Neutron Capture Cross Sections in the keV Region

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Neutron capture cross sections in the keV region are reviewed on the basis of our measurements for about 40 nuclides from ^{1}H to ^{237}Np. It is shown that the p-wave neutron plays a very important role in the non-resonant capture reaction by some light nuclides at stellar energy and that careful measurements for medium and heavy nuclides agree with each other at least within uncertainties of about 10 %.

1. Introduction

Neutron capture reaction plays an important role in the nucleosynthesis in the primordial univers 10 to 1,000 s after the big bang and in stars. A thermonuclear reaction rate is given by a Maxwellian average as a function of temperature *T* as follows:

$$N_A < \sigma v >= N_A \frac{2}{\sqrt{\pi}} \sqrt{\frac{2kT}{\mu}} \frac{\int_0^\infty \sigma(E) E e^{-E/kT} dE}{\int_0^\infty E e^{-E/kT} dE}, \tag{1}$$

where v and E are the velocity and energy of neutron in the center of mass system, respectively, N_A is the Avogadro's number, σ the capture cross section, k the Boltzmann's constant, and μ the reduced mass. In case of non-resonant neutron capture, the reaction rate is usually expanded as follows:

$$N_A < \sigma v >= A + BT_9^{1/2} + CT_9 + \cdots, \quad (T_9 = T / 10^9 {}^\circ K), \tag{2}$$

where the first and third terms in the right-hand side mean the s- and p-wave neutron capture contributions, respectively. In case of general capture, more complicated expansions are used. Then, the expansion coefficients are evaluated from nuclear databases such as JENDL-3.2 for studies on nucleosynthesis. Since the value of kT is around 30 keV, accurate capture cross sections in the keV region are necessary for the determination of coefficients.

This paper reviews the present status of keV-neutron capture cross sections on the basis of our measurements for about 40 nuclides from ^{1}H to ^{237}Np.

2. General view of 30-keV Maxwellian averaged cross sections

Maxwellian (kT=30 keV) averaged capture cross sections are shown in Fig. 1 which are calculated from the data of JENDL-3.2[1]. The cross sections range from 10^{-3} to 10^{4} mb except for the extremely small value of ^{15}N. The general characteristics are the increase with mass number(A) and the saturation around A = 100. Moreover, the dips around A = 90, 140, and 210 are clearly observed which correspond to the neutron magic numbers of 50, 82, and 126. The cross section of ^{15}N should be two or three orders as large as the extremely small value by reason of p-wave neutron capture contribution described below.

3. Cross sections of light nuclides

As seen from Fig. 1, the capture cross sections of light nuclides(A<18) are very small(< 1 mb), so the measurement has been difficult without an activation method. For example, the cross section of ^{12}C, to which an activation method is inapplicable, was measured as 0.2 ± 0.4 mb[2] at 30 keV, but the cross sections of ^{7}Li were measured with errors of about 20 % in the keV region with an activation method[3].

On the other hand, thermal neutron capture cross sections have been measured for almost all stable nuclides, and the 1/v law is well-known for the s-wave neutron capture cross section. Therefore, the cross sections in the keV region of light nuclides such as ^{12}C and ^{16}O have been ordinarily evaluated using the 1/v law and the thermal neutron capture cross sections. The evaluated values of ^{12}C and ^{16}O are 3.2 and 0.17 μb at 30 keV, respectively.

Our group has measured the capture cross sections of ^{7}Li, ^{12}C, and ^{16}O in the keV region[4-9], and the measured values at 30 keV are 39.3 ± 6.0, 15.4 ± 1.0, and 34 ± 4 μb, respectively. The value of ^{7}Li is in good agreement with the previous measurement[3] and the evaluation, 41 μb, from the 1/v law and the thermal neutron capture cross section. However, our results of ^{12}C and ^{16}O are 5 and 200 times as large as the evaluations, respectively.

