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Direct measurement of $^{4}\mathrm{He}(^{12}\mathrm{C},^{16}\mathrm{O})\gamma$ reaction near stellar energies

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A cross section measurement employing a direct ^{16}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 developed several instruments in 2009, including a blow-in type windowless gas target and movable slits for the recoil mass separator. A target thickness of 24×3.9 Torr·cm was achieved using the developed gas target. Trajectories in the recoil mass separator were analyzed to reduce the background generated by scattered ^{12}C ions. Experiment at E_{cm} = 2.4 MeV was performed using these instruments and the cross section was obtained. Experiment at E_{cm} =1.5 MeV was started and first result was obtained.

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1. Introduction

When hydrogen burning ceases in heavy stars, helium burning proceeds by the reactions 3 ^{4}He $\rightarrow^{12}$ C and ^{12}C + ^{4}He$\rightarrow$ ^{16}O + γ. The abundance ratio of ^{12}C to ^{16}O after helium burning depends on the cross sections of these two reactions. It is a very important parameter for predicting the evolution of heavy stars [1, 2] and hence the abundance of elements in the universe. The cross section of the former reaction has been extensively measured indirectly with sufficient precision, whereas the cross section of the latter reaction has not been precisely determined clearly due to the lack of experimental data despite over 40 years of study by researchers all over the world [3]. Since the cross section varies drastically around a stellar energy of 0.3 MeV due to the resonance states of ^{16}O in the subthreshold region, experimental data at very low energies (E_{cm} = 1.5–0.7 MeV) with an error of 10% are required to predict the reaction rate to within an error of 10%.

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}C + ^{4}He including the detection of emitted gamma rays with both a helium and a ^{12}C beam, measuring the decay particles from the ^{16}N, and direct ^{16}O measurement with a carbon beam [4]. In this study, we used a direct ^{16}O recoil particle measurement, since its detection efficiency is very high ($\approx$30%) and the total S-factor can be obtained directly.

To perform this experiment at an energy of 0.7 MeV, it is necessary to develop a high intensity beam of more than 10 pμA. We decided to build a thick gas target of 25 Torr and 3 cm length corresponding to a target thickness of 2.7×10^{18} atoms/cm^2. Furthermore, a background separation system is very important for reducing ^{12}C$_{BG}$ contamination with respect to the primary beam ^{12}C$_{beam}$. A recoil separator with an ultimate rejection factor of ^{12}C$_{BG}/^{12}$C$_{beam} \leq 10^{-19}$ is therefore the goal of our work. The production yield of ^{16}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 the background free circumstances 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 [4]. Also in our experiment a ^{12}C beam is injected on a windowless ^{4}He gas target. In this way, the total cross section can be obtained by detecting only recoil ^{16}O emitted within a forward angle of $\pm2^\circ$, so that all recoil ^{16}O ions having an arbitrarily selected charge state can be observed by using a mass separator to separate them from the ^{12}C beam.

2. Experimental Setup

Cross section measurements for E_{cm} = 2.4 and 1.5 MeV were performed at KUTL by using a tandem accelerator to accelerate ^{12}C$^-$ ions from a sputter ion source (SNICSII, NEC) to 9.6 and 6.0 MeV, respectively. In the E_{cm} = 1.5 MeV experiment, the charge state of 1+ was selected for the ^{12}C beam and an acceleration voltage of 3.0 MV was used. By using such a high voltage, a transmission efficiency of over 20% was obtained. 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. They were operated with the 6.1 and 3.6 MHz clock signals in the respective measurements.

Since the energies of the ^{12}C beam and the generated ^{16}O ions were very low, the target had to be thinner than 20 $\mu g/cm^2$ to ensure that less than 10% of the incident beam energy was lost. Since foils could not be used to confine the ^{4}He gas target, we employed a blow-in windowless gas target by upgrading the old one [5]. 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, which consisted of three mechanical booster pumps, five turbomolecular pumps, and a diffusion pump, was upgraded by replacing the booster pump with one with a higher pumping speed; this enabled a pressure of 24 Torr to be attained at the target center. The effective thickness along the beam axis was measured by p + ^{4}He scattering. The target thickness was optimized by considering the energy loss of the ^{12}C beam.

