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E2 and E1 cross sections of the ^{12}C(α,γ)^{16}O reaction obtained at E_{cm} = 1.6 and 1.4 MeV

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We have measured the angular distributions of the direc α-capture γ-ray of ^{12}C to the grand state of ^{16}O by means of three anti-Compton NaI(Tl) spectrometers using intense pulsed α-particles at E_{cm} = 1.6 MeV and 1.4 MeV. The Rutherford backscattering spectrum of α-particles from ^{12}C targets was measured with a Si detector to obtain an incident α-beam intensity and a target thickness.

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1. Introduction

The ^{12}C(α,γ)^{16}O reaction cross section at the Gamow energy, E_{cm} = 0.3 MeV, plays an important role in determining the mass fraction of ^{12}C and ^{16}O after stellar helium burning, abundance distribution of the elements between carbon and iron, and the iron core mass before supernovae explosion [1]. Therefore, it is quite important to accurately determine the cross section at E_{cm} = 0.3 MeV. The direct measurement of the cross section at E_{cm} = 0.3 MeV, however, is not possible using current experimental technique, because the cross section is too small, around 10^{-17} barn. Hence, one has to derive the cross section by extrapolating a measured cross section at $E_{cm} \geq 1.0$ MeV into the range of stellar temperature. The total cross section of the ^{12}C(α,γ)^{16}O reaction at E_{cm} = 0.3 MeV has been known to be dominated by direct electric dipole (E1) and electric quadrupole (E2) α-capture reactions into the ground state of ^{16}O. However, the extrapolation mentioned is not easy, since there are the two sub-threshold resonance states of $J^{\pi} = 1^{-}$ at $E_R = -45$ keV and $J^{\pi} = 2^{+}$ at $E_R = -245$ keV in ^{16}O [2], and E1 and E2 cross sections have different energy dependence. Hence, it is essential to measure the γ-ray angular distributions of the ^{12}C(α,γ)^{16}O reaction over a wide range of energy, and to determine the energy dependence of both the E1 cross section, $\sigma_{E1}(E)$, and the E2 one, $\sigma_{E2}(E)$. Despite a significant progress has been made in measuring the cross section, both E1 and E2 cross sections have been determined with large uncertainties. It is therefore highly required to carry out a new experiment to accurately determine these E1 and E2 cross sections by measuring the γ-ray angular distribution of the ^{12}C(α,γ)^{16}O reaction.

In the present experiment, we measured the γ-ray angular distribution by employing three anti-Compton NaI(Tl) spectrometers to obtain a sufficient γ-ray yield and using an intense pulsed α-beam to discriminate true γ-ray events from background events due to high energy neutrons from the ^{13}C(α,n)^{16}O reaction with a time-of-flight (TOF) method. Note that a small amount of ^{13}C is contained in the target.

2. Experimental Method

The present experiment was carried out using an intense pulsed α-beam, which was provided from the 3.2 MV Pelletron accelerator at the Research Laboratory for Nuclear Reactors of Tokyo Institute of Technology. An average beam current was about 8 μA at a repetition rate of 4 MHz. A pulse width of the beam was about 1.9 ns (FWHM), which was sufficient to distinguish a true event from the ^{12}C(α,γ)^{16}O reaction from neutron related background events. The γ-ray angular distributions of the ^{12}C(α,γ)^{16}O reaction were measured by constructing a new measurement system. Since a detailed description of the new system is published in elsewhere [3], we briefly describe the present experimental method.