We have adopted a prompt γ-ray detection method with an anti-Compton NaI(Tl) spectrometer, and observed the branching ratios of neutron capture states. The observed ratios for the ^{12}C and ^{16}O target nuclei are shown in Figs. 2 and 3, respectively, together with the ratios of the thermal neutron capture states. The striking feature of 30- or 40-keV neutron capture is the strong transitions to the s- and d-states, which implies the predominance of p-wave neutron capture because the electric dipole(E1) transition is predominant in the non-resonant neutron capture. In case of thermal neutron capture, the strong E1 transitions to the p-states are observed. As for ^{7}Li, the ratios of 30-keV neutron capture states are the same as those of thermal neutron capture states[4,10].

We have also obtained the partial capture cross sections of ^{12}C[5-7] corresponding to the branching ratios, and those to the ground and first excited states of ^{13}C are shown in Fig. 4. The solid line shows the 1/v law normalized to the partial capture cross section at thermal energy. Our results for the ground state below 100 keV are well explained by the 1/v law, but our results at 200 and 550 keV exceed the 1/v law. This excess should be ascribed to the d-wave neutron capture contribution. The dotted line shows a fitting of the v law, which is expected for the p-wave neutron capture, to our results for the first excited state. Our results strongly support the v law, i.e., the p-wave neutron capture.

Figure 5 shows the bound states of relevant compound nuclei. The states are categorized into three groups by the spin and parity selection rule: Those with a solid line could be populated by the E1 transition from the states formed by the p-wave neutron capture, those with a dashed line could be populated by the E1 transition from the states formed by the s-wave neutron capture, and the others are indicated by dotted lines. The p-wave neutron capture would become important in the keV region for the target nuclei whose compound nuclei have solid line states, while the s-wave neutron capture would be still predominant for the target nuclei whose compound nuclei have no solid-line states. As for ^{15}N, its compound nucleus has only solid line states, so a large contribution of p-wave neutron capture would be expected for the keV-neutron capture. In fact, its capture cross section calculated on the basis of a direct neutron capture model is about 10 μb at 30 keV[11], which is about 500 times as large as that evaluated from the 1/v law and the thermal neutron capture cross section.

4. Cross sections of medium and heavy nuclides

The capture cross sections of medium and heavy nuclides are considerably large compared with those of light nuclides, as shown in Fig. 1, except for some nuclides near the neutron magic numbers. Therefore, if an enough amount of chemically and isotopically purified sample is prepared, the capture cross sections of those nuclides could be measured with a prompt γ -ray detection method which is applicable to all target nuclides.

The capture cross sections of ^{147}Sm, ^{163}Dy, and ^{237}Np are shown in Figs. 6 - 8. The large values of Kononov et al.[12] and Mizumoto[13] in Fig. 6 could be ascribed to the influence of the water in their oxide powder samples[14]. Our results of ^{147}Sm are in good agreement with the measurements by Macklin[15] and Wisshak et al.[16] and the evaluations of ENDF/B-VI[17]. As for ^{163}Dy, all the measurements[18-20] well agree with each other. The evaluation of ^{163}Dy for ENDF/B was done many years ago[21], and does not reproduce the measurements. There has existed a large discrepancy between the measurements for ^{237}Np by Hoffman et al.[22] and Weston and Todd[23], as shown in Fig. 8. Our results completely support those of Weston and Todd. Individual laboratories have adopted their own experimental technique. Therefore, the good agreement seen in Figs. 6- 8 implies the reliability of their data, although there still exists detailed discussion about accuracy within 5 - 10 %.

5. Conclusion

The 30-keV Maxwellian averaged capture cross sections range from 10^{-3} to 10^{4} mb. The cross sections increase with mass number(A), and are saturated around A = 100. There exist the dips around A = 90, 140, and 210 which correspond to the neutron magic numbers of 50, 82, and 126.

The p-wave neutron plays a very important role in the non-resonant capture reaction by some light nuclides at stellar energy. Careful measurements for medium and heavy nuclides agree with each other at least within uncertainties of about 10 %.