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. The time of flight (TOF) and the total energy of the particles were determined from data obtained by the Si-SSD detector. The RMS consists of an electric deflector (ED), two dipole magnets (D1 and D2), and focusing magnets. There were two focal planes, F1 (velocity dispersive) and F2 (mass dispersive); all recoil ^{16}O ions were collected in the F2 plane.

To remove background particles based on the flight time difference, we installed a RF deflector, which we termed a long time chopper (LTC), between D1 and D2. 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 $\sim$50 ns. Consequently, the chopper needed to have 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 ($3f_0$). At E_{cm} = 2.4 MeV experiment, an effective voltage of the LTC was set to V_{pp} = 40 kV with a frequency of 6.1 MHz to get deflection angle of 15 mrad for the unwanted ^{12}C.

3. Background Reduction

It is important to reduce the background to obtain systematic errors of less than 10% for the cross section and S-factor at E_{cm} = 1.5 MeV. 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, 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}He(^{12}C,^{16}O)γ reaction. To reduce the background, the particle trajectories in the RMS were calculated using the ORBIT program and the measured field maps of the magnets in the RMS. ^{12}C ions with various charge states and ^{16}O ions were generated from the target with angular and spatial spreads by accounting for the reaction kinematics and multiple scattering in the ^{4}He gas. It was found that 6.0 MeV ^{12}C^{3+} ions and 3.0 MeV ^{12}C^{2+} ions could pass through the RMS and hit the beam pipes near the LTC (see in Fig. 1) and that most of the ^{12}C background could be simulated. Based on these simulation results, we installed movable slits upstream and downstream of the LTC to stop ^{12}C particles from scattering by objects near the LTC (see Fig. 2).

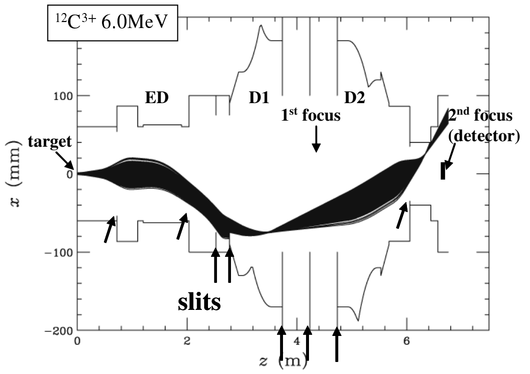

Figure 1: Trajectory of 6.0 MeV ^{12}C^{3+} ions. The horizontal and vertical axes respectively represent the flight path length and the distance from the central ray in the horizontal plane. The charge-exchange background is caused by ions hitting beam pipes and/or slit edges.

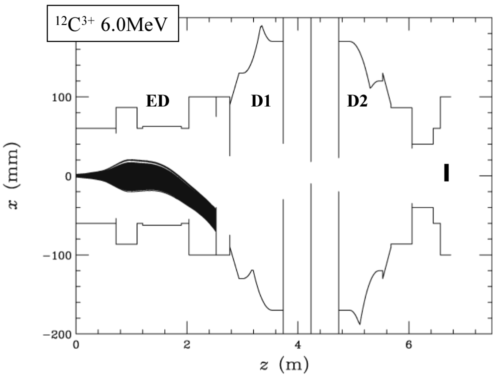

Figure 2: Trajectory of ^{12}C^{3+} ions in the RMS after rearranging the movable slits. The background is removed before the first focal plane ($z \simeq 4.2$ m)

4. Experimental Results

The 2.4 MeV reaction energy experiment was performed in January 2009. A 9.6 MeV ^{12}C^{2+} beam was used and the 7.2 MeV ^{16}O^{5+} ions were observed. The charge state fraction of the ^{16}O ions after passing through the gas target had been measured to be 36.9±2.1 % in a previous experiment. Fig. 3 shows a two-dimensional plot of the particle energy and the TOF correlation measured by the Si-SSD detector. The closed circle indicates the expected region for the ^{16}O events. The LTC drastically reduced the charge exchange background. Consequently, we observed 941 events for ^{16}O ions over 29 h. The experiment at E_{cm} = 1.5 MeV was performed in July 2010. A 6.0 MeV ^{12}C^{1+} beam was used and ^{16}O^{4+} ions were observed for 15 h. Insufficient statistics were obtained due to problems with the pumping system. As shown in Fig. 4, the locus of the ^{16}O event was observed. Although some background remained in the ^{16}O region, 29 events involving ^{16}O ions could be identified by subtracting the ^{12}C background.

