Neutron capture nucleosynthesis in the universe

Masayuki Igashira*, Toshiro Ohsaki

Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152 8550, Japan

Received 7 December 2003; revised 1 March 2004; accepted 17 March 2004

Available online 18 October 2004

Abstract

First, the nucleosynthesis in the universe was reviewed. In particular, the neutron capture nucleosyntheses in the Big-Bang and the s- and r-processes were reviewed in detail. It was pointed out that keV-neutron capture cross sections were important for the study on the neutron capture nucleosynthesis. Second, our measurement of keV-neutron capture cross sections was explained briefly, and the results on \(^{7}\)Li, \(^{12}\)C, and \(^{16}\)O were shown and compared with previous experimental values and the predicted values from the \(1/\nu\) law and the thermal neutron capture cross sections. The results at 30 keV on \(^{12}\)C and \(^{16}\)O were much larger than the \(1/\nu\) predictions, while the result at 30 keV on \(^{7}\)Li was in good agreement with the \(1/\nu\) prediction. The large values for \(^{12}\)C and \(^{16}\)O were ascribed to the non-resonant p-wave neutron capture from the analysis of observed capture \(\gamma\)-ray spectra and the neutron energy dependence of derived partial capture cross sections. As for \(^{7}\)Li, the good agreement was ascribed to the peculiarity of bound states of its residual nucleus, which strongly suppresses the non-resonant p-wave neutron capture. Finally, it was shown that the non-resonant p-wave neutron capture is predominant in the neutron capture nucleosynthesis of light nuclei in the universe.

\(\textcopyright\ 2004\) Elsevier Ltd. All rights reserved.

Keywords: Nucleosynthesis; Universe; keV-neutron capture; Cross sections; Gamma-ray spectra; Non-resonant capture; Electric dipole transition; s-Wave neutrons; p-Wave neutrons

1. Introduction

All elements making the earth were synthesized in the universe before the formation of the solar system. Many researchers are studying this nucleosynthesis in the universe from the scientific viewpoint: the understanding of the evolution of the universe. On the other hand, this nucleosynthesis can be regarded as a femtotechnology employed by God or Nature. Therefore, it is also interesting to study the nucleosynthesis from the viewpoint of femtotechnology.

The present paper is composed of three parts. The first is the review of nucleosynthesis in the universe. In particular, the review of the neutron capture nucleosynthesis in the Big-Bang and in the s- and r-processes is given in detail. The second is the explanation of our neutron capture cross section measurement, and our results on some important light nuclei such as \(^{7}\)Li, \(^{12}\)C and \(^{16}\)O are shown and compared with previous experimental results and predicted values. The last part is the interpretation of the mechanism of keV-neutron capture reaction by light nuclei, and the predominance of the non-resonant p-wave neutron capture is shown from the detailed analysis of our experimental data.

2. Nucleosynthesis in the universe [1]

2.1. Solar-system abundances and nucleosynthesis

The solar-system abundances are shown in Fig. 1, where the abundance of Si is normalized to \(10^{6}\). From the figure, some characteristics are seen. First, the abundances of H and He are very large. In fact, the sum of both abundances is about 99%. These elements were produced in the Big-Bang nucleosynthesis and in the hydrogen burning of stars. Second, those of Li, Be and B are very small. Third, the peaks of four-N nuclei exist. These four-N nuclei such as
C and O were produced from the fusion of He in stars. Fourth, a strong peak exists around Fe. The binding energy per nucleon has the maximum around Fe. In other words, nuclei around Fe are most stable. Therefore, the abundance also has a maximum around Fe. Fifth, a shoulder or peak exists at the neutron magic number of 50, 82, or 126 and a peak exists below the neutron magic number of 82 or 126. Sixth, there are no nuclei above Bi except for Th and U, because the half-lives of other nuclei heavier than Bi are too short compared to the age of solar system. Nuclei heavier than Fe were synthesized by the s- and/or r-processes that are neutron capture reaction processes.

