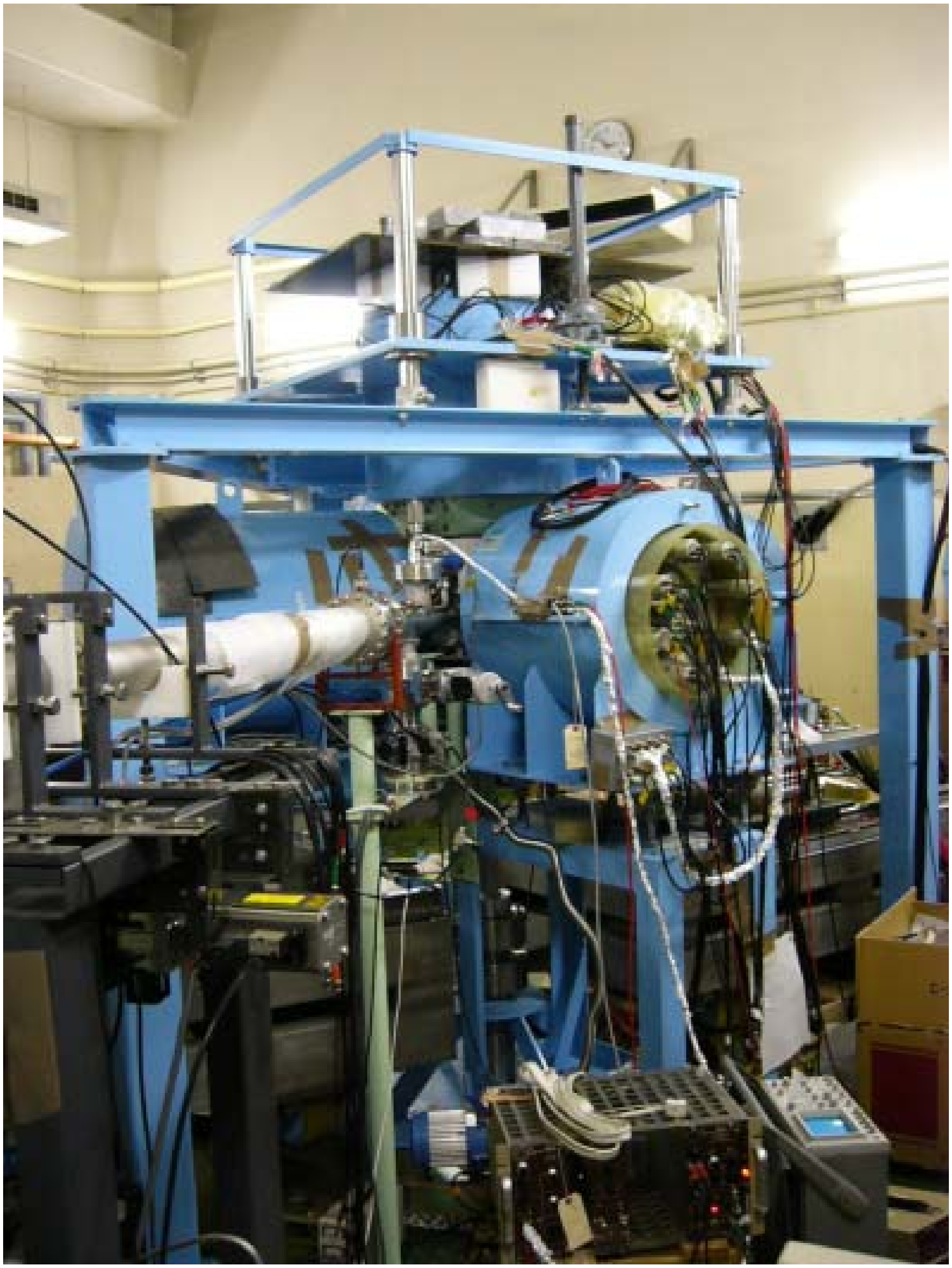

Figure 1: Photograph of the γ-ray detector system for measurement of the $^{12}C(\alpha,\gamma)^{16}O$ reaction cross section.