References

[1] Nakagawa T. et al.: J. Nucl. Sci. Technol., **32**, 1259 (1995).
[2] Macklin R. L. et al.: Phys. Rev., **129**, 2695 (1963).
[3] Imhof E. L. et al.: Phys. Rev., **114**, 1037 (1959).
[4] Nagai Y. et al.: ApJ., **381**, 444 (1991).
[5] Nagai Y. et al.: ApJ., **372**, 683 (1991).
[6] Ohsaki et al.: ApJ., **422**, 912 (1994).
[7] Kikuchi T. et al.: Phys. Rev. C, **57**, 2724 (1998).
[8] Igashira M. et al.: Nucl. Phys., **A536**, 285 (1992).
[9] Igashira M. et al.: ApJ., **441**, L89 (1995).
[10] Nagai Y. et al.: unpublished.
[11] Rauscher T. et al.: ApJ., **429**, 499 (1994).
[12] Kononov V. N. et al.: Sov. J. Nucl. Phys., **26**, 500 (1977).
[13] Mizumoto M.: Nucl. Phys., **A357**, 90 (1981).
[14] Mizumoto M. and Sugimoto M.: Nucl. Instr. and Meth., **A282**, 324 (1989).
[15] Macklin R. L.: Reports EXFOR 12966.003 (1986).
[16] Wisshak K. et al.: Phys. Rev. C, **48**, 1401 (1993).
[17] ENDF/B-VI data file for ^{147}Sm (MAT=6234), evaluated by R.Q.Wright, R.E.Schenter, F.M.Mann and A.Prince (1989).
[18] Beer H. et al.: Reports EXFOR 12881.002 (1984).
[19] Bokhovko M. V. et al.: Yadernie Const., **4**, 8 (1988).
[20] Voss F. et al.: Report FZKA-6104, Forschungszentrum Karlsruhe (1998).
[21] ENDF/B-VI data file for ^{163}Dy (MAT=6646), evaluated by R. F. Schenter and F. Schmittroth (1974).
[22] Hoffman M. et al.: Bull. Am. Phys. Soc., **21**, 655(JE3) (1976).
[23] Weston L. W. and Todd J. T.: Nucl. Sci. Eng., **79**, 184 (1981).

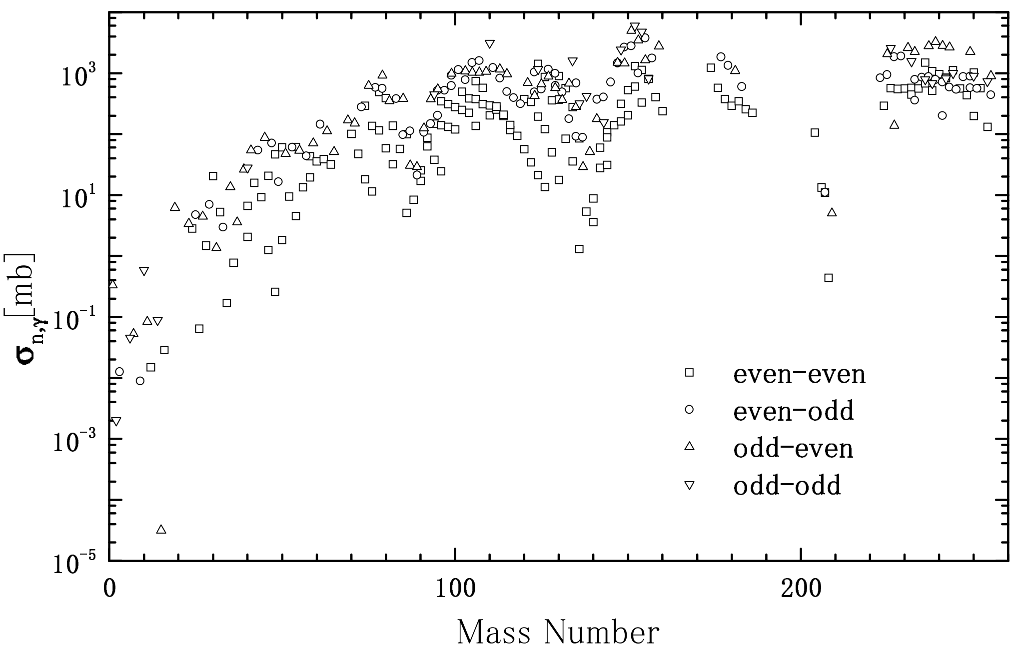

Fig.1. Maxwellian (kT=30keV) averaged neutron capture cross sections calculated from the data of JENDL-3.2.

