Measurement of ^{12}C(n,n') reaction cross section to determine triple-alpha reaction rate in high-density environments

Tatsuya Furuno[1,*], *Takanobu* Doi[2], *Kanako* Himi[1], *Takahiro* Kawabata[1], *Satoshi* Adachi[1], *Hidetoshi* Akimune[3], *Shiyo* Enyo[2], *Yuki* Fujikawa[2], *Yuto* Hijikata[2,4], *Kento* Inaba[5], *Masatoshi* Itoh[6], *Shigeru* Kubono[4], *Yohei* Matsuda[3], *Isao* Murata[7], *Motoki* Murata[8], *Shintaro* Okamoto[2], *Kosuke* Sakanashi[1], and *Shingo* Tamaki[7]

[1]Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
[2]Department of Physics, Kyoto University, Sakyo, Kyoto 606-8502, Japan
[3]Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan
[4]RIKEN Nishina Center, Wako, Saitama 351-0198, Japan
[5]Institute for Advanced Synchrotron Light Source, Quantum Scinence and Technology, Sendai, Miyagi 980-8579, Japan
[6]Cyclotron and Radio Isotope Center (CYRIC), Tohoku University, Sendai, Miyagi 980-8578, Japan
[7]Division of Sustainable Energy and Environmental Engineering, Osaka University, Suita, Osaka 565-0871, Japan
[8]Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan

Abstract. The reaction rate of the triple-alpha reaction can be enhanced in hot and dense environments due to the deexcitation of the Hoyle state in ^{12}C by neutrons. The cross section of the deexcitation should be determined for the enhanced reaction rate. We plan to obtain the cross section by measuring the inverse reaction using a neutron beam around 10 MeV and an active target system. In the present paper, we report a proof-of-principle experiment using a neutron beam at 14 MeV. The obtained cross section is consistent with a previous result, demonstrating the validity of our method.

1 Introduction

The triple-alpha reaction is one of the most crucial nucleosynthesis reactions because it is the doorway reaction from $A < 5$ nuclei to heavier elements. In this reaction, the ground state of ^{12}C nucleus is populated from three alpha particles via the two alpha and three alpha resonance states in ^{8}Be and ^{12}C, followed by the gamma decay of the resonance state in ^{12}C. The resonance state in ^{12}C, known as Hoyle state, is located at $E_x = 7.65$ MeV with the spin parity of 0_2^+.

Since the triple-alpha reaction proceeds via the Hoyle state, its branching ratio to the ground state is directly related to the reaction rate. The probability of the gamma decay is experimentally determined as $(4.16{\pm}0.11){\times}10^{-4}$ [1]. Recently, it is pointed out that in hot and dense environments, the branching ratio of the Hoyle state to the ground state can be greatly enhanced due to the deexcitation scattering with the surrounding nuclei [2]. Because the

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[*] e-mail: furuno@ne.phys.sci.osaka-u.ac.jp

neutrons are not obstructed by the Coulomb barrier, the scattering with the neutrons increases the reaction rate the most by a factor of about 40 at the density of 10^6 g/cm^3 and temperature of 10^9 K.

In order to determine the enhanced reaction rate by the neutrons, it is necessary to measure the deexcitation cross section of the Hoyle state and neutrons. However, it is almost impossible to perform such an experiment because the life time of the Hoyle state is extremely short to use as a target. Instead of measuring the direct process, the deexcitation cross section can be obtained on the basis of the detailed balance principle by measuring the inverse reaction, i.e., the inelastic scattering of the ground state in ^{12}C and the neutron beam at about 10 MeV.

We will reconstruct the excitation energy of ^{12}C by detecting the three alpha particles emitted from the Hoyle state, and calculating the invariant mass. The energy of the alpha particles, however, is extremely small ($\sim$100 keV), thus they cannot be detected with a normal detector system. In our experiment, the low-energy alpha particles will be detected using an active target system MAIKo [3]. The MAIKo active target is based on a gaseous time projection chamber (TPC) and capable of recording three-dimensional trajectories of the incident charged particles. In MAIKo, the detection gas of the TPC plays also as the target gas of the scattering. Since the scattering occurs inside the sensitive volume of the TPC, the detection threshold is lowered.