A system to measure the $^{12}C(\alpha,\gamma)^{16}O$ reaction cross section

H. Makii[1], K. Mishima[1], M. Segawa[1], H. Ueda[1], T. Shima[1], Y. Nagai[1], M. Igashira[2], and T. Ohsaki[2]
[1]*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*
[2]*Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, O-okayama, Meguro, Tokyo 152-8550, Japan*

The performance of a newly installed measurement system of the γ-ray angular distributions of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, which comprised of three high efficiency anti-Compton NaI(Tl) spectrometers, was studied using a pulsed α-beam. True events from the reaction were clearly picked up by discriminating neutron induced background events with a time-of-flight method. The present study demonstrated high sensitivity of the system to detect the γ-rays from the $^{12}C(\alpha,\gamma)^{16}O$ reaction at low energy, and thereby to accurately determine both E1 and E2 cross-sections of the reaction, which are of vital importance in nuclear astrophysics.

One of the most important reactions in the helium-burning phase of stellar evolution is known to be the $^{12}C(\alpha,\gamma)^{16}O$ reaction [1]. The cross-section at the stellar temperature, $E_0 = 0.3$ MeV, determines the $^{12}C/^{16}O$ ratio at the end of helium burning and influences the subsequent stage of stellar evolution. Since its direct measurement at E_0 is not possible using current techniques, the cross-section $\sigma(E_0)$ is derived by extrapolating a measured cross-section at $E_{c.m.} \geq 1.0$ MeV into the range of the stellar temperature with use of theoretical calculations. The extrapolation, however, is not easy because both electric dipole (E1) and electric quadrupole (E2) transition amplitudes contribute to the cross-section with different dependence on the center of mass energy $E_{c.m.}$. In order to derive $\sigma(E_0)$, therefore, it is essential to measure the γ-ray angular distributions of the $^{12}C(\alpha,\gamma)^{16}O$ reaction over a wide range of energy, and to determine the energy dependence of both E1 and E2 cross-sections.

Thirty years ago, the E1 cross-section of the $^{12}C(\alpha,\gamma)^{16}O$ reaction was measured in the energy range $E_{c.m.} = 1.41-2.94$ MeV using a pulsed α-beam by means of an NaI(Tl) detector [2]. After this pioneering work many experiments of the $^{12}C(\alpha,\gamma)^{16}O$ reaction are being made using a BGO detector [3] and Ge detector arrays [4−7]. In spite of these efforts, however, there remains a large error assigned especially to the astrophysical E2 S factor.

In the present study we carried out the performance test of a new measurement system of the γ-ray angular distributions of the reaction, installed at the 3.2 MV Pelletron accelerator laboratory at Tokyo Institute of Technology, to determine both E1 and E2 cross sections accurately.

There are several difficulties inherent to the measurement of the cross-section. The cross section is extremely small, and there is a huge amount of neutron background from the $^{13}C(\alpha,n)^{16}O$ reaction due to ^{13}C contained in ^{12}C targets. In order to obtain a sufficient γ-ray yield of the $^{12}C(\alpha,\gamma)^{16}O$ reaction with a good signal-to-noise ratio we used intense pulsed α beams with a narrow pulse width, and three anti-Compton NaI(Tl) spectrometers. A capacitive pickoff was set inside the beam duct to pick up α-beam signals for the TOF measurement. The pulse width of the α beam was measured as being 1.9 nsec (FWHM). The energy calibration of acceleration voltage of the Pelletron was made by using the $^{27}Al(p,\gamma)^{28}Si$ reaction at two resonances of $E_p = 992$ keV [11] and of 2046 keV [12].

Each spectrometer comprises of a central NaI(Tl) detector with a diameter of 22.9 cm and a length of 20.3 cm, and an annular NaI(Tl) detector with an outer diameter of 33 cm and a length of 27.9 cm [8, 9]. A boron-doped polyethylene with a thickness of 10 cm was placed between the ^{12}C targets and the central NaI(Tl) detector to reduce the neutron flux from the $^{13}C(\alpha,n)^{16}O$ reaction.

