

Direct Measurement of the ${}^4\text{He}({}^{12}\text{C}, {}^{16}\text{O})\gamma$ Total Cross Section Near Stellar Energies

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Abstract. A cross section measurement employing a direct ${}^{16}\text{O}$ detection method for the reaction energies from $E_{cm} = 2.4$ to 0.7 MeV is planned at Kyushu University Tandem Laboratory (KUTL). To perform this experiment and to obtain quantitative information about the cross section to within an error of 10%, we have developed several instruments, including a blow-in type windowless gas target, a recoil mass separator and a RF-deflector. The measurements at $E_{cm} = 2.4$ and 1.5 MeV have been performed with these instruments. For measuring at $E_{cm} < 1.2$ MeV, a hybrid detector employing both, an ionization chamber and a silicon detector was developed to reduce the carbon backgrounds more efficiently. The oxygen ions were clearly separated from carbon background by using the energy deposit in the ionization chamber. Experiment of $E_{cm} = 1.2$ MeV was performed and the cross section was obtained.

1 Introduction

When hydrogen burning ceases in heavy stars, helium burning ignited and proceeds by the "triple α reaction" to produce ${}^{12}\text{C}$ and then further via ${}^{12}\text{C} + {}^4\text{He} \rightarrow {}^{16}\text{O} + \gamma$. The abundance ratio of ${}^{12}\text{C}$ to ${}^{16}\text{O}$ after helium burning depends sensitively on the cross sections of these two reactions. It is a very important parameter for predicting the evolution of heavy stars especially having over 8 solar masses [1, 2] and hence the abundance of elements in the universe. Although extensive experimental research for both the reactions have been performed, the accuracies of the measured cross sections are not sufficient for a reliable extrapolation of the S-factor into the Gamow window [3, 4]. The cross section of the latter reaction at the energy of Gamow window has not been precisely determined clearly due to the lack of experimental data despite over 45 years of study by researchers all over the world [5, 6]. Since the cross section varies drastically around a stellar energy of 0.3 MeV due to the resonance states of ${}^{16}\text{O}$ in the subthreshold region, experimental data at very low energies ($E_{cm} = 1.5$ – 0.7 MeV) with an uncertainty of less than 10% are required for a reliable extrapolation of the S-factor into the Gamow window.

To determine the cross section and the astrophysical S-factor at this stellar energy by extrapolation, we propose measuring experimental cross sections for energies in the range $E_{cm} = 2.4$ to 0.7 MeV. Several methods have been used to measure the cross section of ${}^{12}\text{C} + {}^4\text{He}$ including the detection of emitted gamma rays with both a helium and a ${}^{12}\text{C}$ beam, measuring the decay particles from the ${}^{16}\text{N}$, and direct ${}^{16}\text{O}$ measurement with a carbon beam [7].

In this study, we used a direct ${}^{16}\text{O}$ recoil particle measurement, since its detection efficiency is very high ($\geq 30\%$) and the total S-factor can be obtained directly. To perform this experiment at an energy of 0.7 MeV with high statistical significance, it is necessary to use a high intensity beam of more than $10 \mu\text{A}$ and thick gas target of more than 25 Torr and 3 cm length corresponding to a target thickness of 2.4×10^{18} atoms/cm². Furthermore, a background separation system is very important for reducing ${}^{12}\text{C}_{BG}$ contamination with respect to the primary beam ${}^{12}\text{C}_{beam}$. The background separation system with an ultimate rejection factor of ${}^{12}\text{C}_{BG}/{}^{12}\text{C}_{beam} \leq 10^{-19}$ is therefore the goal of our work. The production yield of ${}^{16}\text{O}$ at an energy of 0.7 MeV is estimated to be 5 counts/day, which requires performing the experiment for about one month in background free conditions to achieve a statistical error of less than 10 %.

A series of experiments was performed at Kyushu University Tandem Accelerator Laboratory (KUTL), where it is possible to perform high efficiency measurements by using inverse kinematics similar to the method used at the Ruhr University in Bochum, Germany [7]. Also in our experiment a ${}^{12}\text{C}$ beam is injected on a windowless ${}^4\text{He}$ gas target. In this way, the total cross section can be obtained by detecting only recoil ${}^{16}\text{O}$ emitted within a forward angle of $\pm 2^\circ$, so that all recoil ${}^{16}\text{O}$ ions having an arbitrarily selected charge state can be observed by using a mass separator to separate them from the ${}^{12}\text{C}$ beam.

2 Experiment

Cross section measurements for $E_{cm} = 2.4$, 1.5 and 1.2 MeV were performed at KUTL by using a tandem accel-

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erator to accelerate $^{12}\text{C}^-$ ions from a sputter ion source (SNICSII, NEC) to 9.6, 6.0 and 4.8 MeV, respectively. We used a pulsed ^{12}C beam to obtain timing information for the scattered particles, which is very effective for reducing the background. To generate a pulsed beam, a beam buncher and a beam chopper were installed at upstream and downstream of the tandem accelerator, respectively.