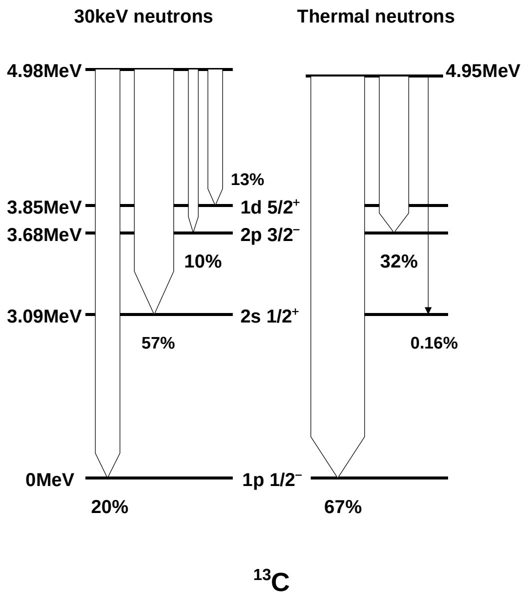

Fig.2. Branching ratios of neutron capture states of ^{13}C

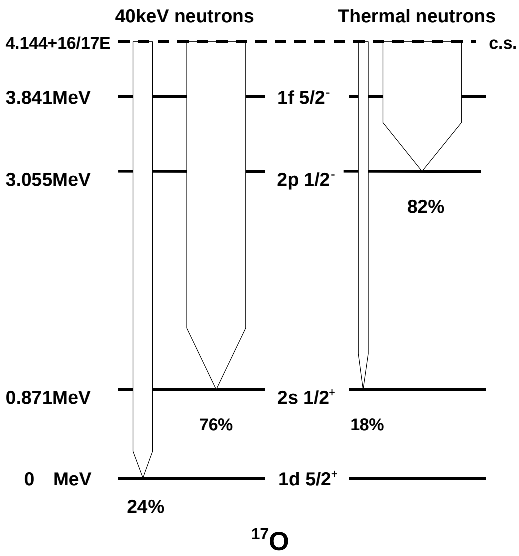

Fig.3. Branching ratios of neutorn capture states of ^{17}O

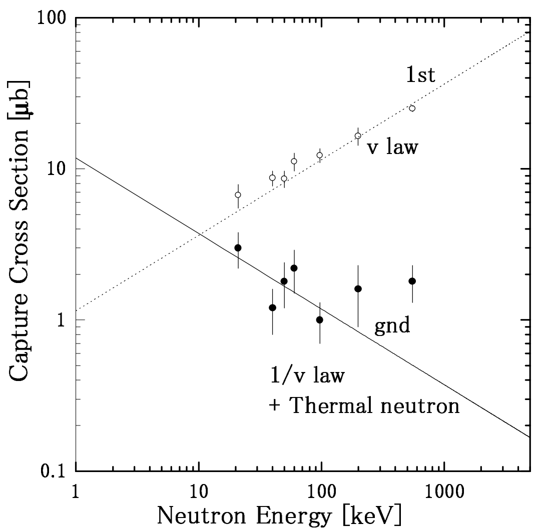

Fig.4. Partial neutron capture cross sections to the ground and first excited states of ^{13}C