We used enriched carbon targets (99.95% enrichment in ^{12}C) with thicknesses of 300$\sim$400 $\mu g/cm^2$, which were made by a thermal cracking of methane gas by Prof. Sugai at KEK. The thickness of ^{12}C targets was determined by measuring the Rutherford backscattering (RBS) spectrum of α-particles with a Si detector. The RBS spectrum was also used to monitor the depth profile of the targets as well as to determine an incident α-beam flux. Note that in order to monitor an instantaneous change of α-beam currents we used a Faraday cup.

The vacuum inside the beam duct was kept as good as about 10^{-8} torr, which was crucial to get rid of deposition of any impurity on ^{12}C targets. The target chamber is made of aluminum, since its neutron capture cross-section is smaller than iron. Note that even if we used such enriched ^{12}C targets, we observed neutron background because the cross-section of the $^{13}C(\alpha,n)^{16}O$ reaction is very large. The neutrons from the reaction interact with stainless steel and/or aluminum, and produce a significant amount of neutron related background.

As for the data-taking system, dynode signals and anode signals from both central and annular NaI(Tl) detectors were used as a common start signal for a time to digital converter (TDC). They were also used as an energy signal for an analog to digital converter. The stop signal of the TDC was obtained from the output of capacitive pick off. Data from CAMAC modules were acquired by a personal computer and were recorded on a hard disk in a list mode.

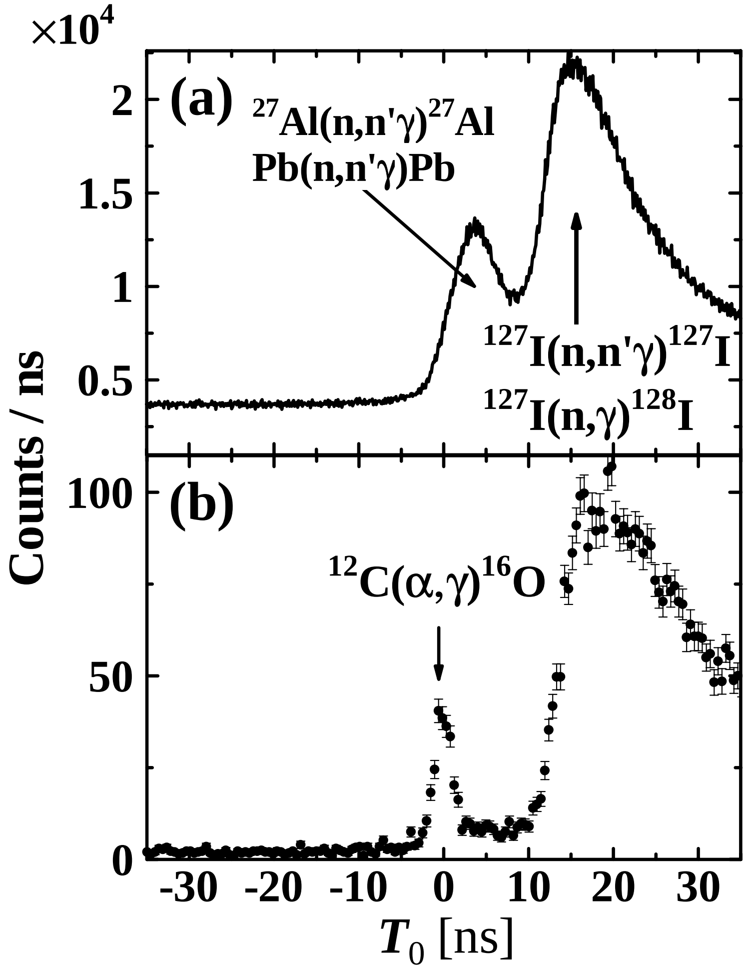

Figure 2: TOF spectrum of the ^{12}C$(\alpha,\gamma)^{16}$O reaction taken by the NaI(Tl) detector. Here, the detected events are shown as a function of the time T_0 relative to the time for the events at the target position. The events at the large peak (a) are due to the ^{127}I$(n,n'\gamma)^{127}$I and ^{127}I$(n,\gamma)^{128}$I reactions in the NaI(Tl) detector. The events at the small peak (a) are due to the ^{27}Al$(n,n'\gamma)^{27}$Al and Pb$(n,n'\gamma)$Pb reactions. The events at the narrow peak (b) are due to the ^{12}C$(\alpha,\gamma)^{16}$O reaction.