2.2. Big-Bang nucleosynthesis

The universe began from the Big Bang about $1.4 \times 10^{10}$ y before. Neutrons and protons appeared after about 1 µs from the Big Bang. The first nucleosynthesis in the universe took place in the period from 10 to 1000 s after the Big Bang. The temperature ($kT$) of the universe ranged from about 100 to 10 keV. Until 10 s from the Big Bang, the temperature was too high to synthesize nuclei. In other words, the temperature was high enough to break the bonding of the lightest composite nucleus, $^2$H. After 1000 s, all neutrons decayed to protons because of its half-life of about 600 s, and the temperature of the universe became low compared to Coulomb barriers for charged-particle reactions.

In the standard Big-Bang model, the densities of protons and neutrons are assumed to be uniform. On the other hand, the inhomogeneous Big-Bang model assumes two types of spatial regions. One is high-density and proton-rich regions, and the other is low-density and neutron-rich regions.

The Big-Bang nucleosynthesis proceeded in the following main sequence:

\[
^1\text{H}(n, \gamma)^2\text{H}(n, \gamma)^3\text{H}(d, n)^3\text{He}(t, \gamma)^7\text{Li}(n, \gamma)^8\text{Li}\ldots \tag{1}
\]

In the standard model, the nucleosynthesis terminates at $^7$Li, because $^4$Li with the half-life of about 1 s $\beta$-decays to $^8$Be that decays to two $\alpha$ particles immediately. There is no stable nucleus with $A=8$, and it is called the $A=8$ gap. On the other hand, in the inhomogeneous model, the nucleosynthesis can across the $A=8$ gap and proceeds up to $A=30$ by neutron capture reaction in the low-density and neutron-rich regions. A main sequence is as follows:

\[
^8\text{Li}(\alpha, n)^11\text{B}(n, \gamma)^12\text{C}(\beta^-)^12\text{C}(n, \gamma)^13\text{C}(n, \gamma)^14\text{C}(n, \gamma)
\]

\[
15\text{C}(\beta^-)^15\text{N}(n, \gamma)^16\text{O}(n, \gamma)^17\text{O}\ldots \tag{2}
\]

As shown in the reaction sequences Eqs. (1) and (2), the neutron capture reaction of light nuclei is important for the study on the Big-Bang nucleosynthesis. The related neutron energy range is 10–100 keV. The cross sections of the under-lined reactions are described in the next chapter.

2.3. Nucleosynthesis in stars

The second nucleosynthesis in the universe took place in the evolution of primordial stars formed after about $1 \times 10^8$ y from the Big Bang. The first stage of evolution is the H burning, where $^3$He is produced from four $^1$H nuclei. Stars in this stage are called main-sequence stars, and the sun is also a main-sequence star. The second stage is the He burning. However, light stars with masses less than half of the solar mass cannot ignite He and become white dwarves. In the He burning, $^{12}$C is produced from the fusion of three $^4$He nuclei, and $^{16}$O is produced by the fusion of $^{12}$C and $^4$He. Heavy stars with masses four times larger than the solar mass can proceed in the C burning stage. The sun will become a white dwarf. The fusion nucleosynthesis in stars stops at Fe, because fusion reactions beyond Fe are endothermic reactions.

The death of massive stars is the supernova explosion which causes an explosive nucleosynthesis up to $A=350$. This nucleosynthesis is regarded as an r-process. All synthesized nuclei are dispersed in the universe by the supernova explosion. Second-generation stars contain a small amount of these dispersed heavy nuclei, so the s-process nucleosynthesis takes place at the helium burning stage of massive second-generation stars.

