can be used for constraining strongly the SN γ-process models. The calculated $N(1\text{st } p)/N(2\text{nd } p)$ ratios (open circles) in Fig. 2 are consistent with the empirical values (filled circles).

We further perform the γ-process nucleosynthesis calculations for the $15M_\odot$ and $40M_\odot$ progenitors to study the progenitor mass dependence. The abundance patterns of two ratios do not change drastically from those in the $25M_\odot$ models. This result indicates that the two ratios are almost independent of the progenitor mass of the massive stars. We calculate the γ process in the different metallicity ($Z = 0.05Z_\odot$) models with the same progenitor mass. The calculated results show that the ratios are almost constant and independent of the metallicity. These results support the proposed universality of the γ process. The calculated results in the previous γ-process studies were shown to compare directly with the solar system abundance of the p nuclei [14,15,19], not in the form of $N(s)/N(p)$ or $N(1\text{st } p)/N(2\text{nd } p)$ as we proposed in the Letter. The γ-process calculations for different models constructed with different explosion energies or the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate showed the similar abundance distributions [14,15]. These results also support the universality of the γ process. Although these results indicate that the p nuclei in the solar system are mainly produced by the γ process in type II SNe, other astrophysical sites such as deflagrating white dwarf stars [9] and supernova-driven supercritical accretion disks [10] may also contribute to the p nuclei. Overproduction factors of p 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 γ process in some other environments as another producer of the p nuclei. We presume that such γ processes should also reproduce the two scalings.

The universality of the SN γ process as presented by the scalings is an important concept for understanding the chemical evolution of the Galaxy. The s nuclei in the solar system were mainly produced by the s process in the low-mass AGB stars [3]. The average $N(s)/N(p)$ ratios are thus proportional to the abundance synthesized by the individual s process and the frequency of the formation of the AGB stars. The s process nucleosynthesis depends highly on the metallicity which increases along the evolution of the Galaxy [21,22]. This fact concerning the s nuclei and the universality of the p nuclei suggests that the $N(s)/N(p)$ ratios may depend on time. Astronomical observations of the time variation of these ratios for various metallicity stars should constrain the galactic chemical evolution of the s nuclei and also lead to new information of the metallicity dependence of the s process nucleosynthesis [23]. The recent progress in spectroscopic studies of extremely metal-poor stars has enabled successfully isotope separation of several heavy elements [24,25]. It is of particular interest to observe the ancient metal-poor stars whose material have been affected by the single or a few SN γ processes. Since the primitive gas is made of the 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 the p nuclei in metal-poor stars are thus expected to be 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 for future studies.

The universal scaling also plays a critical role in constructing a chronometer that can be applied to the analysis of presolar grains in primitive meteorites which have been affected strongly by a single or a few nucleosynthesis episodes. 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 are known [1,26,27]. Historically, a new cosmochronometer with a suitable half-life has not been proposed for the last 30 years. We here propose a new cosmochronometer ^{176}Lu (half-life 37.8 Gyr)-^{176}Hf-^{174}Hf of the γ process in the SN explosion. Although ^{146}Sm and ^{92}Nb have already been proposed as possible chronometers of the γ process [28,29], their half-lives are shorter than the age of the solar system. Therefore our proposed chronometer becomes a unique γ-process chronometer which has a suitable time scale of order of the cosmic age $\sim$10 Gyr.

A ^{176}Lu-^{176}Hf pair was previously proposed as an s-process chronometer [27]. It was pointed out to be a good thermometer but useless as the chronometer [30]. The initial abundance of the daughter nucleus, ^{176}Hf, is uncertain because the β^- decay through the ^{176}Lu isomer is accelerated at a typical s-process temperature. Our proposed chronometer of the SN γ process is completely free from this uncertainty. The initial abundance of ^{176}Hf is calculated from the present abundance of ^{174}Hf by applying the first scaling if the presolar grain is affected strongly by a single SN event. The first scaling indicates that the abundance of ^{174}Hf is proportional to ^{176}Hf. The passing time after the SN γ 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 $N(^AZ)$ means the isotope abundance, and R stands for the $N(s)/N(p)$ ratio in the scaling in meteorites, which should be systematically measured or predicted by γ-process calculations. Heavy elements such as Sr, Zr, Mo, and Ba in primitive material such as the presolar grains have already been successfully separated into isotopes including p nuclei, whose origin is considered to be the ejecta of core-collapse SN explosions [31,32]. Although the presolar 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 three isotopes, $^{174\,176}$Hf and ^{176}Lu, in the presolar grains is highly desirable.