Since the energies of the ^{12}C beam and the generated ^{16}O ions were very low, the target had to be thinner than $18 \mu\text{g}/\text{cm}^2$ (2.4×10^{18} atoms/ cm^2) to ensure that less than 10% of the incident beam energy was lost. Since foils could not be used to confine the ^4He gas target, we employed a blow-in windowless gas target by upgrading the old device [9]. To confine the gas in the target center, a small cylindrical bore with a diameter of 2.5 mm was formed in the target cell. The differential pumping system enabled the pressure of 24 Torr to be attained at the target center. The effective thickness along the beam axis was estimated to be 4.45 cm from measuring of $\text{p} + ^4\text{He}$ elastic scattering. In the practical operation, the target thickness was optimized by considering the energy deposit of the ^{12}C beam. Pressures of 20, 15, and 12 Torr were used for the experiments at $E_{\text{cm}} = 2.4, 1.5,$ and 1.2 MeV, respectively.

The produced ^{16}O was transported to a recoil mass separator (RMS) where it was separated from the unreacted ^{12}C beam and it was detected by a silicon (Si) SSD detector and ionization chamber. The time of flight (TOF) and the total energy of the particles were determined from data obtained by the detectors. The RMS is designed for nuclear astrophysics experiments of zero degree measurements, and consists of an electric deflector (ED), two dipole magnets (D1 and D2), and focusing magnets (Q1~4, SX1, SX2 and MQ). The particles are finally caught by the detector placed at the final focal plane (F2) of the RMS. The schematical layout for the target, the RMS and the detector is shown in Fig.1.

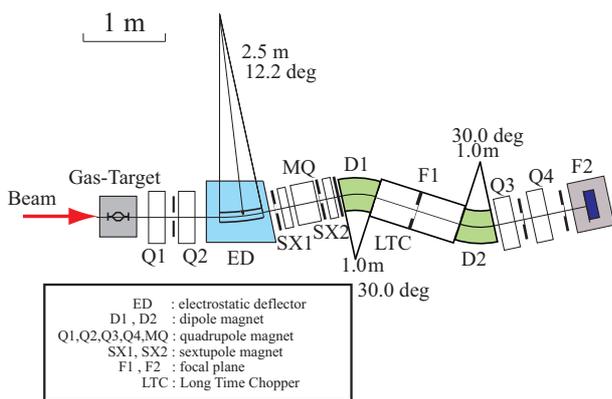


Figure 1. Schematic layout of the recoil mass separator. The names of instruments are given in the insets.

Most of the background was considered to consist of charge-exchanged and degraded ^{12}C ions generated by the ^{12}C beam hitting objects such as the target frame, beam pipes, slits, magnet poles, and the ED electrode. By varying the charge state, some of the ^{12}C ions had the same rigidity as the ^{16}O ions produced from the $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$

reaction. To remove the background particles based on the flight time difference, we installed a RF deflector, which we named a long time chopper (LTC), at the F1 plane (see Fig.1). Since the energies of the recoil ^{16}O ions varied depending on the energy of the generated gamma rays, their arrival times in the F1 plane were spread over ~ 50 ns. Consequently, the chopper needed to have a long time window to accept all recoil ^{16}O ions. The LTC voltage has a flat-bottom profile that was obtained by summing the DC voltage and two RF voltages with the standard frequency (f_0) and three times the standard frequency ($3f_0$). In the $E_{\text{cm}} = 1.5$ MeV experiment, an effective voltage of the LTC was set to $V_{\text{pp}} = 30$ kV with a frequency of 3.2 MHz to get deflection angle of 15 mrad for the unwanted ^{12}C .

The detector is a combination of an ionization chamber with Frisch grid [8] and a silicon SSD (Si-SSD). The information of ΔE in the gas volume for an incident particle is obtained from the ionization chamber, and the residual energy and the timing information are obtained from the Si-SSD. The detector was operated with the PR gas (90% Ar+ 10% CH_4) of 10 Torr, which is corresponded to the ΔE of 0.92 MeV for the ^{16}O ions of 3.6 MeV. The adopted arrangement of the cathode electrode, the Frisch grid and the anode electrode was 0 (GND), +10 and +100 V, respectively. Counting rates of ~ 1 kHz for the ionization chamber and ~ 100 Hz for the Si-SSD were recorded with an incident beam intensity of 100 pA. Since the low energy ^{12}C ions of < 0.8 MeV stop in the PR gas, while the ^{16}O ions of 3.6 MeV penetrate it. Thus the low energy ^{12}C background could be removed easily by the chamber gas.