The s-process is the abbreviation of the slow neutron-capture process, and the r-process is that of the rapid neutron-capture process. ‘Slow’ or ‘rapid’ means that the neutron capture rate is slow or rapid compared to the $\beta$-decay rate, respectively. The s- and r-process paths are shown in Fig. 2. The solar-system nuclei are also shown in Fig. 2. The s-process path lies in the region of the solar-system nuclei. In other words, it is along the $\beta$-stability line. On the other hand, the r-process path is close to the neutron drip line. After the r-process nucleosynthesis, synthesized nuclei immediately $\beta$-decay toward stable nuclei. As described above, the s-process takes place in the He burning stage of massive second-generation stars. The other

![Fig. 1. Solar-system abundances vs. mass number (A); ‘r’ or ‘s’ means that the corresponding peaks or shoulder are caused by the r- or s-process nuclei, respectively.](image-url)
s-process site is the He-shell burning stage of asymptotic giant branch (second-generation) stars. The neutron poisoning effect of $^{12}$C and $^{16}$O is important for the study on the s-process, because they are abundant in the He or He-shell burning stage. It is worth noting that the neutron sources in the s-process are the $^{13}$C($\alpha$,n)$^{16}$O and $^{22}$Ne($\alpha$,n)$^{25}$Mg reactions.

2.4. Conditions of neutron capture nucleosyntheses

Table 1 summarizes the conditions of neutron capture nucleosyntheses in the Big-Bang and the s- and r-processes. The temperatures are almost same: 8–200 keV. Therefore, the neutron capture cross sections in this energy region, especially around 30 keV [1], are very important for the study on the nucleosynthesis in the universe. The Big-Bang process synthesized light nuclei: the standard model predicts nucleosynthesis up to $A = 7$, while the inhomogeneous model predicts that up to $A = 30$. The essential difference between the s- and r-processes is the neutron densities. The r-process synthesized almost all nuclei due to its very high neutron density, while the s-process synthesized nuclei up to $^{209}$Bi along the $\beta$-stability line due to its low neutron density. The time scale of the Big-Bang nucleosynthesis is subject to the half-life of neutron. That of the s-process is determined by the period of the He or He-shell burning, which depends on the mass of star. The time scale of the r-process is the order of seconds, which means the explosive nucleosynthesis.

Table 1

| Process       | $kT$ (keV) | Neutron density (n/cm$^3$) | Synthesized nuclei | Time scale            |
|---------------|------------|---------------------------|--------------------|-----------------------|
| Big-Bang      | 10–200     |                           | $A = 1–7$ or 30    | Min                   |
| s-process     | 8–80       | $10^8$                    | $A = 56–209$       | $10^7–10^8$ y         |
| r-process     | 100        | $10^{24}$                 | Almost all         | S                     |

Fig. 2. Paths of s- and r-processes; boxes near the s-process path show solar-system nuclei.

Fig. 3. Typical experimental arrangement at Tokyo Institute of Technology.

3. Neutron-capture cross-section measurement

As described above, neutron capture cross sections in the keV region are very important for the study on the nucleosynthesis in the universe, so we are measuring them for important nuclei from $^1$H to $^{209}$Bi. The present paper briefly reviews our measurements [2–4] and shows the results on $^7$Li, $^{12}$C, and $^{16}$O. Those nuclei play important roles both in the Big-Bang nucleosynthesis and in the s-process, as described above.

A typical experimental arrangement is shown in Fig. 3. Pulsed keV neutrons were produced by the $^7$Li(p,n)$^7$Be reaction with a 1.5-ns bunched proton beam from the 3-MV Pelletron accelerator of the Research Laboratory for Nuclear Reactors at the Tokyo Institute of Technology. The incident neutron spectrum on a capture sample was measured by means of a time-of-flight (TOF) method with a $^6$Li-glass scintillation detector. Capture $\gamma$ rays from the sample were measured with a large anti-Compton NaI(Tl) spectrometer placed in a heavy shield against background $\gamma$ rays and neutrons. The signals from the spectrometer were stored in a workstation as two-dimensional data of TOF and pulse height (PH). A $^{197}$Au sample was employed as a standard.