In summary, we present two universal scaling laws concerning the p and s nuclei in the solar system abundance. They lead to three novel concepts: a piece of evidence that the SN γ process is the most probable origin of the p nuclei, universality that the abundance ratios $N(s)/N(p)$ of nuclei produced by individual SN γ processes are almost constant in a wide region of the atomic number, and a new nuclear cosmochronometer for the γ process. The scalings are useful for identifying the astrophysical sites of the p nuclei and limiting the contribution from other nuclear processes. We carry out typical type II SN γ-process calculations, and the results support the universality of the γ process. Therefore our proposals lead to new insights into the chemical evolution of the Galaxy as well as the SN γ process.

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[1] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. **29**, 548 (1957).
[2] P. A. Seeger, W. A. Fowler, and D. D. Clayton, Astrophys. J. Suppl. **11**, 121 (1965).
[3] R. Gallino *et al.*, Astrophys. J. **497**, 388 (1998).
[4] S. E. Woosley and W. M. Howard, Astrophys. J. Suppl. Ser. **36**, 285 (1978).
[5] H. Schatz *et al.*, Phys. Rep. **294**, 167 (1998).
[6] H. Schatz *et al.*, Phys. Rev. Lett. **86**, 3471 (2001).
[7] J. Audouze, Astron. Astrophys. **8**, 436 (1970).
[8] M. Arnould, Astron. Astrophys. **46**, 117 (1976).
[9] W. M. Howard, B. S. Meyer, and S. E. Woosley, Astrophys. J. **373**, L5 (1991).
[10] S. Fujimoto *et al.*, Astrophys. J. **585**, 418 (2003).
[11] S. E. Woosley, D. H. Hartmann, R. D. Hoffman, and W. C. Haxton, Astrophys. J. **356**, 272 (1990).
[12] R. D. Hoffman, S. E. Woosley, G. M. Fuller, and B. S. Meyer, Astrophys. J. **460**, 478 (1996).
[13] S. Goriely, M. Arnould, I. Borzov, and M. Rayet, Astron. Astrophys. **375**, L35 (2001).
[14] N. Prantzos, M. Hashimoto, M. Rayet, and M. Arnould, Astron. Astrophys. **238**, 455 (1990).
[15] M. Rayet *et al.*, Astron. Astrophys. **298**, 517 (1995).
[16] P. De Bievre and P. D. P. Taylor, Int. J. Mass Spectrom. Ion Processes **123**, 149 (1993).
[17] K. Takahashi and K. Yokoi, Nucl. Phys. **A404**, 578 (1983).
[18] M. Jung *et al.*, Phys. Rev. Lett. **69**, 2164 (1992).
[19] H. Utsunomiya *et al.*, Phys. Rev. C **67**, 015807 (2003).
[20] N. Iwamoto, H. Umeda, and K. Nomoto, in Proceedings of the International Symposium on Origin of Matter and Evolution of Galaxies (World Scientific, Singapore, to be published).
[21] C. M. Raiteri, R. Gallino, and M. Busso, Astrophys. J. **387**, 263 (1992).
[22] M. Busso, R. Gallino, and C. J. Wasserburg, Annu. Rev. Astron. Astrophys. **37**, 239 (1999).
[23] W. Aoki *et al.*, Astrophys. J. **580**, 1149 (2002).
[24] D. L. Lambert and C. A. Prieto, Mon. Not. R. Astron. Soc. **335**, 325 (2002).
[25] W. Aoki *et al.*, Astrophys. J. **592**, L67 (2003).
[26] D. D. Clayton, Astrophys. J. **139**, 637 (1964).
[27] J. Audouze, W. A. Fowler, and D. N. Schramm, Nature Phys. Sci. **238**, 8 (1972).
[28] J. Audouze and D. N. Schramm, Nature (London) **237**, 447 (1972).
[29] C. L. Jr. Harper, Astrophys. J. **466**, 437 (1996).
[30] H. Beer, F. Käppeler, K. Wisshak, and R. A. Ward, Astrophys. J. Suppl. Ser. **46**, 295 (1981).
[31] M. J. Pellin *et al.*, Lunar Planet. Sci. **31**, 1917 (2000).
[32] Q. Yin, S. B. Jacobsen, and K. Yamashita, Nature (London) **415**, 881 (2002).