3 Results

The experiments at the center-of-mass energy of 2.4, 1.5 and 1.2 MeV were performed. For the $E_{\text{cm}} = 1.2$ MeV experiment, a 4.8 MeV $^{12}\text{C}^{2+}$ beam was used and $^{16}\text{O}^{3+}$ ions of 3.6 MeV were observed. The experimental data were collected for 98 hours with the beam intensity of 200 pA on an average. The beam current and the gas pressure of the target were monitored by a Si-SSD installed on the target, and estimated from the yield of the $^{12}\text{C} + ^4\text{He}$ elastic scattering. We also obtained the background data by using a Ar gas instead of the He gas in the target.

A two-dimensional plot of the correlation between the TOF and total energy is shown in Fig.2. The data in the upper figure were taken without requiring background subtraction by the ΔE data. Almost all events in the plot were due to background ^{12}C ions. The ^{16}O ions are expected to appear in the circled area. The event selection of the ^{16}O ions was performed by the ΔE data, which is shown in the lower part of Fig.2. The background events having the same energy and TOF with ^{16}O ions were found to be drastically reduced. We finally found the 114.6 events of the ^{16}O ions by subtracting the contaminated background of ^{12}C ions. In the previous experiments, the charge state fractions of the ^{16}O ions after passing through the gas target had been measured to be 36.9 ± 0.18 , 35.97 ± 0.34 , and 42.16 ± 0.15 % at $E_{\text{cm}} = 2.4, 1.5,$ and 1.2 MeV. By taking the statistical and systematic errors into account, the

S-factors at $E_{cm} = 2.4, 1.5$ and 1.2 MeV were estimated to be 89.0 ± 2.8 , 26.6 ± 2.8 and 30.3 ± 5.0 keV·barn, respectively. The correlation between the measured S-factor and the center-of-mass energy are shown in Fig. 3.

4 Summary and Future Plan

The direct ^{16}O measurement via the $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reaction was proposed to determine the abundance ratio of ^{12}C and ^{16}O after helium burning. We have measured the cross section at reaction energies of $E_{cm} = 2.4, 1.5$ and 1.2 MeV. The cross section and the S-factor was successfully determined within 20% error for respective measurements.

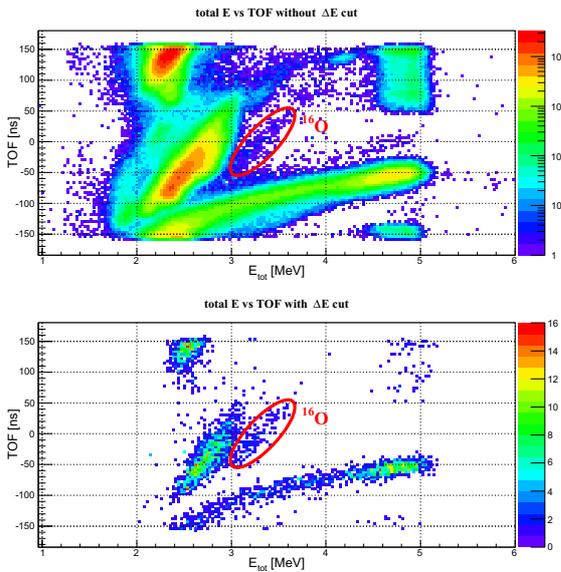


Figure 2. The upper and lower panels show the correlation between the TOF and the total energy with and without the event selection by the ΔE data, respectively. The area of closed by dotted circle represents the expected region of ^{16}O events.

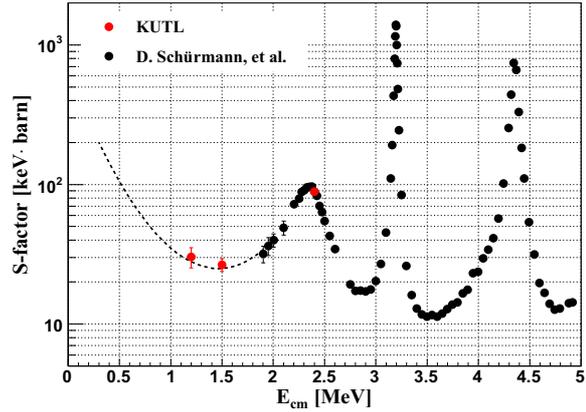


Figure 3. Results for the astrophysical S-factor as a function of the center-of-mass energy. The black circles between $E_{cm} = 5.0$ to 1.9 MeV represent data obtained by D. Schürmann et al.[7], while the three red circles represent data obtained by our experiments.

By using the present instruments, the ratio of the background ions to the ^{12}C beam ions of 10^{-19} was achieved, which is sufficient for measuring the $E_{cm} = 0.7$ MeV cross section. In the next step, we plan to measure the cross section at $E_{cm} = 1.0$ MeV, which is expected to be a factor 2 lower than the cross section at $E_{cm} = 1.2$ MeV. To achieve this goal it also necessary to develop a pulsed carbon beam of higher intensity (up to 1 particle μA).

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