The capture $\gamma$-ray PH spectra for the sample and the standard $^{197}$Au sample were extracted from the two-dimensional data obtained with the $^6$Li-glass spectrometer. Then, the capture yields, i.e. the numbers of capture events, of both samples were obtained by applying a PH weighting technique to the PH spectra. Finally, the capture cross sections of the objective nucleus were derived from the capture yields, the neutron data obtained with the $^6$Li-glass detector, and the standard capture cross sections of $^{197}$Au.
The derived neutron capture cross sections \cite{2,4} of $^{12}$C and $^{16}$O are shown in Figs. 4 and 5, respectively. As for $^{12}$C, there were two experimental data previously: 200 ± 400 μb at 30 keV by Gibbons et al. \cite{5} and an upper limit of 14 μb at 30 keV by Macklin \cite{6}. On the other hand, an extrapolation with the 1/\textit{v} law \cite{7} and the capture cross section \cite{8} at the thermal energy (0.025 eV) gave about 3 μb at 30 keV, where \textit{v} is the velocity of incident neutron in the center of mass system. In these circumstances, our result at 30 keV was about 12 μb, as shown in Fig. 4: our result was about four times larger than the extrapolation at 30 keV. In the case of $^{16}$O in Fig. 5, our result at 30 keV was about 20 μb: 100 times larger than the experimental result, 0.2 ± 0.1 μb, by Allen and Macklin \cite{9} and the 1/\textit{v} extrapolation with the thermal neutron cross section \cite{10}.

There was a puzzle related to the neutron capture cross section of $^7$Li: both the 1/\textit{v} extrapolation and a sophisticated calculation predicted 40 μb at 30 keV, though the latest experimental result \cite{11} was 21.0 ± 1.9 μb. Of course there were old data which were consistent with the theoretical prediction: these \cite{12} were 59 ± 11.8 and 39.5 ± 7.9 μb. In these circumstances, our result \cite{3} was 39.8 ± 6.0 μb: the puzzle was solved. Our result denied the latest measurement and supported one of old data.

As shown in Figs. 4 and 5, the neutron-energy dependence of our results on $^{12}$C and $^{16}$O is much different from the 1/\textit{v} law. On the contrary, our result at 30 keV on $^7$Li is in good agreement with the 1/\textit{v} extrapolation. The reasons are explained in the next chapter.

4. Mechanism of keV-neutron capture by light nuclei

4.1. Non-resonant neutron capture reaction \cite{13}

Since $^7$Li, $^{12}$C, and $^{16}$O have no neutron resonance below 200 keV, the non-resonant capture, i.e. the direct capture \cite{13}, is predominant in the neutron capture reaction below 200 keV for these light nuclei. Therefore, expanding the incident neutron plane wave with incoming spherical waves with orbital angular momenta (\textit{l}), the energy dependence of the \textit{l}-wave neutron capture cross section of these nuclei is expressed as follows \cite{7,13}:

$$\sigma(\textit{l}, E) \propto E^{2\textit{l}-1}v^{2l-1},$$

(3)

where \textit{E} is the incident neutron energy in the center of mass system. The capture cross section is given by the sum of these partial cross sections. As seen from Eq. (3), the 1/\textit{v} law is the result of the s-wave (\textit{l}=0) neutron capture. On the other hand, as seen from Eq. (3), the partial cross section for the second (\textit{l}=1) wave, i.e. p-wave, obeys the \textit{v} law. Therefore, the p-wave neutron capture should become important in a high-energy region.

In the direct neutron capture, the electric dipole (E1) transition is predominant because the effective charges of neutron for other transitions are very small compared to that for the E1 transition. In the case of single-particle E1 transition, the change of \textit{l} of the initial and final single particle states is one: the final state of the s-wave neutron capture is the p-orbit neutron state and those of the p-wave neutron capture are the s- and d-orbit neutron states.

4.2. Detailed analysis of neutron capture data

In our measurement for light nuclei, the final states of transitions could be assigned from the observed capture γ-ray spectra. The observed transitions for $^{12}$C and $^{16}$O are shown in Figs. 6 and 7, respectively. In both figures, the right parts show our results at an average energy of 40 keV, and the left ones show those \cite{8,10} at thermal energy.

