Nuclear Astrophysics Probed by kev Neutrons

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Abstract:

Various elements observed in Galaxies can be used as relics to trace the history of the Galaxy after the Big Bang. Light elements up to 7Li were produced during the primordial nucleosynthesis in the early universe and the rest of the observed elements were synthesized in stars through various nuclear reaction processes. By studying the physics conditions of these processes when these light and heavier elements were synthesized, one could construct models about the evolution of stars and stellar nucleosynthesis to be used to trace the history. In this paper we discuss keV neutron induced reactions of a nucleus to construct the models.

1. Introduction

The history of the universe after the Big Bang has been an interesting subject to be studied. It can be traced by referring various elements observed in the universe and in Galaxy as relics. In order to trace the history, therefore, it is necessary to construct models of the evolution of these elements. It is well known that light elements up to 7Li would have been synthesized during the primordial nucleosynthesis [1] and elements heavier than Fe were produced by slow- and rapid-neutron capture processes in stars [2]. In these processes keV neutron induced reaction of a nucleus plays crucial roles, since the reaction cross-section determines the production yield of these elements, which is necessary to construct the models.

Concerning the light elements a standard Big Bang model predicts the nucleosynthesis up to 7Li in the early universe, and the observed abundance of the light elements are claimed to be in good agreement with the calculated value by standard Big Bang models [3]. A decade ago, however, inhomogeneous Big Bang models have been proposed as alternative models of the standard big bang models [4]. According to the models, an intermediate mass nucleus up to $A\approx30$ could have been produced in neutron rich regions mainly via neutron capture reactions [5]. The prediction differs from that of the standard models, and therefore a possible discrimination between these two models would provide us crucial information about the physics conditions in the early universe. In order to estimate the production yield of the intermediate mass nuclei in the framework of the inhomogeneous models it is certainly important to measure the neutron capture cross section of the light nuclei at astrophysical relevant energy. A possible comparison of the estimated yield with observation can discriminate a certain inhomogeneous model from others.

Concerning the elements heavier than Fe we have reasonable models of the nucleosynthesis in evolved stars such as the sun [6]. However, we do not have proper models for the nucleosynthesis of heavy elements in less-evolved metal-deficient stars [7]. Currently a lot of efforts are being made to observe the heavy elements abundance in these less-evolved stars to construct the models of stellar evolution and nucleosynthesis [8]. The observed abundance is considered to carry important information on the nucleosynthetic processes in the earlier Galactic stellar generations. Concerning the s-process nucleosynthesis in these metal-deficient stars, light nuclei abundant in the stars would act as a strong neutron poison to influence the production yield of the heavy elements [7]. How these light elements strongly act as a neutron poison depends on the cross section of the neutron capture reaction of these elements. Concerning the r-process nucleosynthesis the astrophysical site remains as an open question. It has been claimed as one of the possible site to be in nascent neutron star winds [9], in which light nuclei would also act as a possible neutron poison.

Both in the primordial- and stellar-nucleosyntheses a neutron induced reaction of light nuclei plays an important role for the construction of the models of the stellar evolution and nucleosynthesis in the Galaxy. While, the study of the neutron induced reaction of light nuclei is also quite important for nuclear physics. Since the main part of the gamma-ray transition amplitude after the keV neutron capture reaction of few-body system is usually either forbidden or hindered, one can learn the roles of non-nucleonic degrees of freedom in the reaction, which has been an important subject for many years [10]. In addition, since the level density of light nuclei is low, one can observe a discrete γ-ray emitted promptly from a neutron capturing state feeding to a low-lying state of a final nucleus [11]. The γ-ray carries unique information of electromagnetic property, and therefore one can learn the mechanism of the keV neutron capture reaction. The information is quite important to estimate the neutron capture reaction cross section of an unstable nucleus at stellar energy for calculating the production yield for primordial intermediate mass nuclei and r-process nuclei.

