Critical Role of Nuclear Data in Nuclear Astrophysics

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Accurate data of the photon-, alpha-, and neutron-induced reaction cross sections of a nucleus at astrophysics relevant energy are necessary to construct stellar models of nucleosynthetic yields of stars to trace the history of Galaxy. The cross section measurements of the ^{4}He(γ,*xnyp*), ^{12}C($^{4}He,\gamma$)^{16}O, and ^{62}Ni(n,γ)^{63}Ni reactions were carried out using a quasi-monoenergetic pulsed photon beam with a newly developed 4π time projection chamber, a pulsed intense alpha beam with a newly installed high efficiency NaI(Tl) spectrometer, and a pulsed keV neutron beam with a high sensitive anti-Compton NaI(Tl) spectrometer, respectively. The present results were compared to previous data, recent theoretical calculations, and their astrophysics impacts were discussed.

1. Introduction

The photodisintegration reaction and its inverse reaction on few body systems provide important information both on nuclear astrophysics and nuclear physics. In fact, the proton and/or neutron capture reactions and/or their reverse reactions on light nuclei at a temperature relevant to the primordial nucleosynthesis are key reactions in estimating the primordial light element abundance in the early universe, and the remaining uncertainties of these reaction cross sections give rise to the uncertainties in the estimated abundance mentioned [1]. From a point of view of nuclear physics, γ-ray transitions following radiative and/or inverse reactions relevant to the primordial nucleosynthesis such as p(n,γ)^{2}H and ^{2}H(n,γ)^{3}H reactions are characterized as being hindered and/or forbidden transitions in an impulse approximation [2]. The ^{2}H(n,γ)^{3}H cross section for thermal neutron is very small [3], 1/660 of that for proton, due to the nuclear structures of ^{2}H and ^{3}H, and the electromagnetic transition proceeds via a small component of wave functions. The cross section has not ever been measured at keV energies, and therefore it is quite interesting to measure it to learn the role of sub-nucleonic degrees of freedom in the reaction process with increasing the neutron energy. The photodisintegration study of ^{4}He could provide useful information on the scenario of the rapid process nucleosynthesis induced by neutrino driven wind from a nascent neutron star [4], and of the delayed supernovae explosion [5], where the neutrino heating by its interaction with ^{4}He would influence the explosion process [6]. Here, the neutrino-nucleus interaction is analogous to the electromagnetic interaction with a nucleus via an $E1$ transition [7]. In nuclear physics, the photodisintegration of ^{4}He, the lightest self-conjugate nucleus with closed shell structure, has been a quite interesting subject, since the study could provide a testing ground for theory on *NN*, three-body forces and collective nuclear motion [8]. In addition, the cross section ratio of the ^{4}He(γ,p) to ^{4}He(γ,n) in the giant dipole region has been used to test the validity of the charge symmetry of the strong interaction in nuclei [9]. So far, the photodisintegration cross sections of ^{4}He were measured in the energy range from 20 to 215 MeV using quasi-monoenergetic photon beams and/or bremsstrahlung photon beams [10]. Although above 35-40 MeV most of the old ^{4}He(γ,p)^{3}H and ^{4}He(γ,n)^{3}He data agree with each other within their respective data sets, they are controversial especially in the peak region of 25-26 MeV, and show either a pronounced GDR peak or a fairly flat excitation function, requiring a new precise measurement. It should be mentioned that the systematic uncertainties of the old data seem to be much larger than the statistical uncertainties. Theoretical calculations also predict different cross sections in the region of the electric dipole resonance (25~26 MeV) [11].

The ^{12}C(α,γ)^{16}O reaction cross section at the center-of-mass energy $E_{\mathrm{c.m.}}$ of 0.3 MeV, $\sigma_{tot.}(E_{\mathrm{c.m}}=300)$, plays an important role in determining the mass fraction of ^{12}C and ^{16}O after stellar helium burning, the abundance distribution of elements between carbon and iron, and the iron-core mass before super-nova explosion [12]. The direct measurement of the $\sigma_{tot.}(E_{\mathrm{c.m.}}=300)$, however, is not possible using current experimental techniques, since the $\sigma_{tot.}(E_{\mathrm{c.m.}}=300)$ is very small of ~10^{-17} b [13]. Hence, $\sigma_{tot.}(E_{\mathrm{c.m.}}=300)$ is derived by extrapolating a measured cross section at $E_{\mathrm{c.m.}} \geq 1.0$ MeV into the range of the stellar temperature with use of theoretical calculations [14]. The $\sigma_{tot.}(E_{\mathrm{c.m.}}=300)$ is considered to be dominated by direct electric dipole ($E1$) and electric quadrupole ($E2$) α-capture reactions into the ground state of ^{16}O [15]. Because of the different energy dependence of the $\sigma_{E1}(E_{\mathrm{c.m.}})$ and $\sigma_{E2}(E_{\mathrm{c.m.}})$ it is necessary to separately extrapolate the $\sigma_{E1}(E_{\mathrm{c.m.}})$ and $\sigma_{E2}(E_{\mathrm{c.m.}})$ to obtain the total cross section of the ^{12}C(α,γ)^{16}O reaction at $E_{\mathrm{c.m.}}=0.3$ MeV, $\sigma_{tot}(E_{\mathrm{c.m.}}=300)$. Despite extensive studies of the angular distribution measurement, there remain significant uncertainties of $\sigma_{E1}(E_{\mathrm{c.m.}})$ and $\sigma_{E2}(E_{\mathrm{c.m.}})$ [16].