In the case of $^{12}$C in Fig. 6, the transition to the s-orbit neutron state at 3.089 MeV is predominant in the 40-keV neutron capture, which means the p-wave
neutron capture on the assumption of E1 transition, while the transition to the p-orbit neutron state at 0 MeV is predominant in the thermal neutron capture. The partial cross sections corresponding to both transitions were derived up to 550 keV and are shown in Fig. 8, where the 1/\(v\) and \(v\) laws are also shown. The cross sections corresponding to the transition to the 3.089-MeV state (1st) well obey the \(v\) law, which confirms the p-wave neutron capture. On the other hand, the cross sections below 100 keV corresponding to the transition to the 0-MeV state (gnd) are in good agreement with the extrapolation with the 1/\(v\) law and the thermal cross section [8]. The deviations at 200 and 550 keV from the 1/\(v\) law must be due to the contribution of d-wave neutron capture. Assuming the s- and p-wave neutron capture for \(^{12}\text{C}\), a cross section curve was fitted to our data and the thermal data. The fitted curve is shown in Fig. 4. The first and second terms of the fitted curve represent the s- and p-wave neutron capture contributions, respectively. The p-wave neutron capture is predominant in the energy region relevant to the nucleosynthesis in the universe, as shown in Fig. 4.

In the case of \(^{16}\text{O}\) in Fig. 7, the transition to the p-orbit state at 3.055 MeV is predominant in the thermal capture. It is the E1 transition, but its intensity is weak because the intensity of dipole transition is proportional to \(E_\gamma^3\), where \(E_\gamma\) is the \(\gamma\)-ray energy. In the thermal neutron capture, the transition to the s-orbit state at 0.871 MeV is the magnetic dipole (M1) transition and its intensity is considerably weak compared to the E1 transition to the 3.055-MeV state due to the small effective charge of M1 transition although the energy of the M1 transition is about three times larger than that of the E1 transition. These are the reasons why the capture

Fig. 6. Observed \(\gamma\)-ray transitions in the neutron capture reaction of \(^{12}\text{C}\).

Fig. 7. Observed \(\gamma\)-ray transitions in the neutron capture reaction of \(^{16}\text{O}\).
cross section of $^{16}$O is so small at the thermal energy. In the 40-keV neutron capture, the observed transition to the d-orbit state at 0 MeV is due to the p-wave neutron capture. As for the transition to the s-orbit state at 0.871 MeV in the 40-keV neutron capture, its intensity is about three times larger than that of the E1 transition to the ground state. Therefore, most of its intensity is due to the E1 transition from the p-wave neutron capture instead of the M1 transition in the thermal neutron capture. It is worth noting that the transition to the p-orbit state at 3.055 MeV that is the main transition in the thermal neutron capture was not observed in the keV-neutron capture region because its intensity was weaker than the $\gamma$-ray detection sensitivity in our measurement. A cross section curve was fitted to our data and the thermal data [10], as was in the case of $^{13}$C. The fitted curve is shown in Fig. 5. The p-wave capture is completely predominant in the keV-neutron capture by $^{16}$O.

As for $^7$Li, its residual nucleus has only two bound states: the ground state and the 0.981 MeV state. Moreover, both are p-orbit states. Therefore, the p-wave neutron direct capture by $^7$Li is strongly suppressed, while there is no restriction on the s-wave neutron capture. This is the reason why the cross section of $^7$Li obeys the $1/\nu$ law below 200 keV. It is worth noting that the first resonance [10] at 255 keV of $^7$Li is a p-wave resonance but is an M1 resonance.

4.3. Predominance of the non-resonant p-wave neutron capture by light nuclei

In general the non-resonant capture is predominant in the neutron capture reaction by light nuclei in the energy region relevant to the nucleosynthesis in the universe. Moreover, most of their residual nuclei have s- and/or d-orbit neutron states. Therefore, one could predict the possibility that the p-wave neutron capture becomes important in this energy region. However, the $1/\nu$ law derived from the s-wave neutron capture has been adopted because of no experimental evidence. As described above, our measurement has provided the clear evidence that the non-resonant p-wave neutron capture is generally predominant in the keV-neutron capture by light nuclei.