In the present article, we report the proof-of-principle experiment using MAIKo to detect the low-energy alpha particles emitted from the Hoyle state and reconstruct the invariant mass of ^{12}C.

2 Experiment

The experiment was carried out at the intense deuterium-tritium neutron source facility (OKTAVIAN) of Osaka University. The mono-energetic neutron beam at 14 MeV was produced by the DT fusion reaction of a tritium target bombarded by a deuteron beam at 300 keV from a Cockcroft-Walton accelerator. Figure 1 shows the setup of the experiment. The neutron beam was collimated by a polyethylene collimator with a diameter of 20 mm installed inside the concrete wall of 1-m thick. The MAIKo active target was installed just behind the collimator. The number of the incident neutron beam was monitored with a BC501 liquid scintillator. The intensity of the neutron beam at MAIKo was approximately 10k cps in average.

The MAIKo TPC was operated with the iso-C_4H_{10}(10%)+H_2(90%) gas at 100 hPa. The iso-C_4H_{10} gas was used as the carbon target and the H_2 gas was added to suppress the diffusion of the drift electrons and improve the track reconstruction efficiency. The effective length of the target gas was 92.4 mm. When the inelastic scattering of carbon with neutron occurs and the excited carbon nucleus decay into three alpha particles, the alpha particles ionize the TPC gas. The electrons produced in the ionization drift along the electric field formed by the TPC field cage. The drift electrons are multiplied by a gas electron multiplier. The electrons are further amplified and detected by a micro pixel chamber (μ-PIC) [4]. The μ-PIC consists of 256 anode strips and 256 cathode strips with a pitch of 400 μm. The cathode strips are orthogonal to the anode strips. The sensitive area of the μ-PIC is 102.4×102.4 mm^2. Each strip of the μ-PIC is connected to the readout circuits which record the electron drift time. The drift time as a function of anode and cathode strip number provides the two-dimensional projection of the trajectories of the charged particles.

3 Data analysis and results

Figure 2 shows an example of the TPC track of the signal events in which the excited ^{12}C nucleus decay into three alpha particles. The left and right images show the anode and cathode

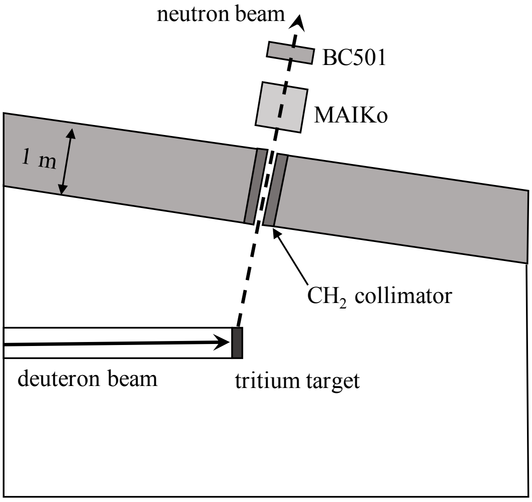

Figure 1. Experimental setup at OKTAVIAN.

projections, respectively. In addition to the signal events, many background events were acquired during the measurement. The background events consist of the elastic scattering with the hydrogen or ^{12}C, and the ^{12}C+n $\rightarrow ^{13}$C*$\rightarrow ^{9}$Be+^{4}He reaction. The signal events can be distinguished from the background events according to the number of trajectories contained in the TPC images. The signal events contain three trajectories whereas the elastic scattering events contain only one trajectory and the ^{13}C* events contain two trajectories of ^{9}Be and ^{4}He.

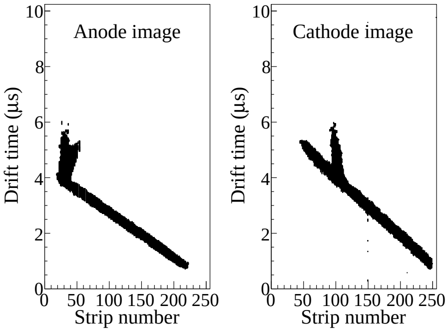

Figure 2. Example of the TPC track of three alpha decay from ^{12}C event. The left and right panels shows the anode and cathode iamges, respectively.