The NaI(Tl) spectrometers were set at 33 cm away from the ^{12}C targets to separate a true γ-ray event due to the ^{12}C$(\alpha,\gamma)^{16}$O reaction from neutron background events by the TOF method. The absolute γ-ray detection efficiency of each anti-Compton NaI(Tl) spectrometer was calculated using the Monte-Carlo code, GEANT4 [10]. The calculated efficiency was compared to the measured one using the standard γ-ray sources (^{60}Co and ^{88}Y) with known intensities, and γ-rays from the ^{27}Al$(p,\gamma)^{28}$Si reaction measured at $E_p = 992$ and 2046 keV [11, 12]. The response function of the NaI(Tl) spectrometer obtained using the GEANT4, was shown to be in good agreement with the measured one. We also calculated an attenuation factor of the NaI(Tl) spectrometer using the GEANT4. T his calculated value was checked by measuring the well-known γ-ray angular distributions of the ^{27}Al$(p,\gamma)^{28}$Si reaction at $E_p = 2046$ keV [12].

We studied the performance of the present system using 2.27 MeV α-beams by measuring γ-rays from the bombardment of enriched ^{12}C targets with intense α-beams.

The TOF spectrum taken by the NaI(Tl) detector is shown in Figs. 2a and 2b, where a detected event is shown relative to an event at the target position. In Fig. 2a, we see clearly two peaks; the high peak at about 15 nsec and the low one at about 3 nsec. Based on the time differences of these peaks from the origin of the time in the TOF spectrum, the events at the high peak was assigned to be due to γ-ray events from the ^{127}I$(n,n'\gamma)^{127}$I and ^{127}I$(n,\gamma)^{128}$I reactions in the NaI(Tl) detector, and the events at the low peak was assigned to be due to γ-ray events from the $(n,n'\gamma)$ reactions by aluminum (^{27}Al), and natural lead (^{206}Pb, ^{207}Pb and ^{208}Pb).

The events at the narrow peak at 0 nsec in the TOF spectrum in Fig 2b contains an event caused by the

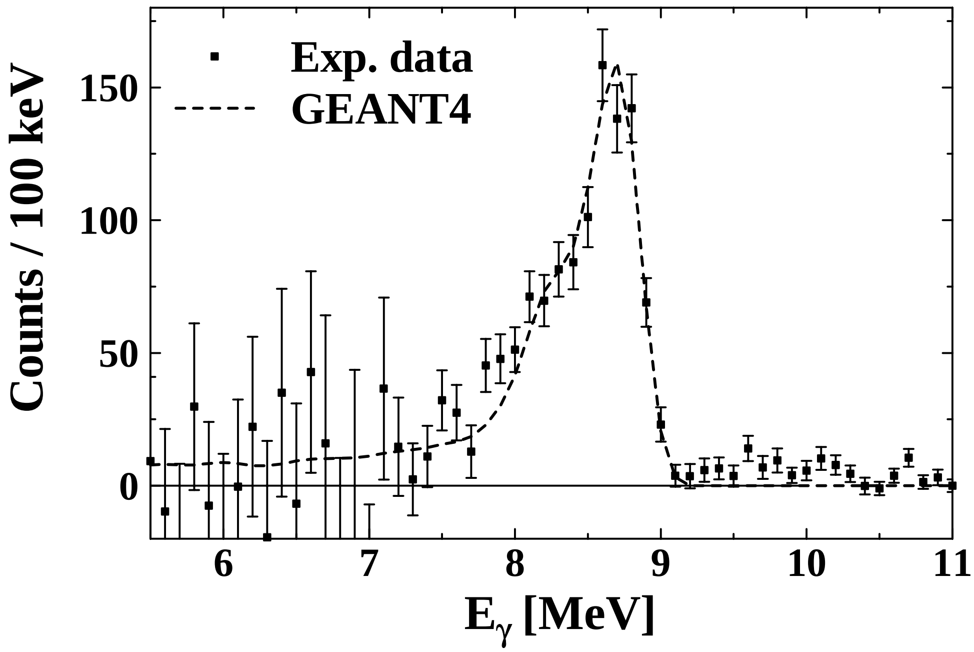

Figure 3: Net γ-ray energy spectrum of the $^{12}C(\alpha,\gamma)^{16}O$ reaction in the energy range from 5.5 to 11 MeV, which is obtained by gating the narrow peak at 0 ns of the TOF spectrum.