The new system consists of three high efficiency anti-Compton NaI(Tl) spectrometers and of a Si counter to monitor the ^{12}C target thickness. A schematic view of the experimental setup is shown in Figure 1. Each spectrometer consists of a central NaI(Tl) detector with a diameter of 9 inches and a length of 8 inches, and an annular NaI(Tl) detector with a size of 2 inches in thickness and 14.5 inches in length. These NaI(Tl) detectors were covered by heavy shield composed of lead and Boron-doped polyethylene, and set at 40°, 90° and 130° with respect to the α-beam direction. The γ-ray yield at angles of 40° and 130° provided information on the E2 strength and that at

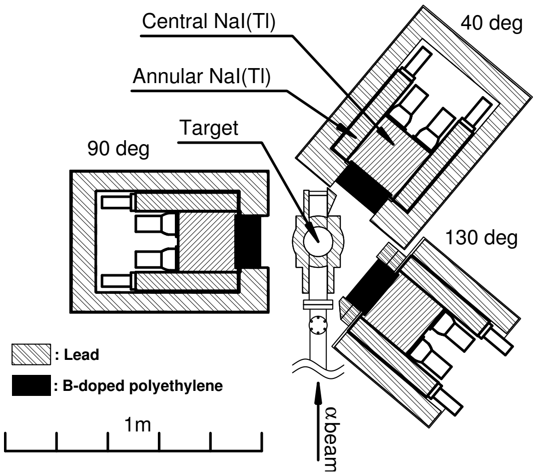

Figure 1: Schematic view of the NaI(Tl) spectrometers placed at 40°, 90° and 130° with respect to the α-beam direction.

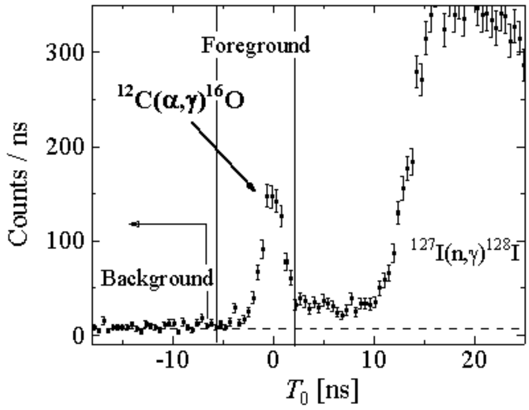

Figure 2: TOF spectrum, which was obtained by putting the gate in the region of between 8.0 MeV and 9.0 MeV on the γ-ray energy spectrum, taken by the NaI(Tl) spectrometer placed at 90°.A dashed line indicates the time-independent background events due to thermal neutrons and cosmic rays.

90° gave information on the E1 strength. The absolute γ-ray efficiency of each spectrometer was calculated using the Monte-Carlo code, GEANT4 [4] by referring the measured one, which was obtained with use of the standard γ-ray sources (^{60}Co and ^{88}Y) and γ-rays from the ^{27}Al(p,γ)^{28}Si reaction measured at E_p = 992 and 2046 keV [5].

An enriched (more than 99.95 %) ^{12}C target foil with a thickness of about 300 $\sim$ 400 μg/cm^2 was made by a thermal cracking of methane. A gold with a thickness of 0.1mm was used as a backing of ^{12}C target. We took the Rutherford backscattering spectrum (RBS) of α-particles from the enriched ^{12}C targets with a Si detector to determine their thickness and the incident α-particle intensity. The spectrum was used also to check any change of the target thickness during the measurement.

3. Analysis

A typical TOF spectrum measured by the central NaI(Tl) spectrometer placed at 90° is shown in Figure 2. We see clearly the peak due to the ^{12}C(α,γ)^{16}O reaction event, which is well separated from a broad peak due to the ^{127}I(n,γ)^{128}I reactions. Events in the plateau region below about -5 ns are due to time-independent background events caused by scattered neutrons and cosmic rays. We could obtain true events from the ^{12}C(α,γ)^{16}O reaction by subtracting both the neutron induced background and the time-independent background with use of the TOF method as shown in Figure 3, where we see the discrete γ-ray from the direct α-capture of ^{12}C into the ground state of ^{16}O with a large S/N ratio. A dashed line is the fitted spectrum for the γ-ray using the response function, which was calculated by taking account of the energy loss of α-particles in the ^{12}C target, energy dependence of the ^{12}C(α,γ)^{16}O cross section, Doppler shift of the γ-ray and the intrinsic energy resolution of the NaI(Tl) spectrometer. Regarding the energy dependence of

