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Direct measurement of the ^{4}He(^{12}C,^{16}O)γ cross section in inverse kinematics

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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 have developed several instruments, including a blow-in type windowless gas target and an ionization chamber. A target thickness of 24×3.9 Torr·cm was achieved using the developed gas target. The particle identification was successfully performed by using the energy deposit in the ionization chamber. Experiments were performed at E_{cm} = 2.4 and 1.5 MeV using the developed instruments and the cross sections were obtained. A hybrid detector employing both an ionization chamber and a Si-SSD detector was developed to reduce the carbon backgrounds more efficiently. It was found that the new detector could reduce the background ratio by three orders, and the experiments in $E_{cm} < 1.2$ MeV were ready for carrying out.

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1. Introduction

When hydrogen burning ceases in heavy stars, helium burning proceeds by the reactions $3\,^4\mathrm{He} \rightarrow ^{12}\mathrm{C}$ 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. Although the experimental research for both the reactions have been perfomed extensively, the accuracies of the measured cross sections are still insufficient [3]. The cross section of the latter reaction, in particular, 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 [4]. 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 [5]. In this study, we used a direct ^{16}O recoil particle measurement, since its detection efficiency is very high ($\sim$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 thick gas target as well as a high intensity beam. We decided to build the 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 $^{12}\mathrm{C}_{BG}$ contamination with respect to the primary beam $^{12}\mathrm{C}_{beam}$. A recoil separator with an ultimate rejection factor of $^{12}\mathrm{C}_{BG}/^{12}\mathrm{C}_{beam} \leq 10^{-19}$ 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 [5]. 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. Experiment

Cross section measurements for E_{cm} = 2.4 and 1.5 MeV were performed at KUTL by using a tandem accelerator to accelerate $^{12}\mathrm{C}^-$ ions from a sputter ion source (SNICSII, NEC) to 9.6 and 6.0 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. They were operated with the 6.1 and 3.6 MHz clock signals(equivalent to the interval of the beam pulses of 164 and 278 ns) in the respective measurements. The pulse width of the beam were typically 6 and 10 ns, 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 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 [6]. 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.

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 remove the 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} = 1.5 MeV experiment, an effective voltage of the LTC was set to V_{pp} = 30 kV with a frequency of 3.2 MHz to get deflection angle of 15 mrad for the unwanted ^{12}C.

3. Experimental Results

The experiments at the center-of-mass energy of 2.4 and 1.5 MeV were performed in 2009 and 2010. For the E_{cm} = 1.5 MeV experiment, a 6.0 MeV $^{12}C^{1+}$ beam was used and $^{16}O^{3+}$ ions were observed. Fig. 1 shows a two-dimensional plot of the particle energy and the TOF correlation measured by the Si-SSD detector. The closed area of the parallelogram indicates the expected region for the ^{16}O events. By using the background reduction system mentioned previous section, the locus of the ^{16}O event was clearly separated from the ^{12}C background, and 208 events were obtained. The charge state fractions of the ^{16}O ions after passing through the gas target had been measured to be 39.11 $\pm$ 0.40 % at the setting of E_{cm} = 1.5 MeV.

The cross section and S-factor at 1.5 MeV were respectively obtained to be 0.900 $\pm$ 0.09 nb and 26.6 $\pm$ 2.8 keV$\cdot$b. The correlation between the measured S-factor and the center-of-mass energy are shown in Fig. 2.

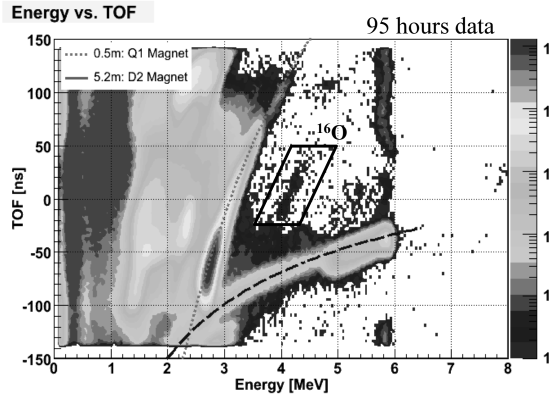

Figure 1: Results of the E_{cm}=1.5 MeV experiment. ^{16}O events can be seen in the area enclosed by the solid lines. The dashed and dotted curves represent background curves from different source points (see inset).