5. Summary

The nucleosynthesis in the universe, especially the neutron capture nucleosynthesis, was reviewed. It was pointed out that keV-neutron capture cross sections were important for the study on the neutron capture nucleosynthesis. Then, our results on $^7$Li, $^{12}$C, and $^{16}$O were shown and compared with previous experimental values and the predicted values from the $1/\nu$ law and the thermal neutron capture cross sections. The results around 30 keV on $^{12}$C and $^{16}$O were much larger than the $1/\nu$ predictions, while the result around 30 keV on $^7$Li was in good agreement with the $1/\nu$ prediction. The large values for $^{12}$C and $^{16}$O were ascribed to the non-resonant p-wave neutron capture from the detail analysis of our experimental data. As for $^7$Li, the good agreement was explained by the peculiarity of bound states of its residual nucleus. Finally, it was shown that the non-resonant p-wave neutron capture is generally predominant in the neutron capture nucleosynthesis of light nuclei in the universe.

References

[1] (a) D.D. Clayton, Principles of Stellar Evolution and Nucleosynthesis, The University of Chicago Press, Chicago, 1983;
(b) B.E.J. Pagel, Nucleosynthesis and Chemical Evolution of Galaxies, Cambridge University Press, UK, 1997.
[2] (a) Y. Nagai, et al., Measurement of the neutron capture rate of the $^{12}$C(n,$\gamma$)$^{13}$C reaction at stellar energy, Astrophys. J. 372 (1991) 683–687;
(b) T. Ohsaki, et al., New measurement of the $^{12}$C(n,$\gamma$)$^{13}$C reaction cross section, Astrophys. J. 422 (1994) 912–916;
(c) T. Kikuchi, et al., Nonresonant direct p- and d-wave neutron capture by $^{12}$C, Phys. Rev. C 57 (1998) 2724–2730.
[3] Y. Nagai, et al., Capture rate of the $^7$Li(n,$\gamma$)$^8$Li reaction by prompt gamma-ray detection, Astrophys. J. 381 (1991) 444–448.
[4] M. Igashira, et al., Measurement of the $^{16}$O(n,$\gamma$)$^{17}$O reaction cross section at stellar energy and the critical role of nonresonant p-wave neutron capture, Astrophys. J. 441 (1995) L89–L92.
[5] J.H. Gibbons, et al., Average radiative capture cross sections for 7- to 170-keV neutrons, Phys. Rev. 122 (1961) 182–201.
[6] R.L. Macklin, Neutron capture by $^{12}$C at stellar temperatures, Astrophys. J. 357 (1990) 649–652.
[7] J.M. Blatt, V.F. Weisskopf, Theoretical Nuclear Physics, Wiley, New York, 1952.
[8] M.A. Lone, Thermal-neutron-capture cross section measurements, in: T. von Egidy, F. Gonnenwein, B. Maier (Eds.), Proceedings of the Fourth International Symposium on Neutron-Capture Gamma-Ray Spectroscopy and Related Topics, Institute of Physics Conference Series No. 62, Institute of Physics, Bristol, UK (1981), pp. 383–392.
[9] B.J. Allen, R.L. Macklin, Neutron capture cross sections of $^{13}$C and $^{16}$O, Phys. Rev. C 3 (1971) 1737–1740.

[10] (a) A.B. McDonald, et al., Doubly radiative thermal neutron capture in $^7$H and $^{16}$O: Experiment and study, Nucl. Phys. A281 (1977) 325–344; (b) S.F. Mughabghab, et al., Neutron Cross Sections, Vol. 1, Part A, Academic Press, New York, 1981.

[11] M. Wiescher, et al., $^7$Li(n,$\gamma$)$^8$Li-trigger reaction to a primordial r-process?, Astrophys. J. 344 (1989) 464–470.

[12] W.L. Imhof, et al., Cross sections for the $^7$Li(n,$\gamma$)$^8$Li reaction, Phys. Rev. 114 (1959) 1037–1039.

[13] (a) A.M. Lane, J.E. Lynn, Theory of radiative capture in the resonance region, Nucl. Phys. 17 (1960) 563–585; (b) A.M. Lane, J.E. Lynn, Anomalous radiative capture in the neutron resonance region: analysis of the experimental data on electric dipole transitions, Nucl. Phys. 17 (1960) 586–608.