The cross section and S-factor at 2.4 MeV were respectively obtained to be 64.6 ± 7.4 nb and 89.0 ± 10.2 keV·b. The S-factor at 1.5 MeV was determined to be 30±12 keV·b, although a large error remained due to the residual backgrounds (see Fig. 5).

5. Summary

Direct ^{16}O measurement via the ^{4}He(^{12}C,^{16}O)γ reaction was proposed to determine the abundance ratio of ^{12}C and ^{16}O after helium burning in heavy stars. We developed a windowless gas target with a thickness of 24×3.9 Torr·cm by adopting a blow-in architecture. To reduce the background, trajectory analysis was performed for ^{12}C and ^{16}O ions in the RMS. We found that most of the background could be eliminated by suitably positioning the movable slits.

Cross-section measurements were performed for reaction energies of E_{cm} = 2.4 and 1.5 MeV. The S-factor at E_{cm} = 2.4 MeV was determined to be 89.0±10.2 keV·barn. The S-factor at E_{cm}

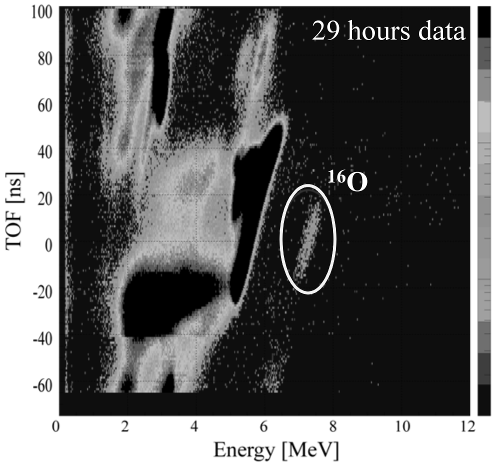

Figure 3: Two-dimensional scatter plot of the kinetic energy and the TOF obtained from the E_{cm} = 2.4 MeV experiment. ^{16}O events can be seen in the area enclosed by the solid ellipse.

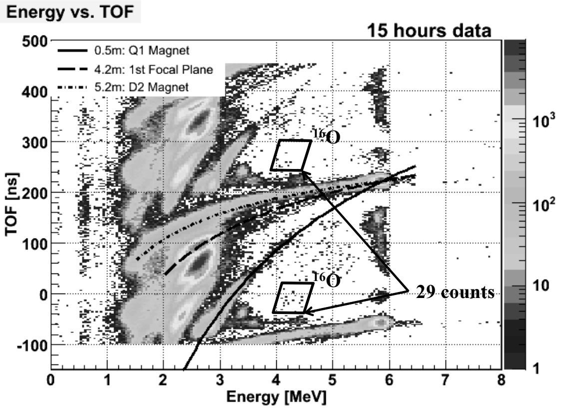

Figure 4: Results of the E_{cm}=1.5 MeV experiment. Two RF cycles are shown. ^{16}O loci are visible in the closed circles. The three curves represent background curves from different source points (see inset).

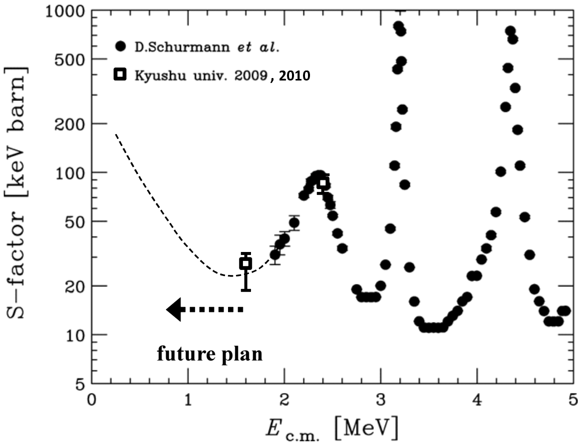

Figure 5: Preliminary results for the astrophysical S-factor as a function of the center-of-mass energy. The closed circles between E_{cm} = 5.0 to 1.9 MeV represent data obtained by Ruhr University [4], while the two open squares represent data obtained by our experiments in 2009 and 2010.

= 1.5 MeV was not precisely determined, since the background reduction was insufficient. To identify the ^{16}O, we plan to develop a detector to obtain ΔE-E data of the recoil particles.

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