Comparison of observed elemental abundance of various metallic stars with calculated nucleosynthetic yields based on stellar nucleosynthetic models provides crucial information to finally construct models for chemical evolution of galaxies [17]. According to the recent estimation of the nucleosynthetic yields of massive stars, several isotopes such as ^{61}Ni, ^{62}Ni and ^{64}Ni are overproduced, and one of the largest overproductions is ^{62}Ni [18]. The origin of the overproduction is considered to be due to residual uncertainties in the stellar models and/or in the nuclear physics inputs used for the calculation such as the neutron capture cross-section of Ni isotopes.

Because of the nuclear astrophysics and nuclear physics interest we determined the cross sections of the ^{4}He(γ,*xnyp*), ^{12}C(^{4}*He,γ*)^{16}O, ^{2}H(*n,γ*)^{3}H, and ^{62}Ni(*n,γ*)^{63}Ni reactions with small systematic uncertainty by developing a new measurement system, as described below.

2. Experimental Method

2.1 Photodisintegrations of ^{4}He

The ^{4}He photodisintegration cross section was performed at the National Institute of Advanced Science and Technology at Tsukuba by using pulsed laser Compton backscattering (LCS) photons, and a newly constructed time projection chamber (TPC) with an active He target, which allowed to simultaneously measure the (γ,*p*) and (γ,*n*) reaction channels [19]. There are several key points in the present method to obtain real events with a large signal to noise ratio. Real events are only produced along the photon axis with a diameter of 2 mm, when a pulsed photon beam entered the TPC, we could obtain information on the track shape of a charged fragment, energy loss deposited by the fragment, and the reaction point, necessary to clearly identify the event, angular distribution of a fragment, using the TPC, and the solid angle is large, nearly 4π, and the detection efficiency is as high as 100% [20]. The photodisintegration cross section of ^{4}He is given as products of the reaction yield, the number of ^{4}He target, the incident LCS γ-ray flux, and the detection efficiency of the TPC. The target number was obtained by measuring the gas pressure and temperature in the TPC, and the efficiency was determined by using the ^{241}Am α-ray source. The reaction yield and the incident γ-ray flux were obtained by referring to the track shape of charged fragment from the reaction together with its pulse height, and by measuring the γ-ray spectrum by means of a BGO detector.

2.2 ^{12}C(α,γ)^{16}O reaction

The differential cross sections of the ^{12}C(α,γ)^{16}O reaction have been measured at center-of-mass energy of 1.4 and 1.6 MeV with a new measurement system installed at the 3.2 MV Pelletron accelerator laboratory of the Research Laboratory for Nuclear Reactors at Tokyo Institute of Technology [21]. We used an intense pulsed α-beam together with three anti-Compton NaI (Tl) spectrometers. The spectrometer was heavily shielded against neutrons from the ^{13}C(α,*n*)^{16}O reaction and background γ-rays produced by thermalized neutrons capture reaction by various materials in the measurement room. It was essential to use a pulsed α-beam to get rid of neutron induced background from $^{13}C(\alpha,n)^{16}O$ from real events due to $^{12}C(\alpha,\gamma)^{16}O$ with a time-of-flight method [21]. Note that a small amount of ^{13}C is known to produce significant amounts of background since the cross section of the $^{13}C(\alpha,n)^{16}O$ reaction is about 10^7 times larger than that of the $^{12}C(\alpha,\gamma)^{16}O$ reaction. In addition, preparation of the enriched targets which could stand against an intense beam was crucial since we used an intense α-beam. We measured the Rutherford backscattering spectrum of α-particles from targets to obtain the flux of incident α-beam and monitor any change of the target thickness during measurements.

2.3 $^2H(n,\gamma)^3H$ and $^{62}Ni(n,\gamma)^{63}Ni$ reactions

The (n,γ) cross sections for ^2H [22] and ^{62}Ni [23] at keV energy were measured using pulsed neutrons at the 3.2 MV Pelletron accelerator at Tokyo Institute of Technology. A discrete γ-ray promptly emitted from the neutron capture reaction by deuteron was detected by means of an anti-Compton NaI(Tl) spectrometer [24]. Gold was used to normalize the neutron capture cross section of a sample, since the cross section of Au is well known within an uncertainty of 3 %.