2. Experimental method

keV neutron capture reaction cross section of a nucleus has been measured by either an activation or a prompt γ-ray detection method. In the latter method a prompt discrete γ-ray emitted from a neutron capturing state feeding to a low-lying state of a final nucleus is measured. Since a discrete γ-ray characterizes a final nucleus, one can identify a true signal from the neutron capture reaction of a target nucleus free from background and determine a small capture cross section of a light nucleus unambiguously. The discrete γ-ray carries a unique electromagnetic property such as E1, M1 and E2 etc. Therefore its observation gives us unique information of initial and final states of a final nucleus, which connects the γ-ray. Through the information one can learn the neutron capture reaction mechanism and nuclear structure of the final nucleus. It could happen that such nuclear physics information is quite unique and can be hardly obtained by other experimental approaches. Our experimental method to use the prompt γ-ray detection method is described briefly [12]. Pulsed keV neutrons are produced by the $^{7}Li(p,n)^{7}Be$ reaction using pulsed protons provided from the 3MV Pelletron Accelerator of the Research Laboratory for Nuclear Reactors at the Tokyo Institute of Technology. Discrete prompt γ-rays from a capturing sample are detected by an anti-Compton NaI(Tl) γ-ray spectrometer [13]. The spectrometer is placed at 125.3° with respect to the proton beam direction to obtain an angle-integrated γ-ray intensity for the dipole transition. A gold sample has been used for normalization of the cross section, since the capture cross section of gold is well known.

Since the (n,p) and/or (n,α) reaction of a light nucleus also plays important roles in stellar nucleosynthesis, we have developed a gas scintillation drift chamber (GSDC) to detect low energy charged particles with a large solid angle of 4 π and high efficiency of 100 % [14]. Here, it should be noted that both the reaction cross section and energy of emitted charged particles induced by low energy neutrons are low. The high sensitivity of the GSDC for detecting low-energy charged particles emitted from the keV neutron-induced reaction of a nucleus has been shown for the measurement of the $^{14}N(n,p)^{14}C$ reaction cross section [15].

3. Results and discussions

The cross-section of the neutron-capture reaction of various light nuclei has been successfully measured by detecting their discrete γ-rays at several neutron energies between 10 and 550 keV with an uncertainty of 5~10 %. What we have learned through the studies are as follows. First, we have for the first time observed a non-resonant direct p-wave capture reaction process at astrophysical relevant energy of a few 10 keV [11]. Because of the new process in the reaction the cross section we obtained is significantly larger than the value estimated assuming a 1/v law and using the thermal neutron capture cross section. The present result has a big astrophysical impact. It indicates clearly that light nuclei act as a strong neutron poison in the nucleosynthesis of heavy elements especially in less evolved metal deficient stars [16] and in addition in estimating the production yield of various nuclei in many astrophysical sites one must take into account the new process so far ignored. Second, we could clearly clarify the important role of the meson exchange currents in the keV neutron capture reaction of few-body system [17]. Third, the physics reason why the non-resonant direct p-wave capture reaction process becomes important even in the keV energy region is clarified as the unique nature of the neutron capturing nucleus with a $1^+/2$ ($s_{1/2}$) state and with relatively low neutron binding energy [18]. Hence the keV incident neutrons can be captured directly by a target nucleus transferring an orbital angular momentum of 1 to the final nucleus.

4. Future Prospect

Elemental abundance observed in less-evolved ultra metal deficient stars provides us crucial information to construct the models to trace the history of the Galaxy. Among various elements, heavier elements than iron carry important information of the generation of stars, in which the elements were synthesized by the slow- and rapid-neutron capture process of a nucleus. Since many important and interesting problems of the neutron induced reaction of a nucleus remain to construct the solid models of stellar evolution and nucleosynthesis, it would be extremely important to extend such studies using intense spallation neutrons provided such as by J-PARC. Here, one can use rare-abundant samples and even long-lived radioisotopes.

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