α-beam bombardment on the enriched ^{12}C targets at the target position. In order to see characteristic γ-rays from the $^{12}C(\alpha,\gamma)^{16}O$ reaction as well as γ-rays due to any contaminants in the target, the γ-ray spectrum was obtained by gating this narrow peak in the TOF spectrum as shown in Fig. 3. We clearly observed the characteristic γ-ray from the $^{12}C(\alpha,\gamma)^{16}O$ reaction at about 8.8 MeV with a large signal to noise ratio. One may wonder that there may be γ-ray background beneath the peak, which may be hard to be well separated from the true event with the TOF method. Hence, we made detailed studies of the spectrum. We observed discrete γ-ray peaks around 4 MeV together with the γ-ray peaks due to the inelastic collisions of neutrons with aluminum and lead. The discrete γ-ray peaks turned out to be due to the $^{10}B(\alpha,p\gamma)^{13}C$ and $^{9}Be(\alpha,n\gamma)^{12}C$ reactions. Namely, the enriched targets with gold backing contained both ^{9}Be and ^{10}B. However, because of the Q-values of the $^{10}B(\alpha,p)^{13}C$ and $^{9}Be(\alpha,n)^{12}C$ reactions, γ-ray energies from these reactions using α-beams of 2.27 MeV are lower than the characteristic γ-ray energy of 8.8 MeV from the $^{12}C(\alpha,\gamma)^{16}O$ reaction.

Through the study mentioned above we succeeded to observe the characteristic γ-ray events from the $^{12}C(\alpha,\gamma)^{16}O$ reaction with a good signal-to-noise ratio, and the origins of background γ-rays are identified. These results demonstrate high sensitivity of the present system to study the $^{12}C(\alpha,\gamma)^{16}O$ reaction at low α-beam energy below $E_{c.m.} = 1$ MeV.

Acknowledgments

We would like to thank Prof. I. Sugai and Mr. Y. Takeda for making enriched ^{12}C targets with excellent performance, and Mr. K. Tosaka for his help in measuring the pulse width of α beam and for his nice operation of the Pelletron accelerator. The present work was supported by Grant-in-Aid for Specially Promoted Research of the Japan Ministry of Education, Science, Sports, and Culture.

References

[1] T.A. Weaver and S.E.Woosley, Phys. Rep. **227** (1993) 65.

[2] P. Dyer and C.A. Barnes, Nucl. Phys. **A233** (1974) 495.

[3] G. Roters, C. Rolfs, F. Strieder, and H.P. Trautvetter, Eur. Phys. J. **A6** (1999) 451.

[4] A. Redder et al., Nucl. Phys. **A462** (1987) 385.

[5] J.M.L. Ouellet et al., Phys. Rev. **C54** (1996) 1982.

[6] R. Kunz et al., Phys. Rev. Lett. **86** (2001) 3244.

[7] L. Gialanella et al., Eur. Phys. J. **A11** (2001) 357.

[8] T. Ohsaki, Y. Nagai, M. Igashira, T. Shima, T. S. Suzuki, T. Kikuchi, T. Kobayashi, T. Takaoka, M. Kinoshita, and Y. Nobuhara, Nucl. Instr. and Meth. in Phys. Res. **A425** (1999) 302.

[9] H. Makii, K. Mishima, M. Segawa, E. Sano, H. Ueda, T. Shima, Y. Nagai, M. Igashira, and T. Ohsaki, Nucl. Instr. and Meth. in Phys. Res. **A547** (2005) 411.

[10] S. Agostinelli, et al., Nucl. Instr. and Meth. in Phys. Res. **A506** (2003) 250.

[11] F. Zijderhand, F.P. Jansen, C. Alderliesten and C. Van Der Leun, Nucl. Instr. and Meth. in Phys. Res. **A286** (1990) 490.

[12] D.K. Kennedy, J.C.P. Heggie, P.J. Davies and H.H. Bolotin, Nucl. Instr. and Meth. **140** (1977) 519.