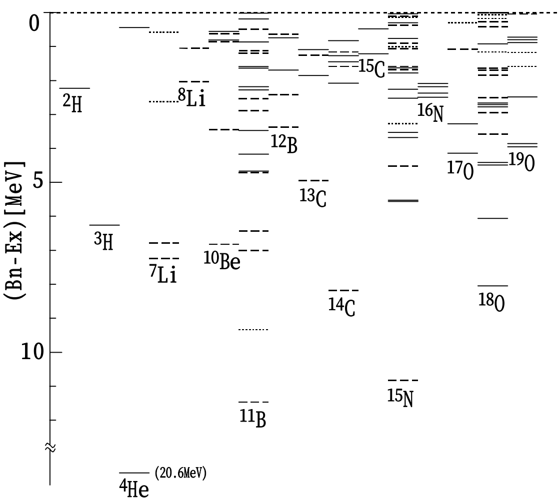

Fig.5. Bound states of relevant compound nuclei

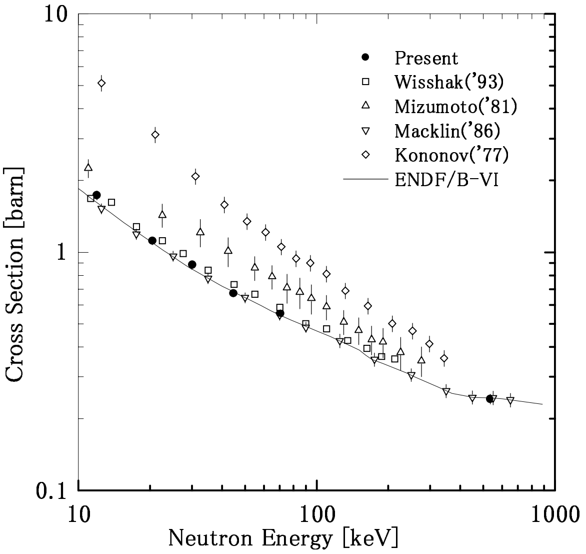

Fig.6. Neutron capture cross sections of ^{147}Sm

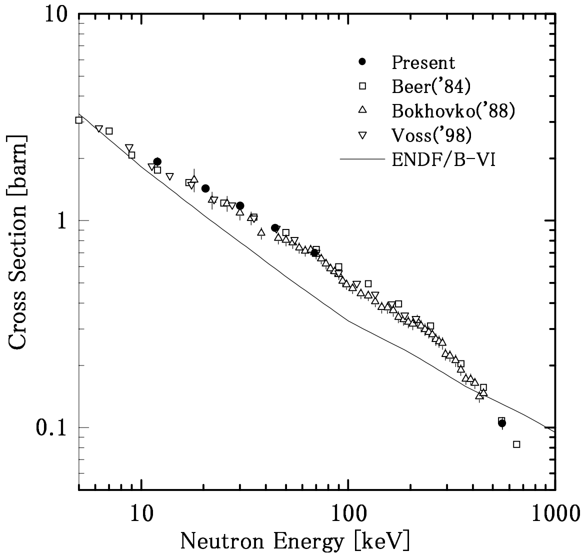

Fig.7. Neutron capture cross sections of ^{163}Dy

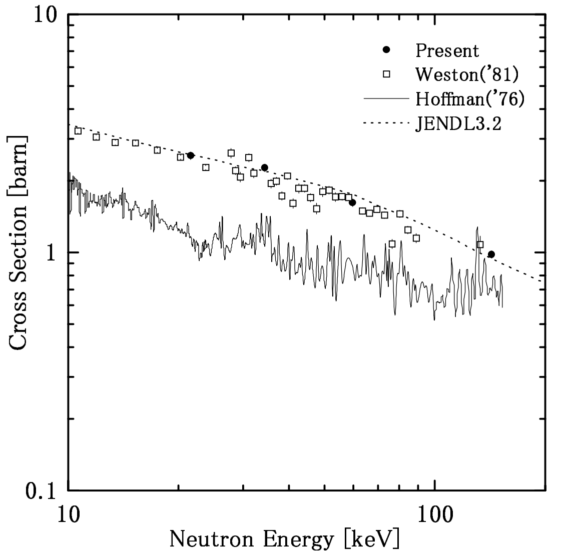

Fig.8. Neutron capture cross sections of ^{237}Np