3. Results

3.1 Cross section of the ^4He photodisintegration reactions

Using the reaction yield, the photon flux, the target number of ^4He, and the detection efficiency of the TPC mentioned above, we could obtain the photodisintegration cross section of ^4He. Here, in order to learn about any possible systematic uncertainty of the present experimental method, we measured the photodisintegration cross section of deuteron using CD_4 gas at E_γ=22.3 MeV. Note the reaction cross section has been well known with good accuracy. The obtained result is in good agreement with old data and with a theoretical value [25], confirming the validity of the new method including its analysis.

The thus obtained cross sections for the (γ,p) and (γ,n) reactions on ^4He are shown together with previous data and theoretical calculations in **Fig. 1** [20]. They increase monotonically with increasing the γ-ray energy up to 30 MeV, and do not show a prominent peak in the region of 25 ~26 MeV, contrary to several old data and a recent theoretical calculation [11]. The cross section ratio of the (γ,p) to the (γ,n) reactions derived from the present measurement agrees with the expected value assuming the charge conservation of the strong interaction in nuclei.

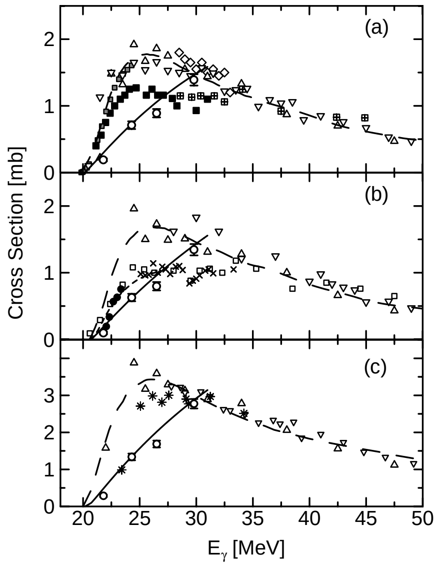

Fig. 1 ^{4}He photodisintegration cross sections. Open circles: present result. Solid curves: most probable cross sections obtained from the present data. Other symbols: previous data (see Ref. 20). (a) (γ,p) cross sections. (b) (γ,n) cross sections. (c) total photoabsorption cross sections.

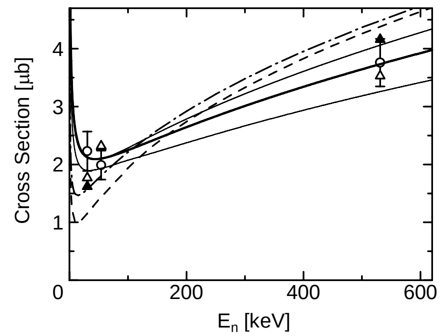

Fig. 2 Cross section of the D(n,γ)^{3}H reaction vs. neutron energy (in the center-of-mass energy). Open circles: present results. Other symbols: calculated values see Ref. 22.

3.3 *Cross sections of the* ^{2}H(n,γ)^{3}H and ^{62}Ni(n,γ)^{63}Ni reactions

The present result of the ^{2}H(n,γ)^{3}H reaction is shown in **Fig. 2** together with theoretical calculations based on the Faddeev approach and the pionless effective field theory [22].

The cross section of the ^{62}Ni(n,γ)^{63}Ni reaction was precisely measured in the neutron energy range from 5.5 to 90 keV and obtained the MACS at 30 keV as being 37.5±2.5 mbarn (preliminary), about 3 times larger than the value used for the nucleosynthetic yield estimation of massive stars [18]. This large MACS could solve the longstanding problem of the overproduction of ^{62}Ni in the yield estimation.

4. Summary

We have successfully measured the photodisintegration cross section of ^{4}He (in addition, ^{2}H and ^{3}He) by constructing a new measurement system with a small systematic uncertainty. The present studies for the direct simultaneous measurements of these nuclei solved a longstanding problem of the discrepancy of the existing ^{4}He two-body photodisintegration cross sections. Further theoretical developments are highly required to get deeper insight of the obtained excitation function of the ^{4}He photodisintegration. We also succeeded to measure the γ-ray angular distribution from the $^{12}C(\alpha,\gamma)^{16}O$ reaction to the ground state of ^{16}O by installing also a new measurement system with use of an intense pulsed α-beam together with high sensitive anti-Compton NaI(Tl) spectrometers at $E_{c.m.}$=1.4 and 1.6 MeV. The neutron capture cross sections of ^{2}H and ^{62}Ni were measured at keV energies using a pulsed neutron beam with use of a prompt γ-ray detection method. These data are important in the nucleosynthetic yield estimation in the primordial nucleosynthesis and stellar nucleosynthesis. They also serve as a testing ground of various theoretical calculations.

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