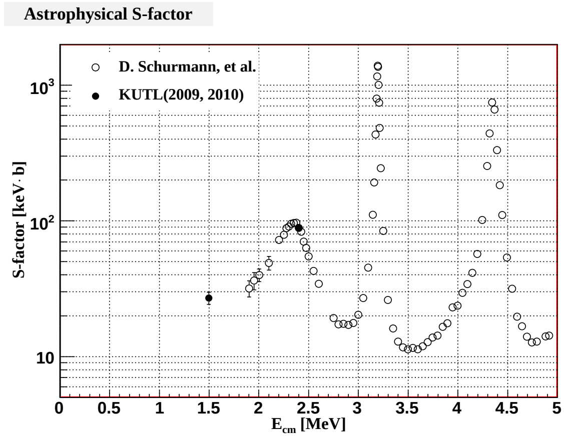

Figure 2: Results for the astrophysical S-factor as a function of the center-of-mass energy. The open circles between E_{cm} = 5.0 to 1.9 MeV represent data obtained by Ruhr University [5], while the two closed circles represent data obtained by our experiments in 2009 and 2010.

4. Detector Development

The ratio between background and the beam was estimated to be $^{12}C_{BG}/^{12}C_{beam} = 10^{-16}$ in the present setting, although the ratio of 10^{-19} is necessary for the E_{cm} = 0.7 MeV experiment. To reduce the background more efficiently, we proposed to develop a oxygen detector introducing an ionization chamber technology. The ^{16}O would be distinguished from the $^{12}C_{BG}$ by the energy deposit information. From the simulation calculation, the determination of the energy deposit with the accuracy of better than 10% was found to be necessary for separating the oxygen and the carbon event in the energy ranges of E_{cm} = 0.7–1.5 MeV. It is also of importance to have enough large effective area to cover all of the oxygen particles, whose spatial spread was expected to be $\sim$10$\times$15 mm from the simulation calculation. Furthermore, since the kinetic energy of produced oxygen is very small ($<$4.5 MeV for $E_{cm} < 1.5$ MeV experiments), the thickness of the entrance foil and chamber gas should be smaller than $\sim$ 100 $\mu g/cm^2$. As described previous section, the TOF information obtained from the Si-SSD detector is indispensable, since the timing resolution should be better than 1 ns in order to identify the oxygen events.

Considering the requirement for the oxygen detector, a new detector based on a gas chamber technology was developed. As shown in Fig. 3, the oxygen detector consists of the ionization chamber and the Si-SSD detector. The ionization chamber provides data of the energy deposit in the gas chamber, and the Si-SSD detector provides two kinds of data i.e., the TOF and the energy. The entrance window consists of PET foil with a thickness of 65$\mu g/cm^2$ and a diameter of $\phi 45 mm$, and PR-gas(Ar/CO_2, 9:1) of 10–30 Torr is used for the counter gas.

The examination with the same setting as E_{cm} = 1.5 MeV experiment was carried out on the performance of the detector. We used pilot ^{16}O beam and produced ^{12}C backgrounds for such purposes. An example of a two-dimensional plot representing the energy deposit and total energy correlation is shown in Fig. 4. We can see the ^{16}O and the ^{12}C particles having the same energies are clearly separated. From this result, the background reduction ratio is estimated to be 10^{-3}, which satisfy the requirement as mentioned above.

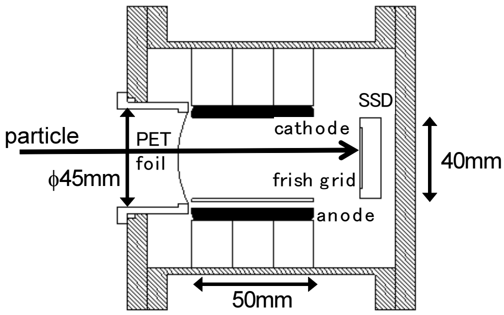

Figure 3: Schematical view of the arrangement of the oxygen detector consisting of the ionization chamber and the Si-SSD detector.

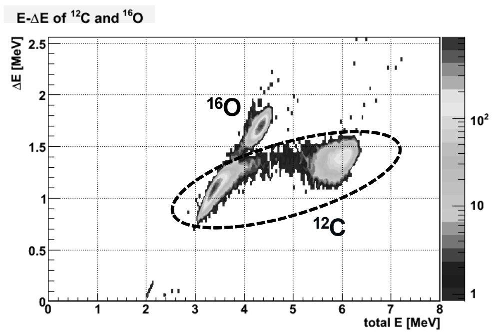

Figure 4: Correlation between the total energy and the energy deposit in the ionization chamber.

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. 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 and 1.5 MeV was determined to be 89.0 $\pm$ 3.8 and 26.6 $\pm$ 2.8keV·barn, respectively. The performance test of the developed oxygen detector was performed, and the background ^{12}C having the same energy as ^{16}O were clearly separated by using the energy deposit in the ionization chamber. Since, it was found that the background ratio(^{12}C$_{BG}$/^{12}C$_{beam}$) was reduced by three orders, we are ready to perform the experiment at $E_{cm} < 1.2$ MeV.

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