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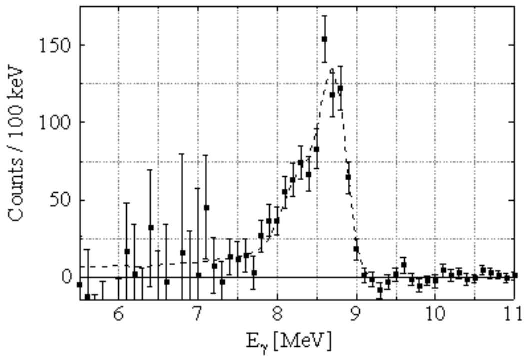

Figure 3: Background subtracted (net) γ-ray energy spectrum. A dashed line indicates the fitted spectrum using the response function of the spectrometer. ($E_{cm} = 1.6$ MeV, $\theta_\gamma = 90^\circ$)

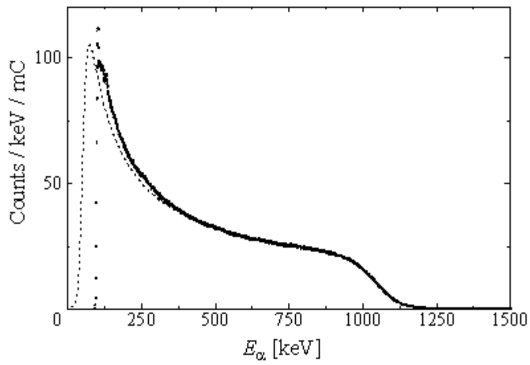

Figure 4: RBS spectrum obtained with a Si detector by bombarding 2.270 MeV α-particles on enriched ^{12}C targets on a gold backing. A dashed line indicates the calculated spectrum using a simulation code.

the cross section we took only the Coulomb part of the cross section. Note that since the nuclear part, which is an astrophysical S-factor, changes gently with changing the energy of α-particle, it can be ignored. It should be mentioned that the average energy of full-energy γ-ray peak obtained by the calculation is in good agreement with observed one. Observed γ-ray yield for each NaI(Tl) spectrometer was obtained by integrating the counts of the response function fitted to measured data.

The RBS spectrum of α-particles is shown in Figure 4. Since the thickness of the ^{12}C target was thin, about 300 $\sim$ 400 μg/cm^2, and the target backing was gold with a thickness of 0.1 mm, incident α-particles were scattered by gold while loosing their energies in passing through the ^{12}C target. The target thickness of ^{12}C was determined accurately by fitting spectrum using the simulation code SIMNRA [6] as shown in Figure 4.

Since the cross section of the ^{12}C$(\alpha,\gamma)^{16}$O reaction changes with decreasing the energy of α-beam over the target thickness, it is necessary to define an effective cross section by considering the energy dependence of the cross section as given in ref. [2]. Here we took the Coulomb part of the cross section as is the case with the calculation of the response function for the characteristic γ-ray from the ^{12}C$(\alpha,\gamma)^{16}$O reaction.

4. Results

In order to obtain σ_{E1} and σ_{E2} the resulting differential cross sections were fitted using the angular distribution formula, which is given in ref. [7]. Here we used elastic scattering data of Plaga *et al.* [8] for the relative phase between E1 and E2 amplitude of the of the ^{12}C$(\alpha,\gamma)^{16}$O reaction. The thus obtained preliminary result for σ_{E2}, agree with three data set [9, 10, 11] and marginally agree with the data set of Kunz *et al.* [12] and Assunção *et al.* [13].

5. Summary

With use of a new system we succeeded to measure the γ-ray angular distributions at E_{cm} =

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1.6 MeV and 1.4 MeV using intense pulsed α-beams together with high efficiency anti-Compton NaI(Tl) spectrometers with a large S/N ratio and high statistics. The detailed analysis to determine absolute differential cross sections are in progress by taking account of energy dependence of the differential cross section . We expect that from the γ-ray angular distribution both the σ_{E1} and σ_{E2}/σ_{E1} ratio could be accurately determined. To obtain the energy dependence of both σ_{E1} and σ_{E2}, a new measurements of the angular distribution at lower energy is in progress.

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