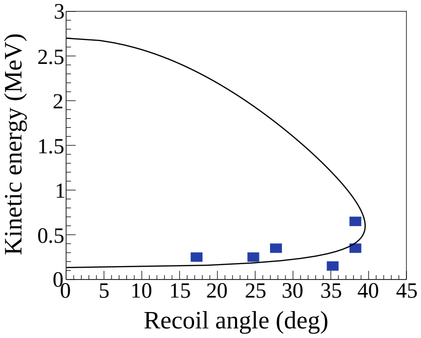

Figure 3. Scatter plot of the kinetic energy and angle of the recoil ^{12}C. The solid line represents the calculated energy and angle for the 0_2^+ state.

We performed an eye scan analysis to categorize the TPC images according to the number of trajectories. About 63,000 events were analyzed by 10 eye scanners. For events that were

Table 1. Summary of the experimental results.

Y	6 ± 2(stat.)
N_b	$[4.5 \pm 0.3$(syst.)$] \times 10^8$
N_t	9.2×10^{18} /cm^2
ϵ	0.104 ± 0.014(syst.)
σ (Present)	14 ± 6(stat.) $\pm$ 2(syst.) mb
σ (Previous [7])	8.4 mb

categorized as a candidate of the signal event, the eye scanner recorded the coordinates of the vertex position of three alpha trajectories and the end points of the trajectories in the anode and cathode images by mouse clickings. The kinetic energy and momentum of each alpha particle were calculated from the vector between the vertex position and the end point using a computer program SRIM [5]. The kinetic energy, recoil angle, and excitation energy of the ^{12}C nucleus were calculated with the invariant mass spectroscopy method.

Figure 3 represents the correlation between the reconstructed kinetic energy and recoil angle of ^{12}C. The calculated energies and angles for the 0_2^+ state in ^{12}C are plotted with the solid line. The events which lie around the solid line correspond to the inelastic scattering in which the ^{12}C was excited to the 0_2^+ state.

The detection and analysis efficiency of the inelastic scattering events to the 0_2^+ state was estimated by a Monte-Carlo simulation. In the simulation, the inelastic scattering events were generated along the beam region. The decay three alpha particles were then generated from the interaction point. The ionization of the TPC gas by the alpha particles was calculated using SRIM. The electrons due to the ionization were transported towards the μ-PIC plane taking into account for the drift speed and diffusion of the electrons in the gas. The analog signal from the μ-PIC for a single electron was simulated with the computer code Garfield++ [6]. The arrival time of the electrons at the μ-PIC was folded by the analog signal for a single electron. The simulated signals were virtually processed to generate the anode and cathode images. The generated images were analyzed by the eye scanner in the same manner as the experimental data. The detection and analysis efficiency was obtained by the number of events in which three alpha particles stopped inside the sensitive volume of the TPC and the eye scanner identified as the signal event, divided by the number of total generated signal events.

The cross section if the inelastic scattering to the 0_2^+ state was obtained by $\sigma = Y/(N_b N_t \epsilon)$. Y, N_b, N_t, and ϵ are the yield of the signal events reconstructed in the analysis, number of incident neutrons, number of target nuclei for the unit area, and the detection and analysis efficiency, respectively. These values are summarized in Table 1. The cross section determined by the present measurement is, $\sigma = 14 \pm 6$(stat.)± 2(syst.) mb. This cross section is consistent with the previous one of $\sigma = 8.4$ mb reported by Kondo et al. [7], demonstrating the validity of our method using the MAIKo active target.

4 Future perspectives

We are now constructing a larger active target called MAIKo+ that has a sensitive volume of $300 \times 300 \times 300$ mm^3 to increase the statistics by 10 times from the present MAIKo. The MAIKo+ system will be commissioned at OKTAVIAN in 2022 to measure the same reaction as the present paper. After the commissioning experiment, the physics measurement using the neutron beam at around 10 MeV will be performed at CYRIC, Tohoku University.

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