Measurement of the 3-α decay from the Hoyle and the broad 10 MeV states in $^{12}$C

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Abstract. The measurements of the 3-α decay from the Hoyle and the broad 10 MeV state in $^{12}$C have been performed using an inverse kinematic method of the $^{12}$C($^{12}$C,3$\alpha$)$^{12}$C reaction at $E_{^{12}C} = 110$ MeV. In the measurement of the Hoyle state, the upper limit of the direct decay was improved to be 0.2 %. This was inconsistent with the recent reported nonzero value of 0.9 %, but an order larger than the direct decay branch predicted in the 3-α model. The branching ratios of the sequential decay for the broad 10 MeV state were also obtained. They were higher than those obtained in the RCNP experiment, since they contained the contributions of higher multipole components. Their contributions will be estimated.

1. Introduction

The second $0^+$ state at $E_x = 7.65$ MeV in $^{12}$C, which is called the Hoyle state, plays an important role in the creation of the $^{12}$C nucleus in stellar nucleosynthesis. However, its structure is not understood well, since the $0^+$ state does not appear at such a low excitation energy of 7.65 MeV in the simple shell model. According to the microscopic $\alpha$ cluster model, the Hoyle state is considered to have a dilute 3-α gaslike structure. Tohsaki et al. showed it was similar to the Bose-Einstein condensation of $\alpha$ clusters in the nucleus by their model wave function [1]. Recently, some ab initio calculations have been tried to explain properties of the Hoyle state including the ground state band in $^{12}$C [2, 3]. Among them, a lattice approach with chiral effective field theory succeeded in reproducing the excitation energy of the Hoyle state. In their result, the Hoyle state is considered to have a “bent-arm” or obtuse triangular configuration. The algebraic cluster model also succeeded to explain the spectrum of $^{12}$C with equilateral triangular configuration [4, 5]. In their model, the Hoyle state is considered to be the A symmetric stretching vibration or breathing mode of the triangular configuration. As described above, the configuration of 3-α clusters for the Hoyle state is still controversial.

It is difficult to determine the structure of the nuclear excited state, particularly the unbound states, experimentally. One possible way is the decay particle measurement. The first experiment was performed by Freer et al. [6]. They measured the decay 3-α particles from the Hoyle state via the $^{12}$C($^{12}$C,3$\alpha$)$^{12}$C reaction and found the Hoyle state decay to the 3-α particles through the ground state of $^8$Be + $\alpha$ channel and the upper limit of the direct decay branch was 4 %. In 2011, Raduta et al. reported the direct decay branch of $17 \pm 5$ % from the Hoyle state [7]. They measured the correlation function of three $\alpha$ particles emitted from the $^{40}$Ca + $^{12}$C...
reaction at the incident energy of 25 MeV per nucleon. In their results, the branching ratio of the direct decay with an equal energy of 3-α particles was 7.5 ± 4.0 %. They emphasized this was evidence for the α cluster condensation. However, it was inconsistent with the result of the first experiment by Freer et al.

This inconsistency has been tested by two experiments at first. One is the analysis of the \(^{10}\text{C} + \text{C}\) (Be) reaction by Manfredi et al. [8]. They obtained the upper limit of the 3.9 % for the direct decay from the Hoyle state, which was consistent with the result of the first experiment by Freer et al. Another is the experiment of the \(^{11}\text{B}(^{3}\text{He}, d\alpha)\) reaction by Kirsebom et al. [9]. They highly improved the upper limit of the direct decay to \(5 \times 10^{-3}\). In this way, the huge branching ratio of 17 % for the direct decay was excluded. Recently, the nonzero value of the direct 3-α decay branch from the Hoyle state was reported by Rana et al. [10]. They claimed their obtained nonzero branching ratio of 0.9 % for the direct decay was consistent with the upper limit obtained by Kirsebom et al. Therefore, more precise measurement was desired in order to verify this nonzero branching ratio obtained by Rana et al.

In this paper, the measures of the 3-α decay from not only the Hoyle state but also the broad 10 MeV state via the \(^{12}\text{C}(^{12}\text{C},3\alpha)\) reaction at \(E_{12C} = 110\) MeV are reported. The structure of the broad 10 MeV state in \(^{12}\text{C}\) is also still unclear. In our previous studies [11, 12], we pointed out the possibility of consisting of two components of the broad 0\(^+\) state at 10 MeV. In order to investigate the structure of the broad 10 MeV state, we studied the decay mechanism by the measurement of 3-α decay.

2. Experiment

The experiments were performed at the Cyclotron and Radioisotope Center (CYRIC), Tohoku University. The \(^{12}\text{C}^{4+}\) beams were accelerated up to 110 MeV by AVF cyclotron, and bombarded to the self-supported carbon foil with a thickness of 50 \(\mu \text{g/cm}^2\). The target was tilted to the beam direction in order to minimize the energy loss of the recoil \(^{12}\text{C}\) particle in the target. The decay 3-α particles were detected by the double-sided silicon strip detector (DSSD) with a size of \(50 \times 50 \text{ mm}^2\) and with a thickness of 1500 \(\mu \text{m}\) which has 16 \(\times\) 16 strips oriented vertically in the front side and horizontally in the rear side. Recoil \(^{12}\text{C}\) particles were caught by a silicon detector with a thickness of 150 \(\mu \text{m}\) at 67°. The silicon detectors were kept cooling around 0°\(\text{C}\) during the experiment. The \(^{12}\text{C}\) particle was identified by the time of flight method. From a complete kinematics method, in which all particles participated in the reaction were measured, we reconstructed the excitation energy of \(^{12}\text{C}\) and determined the decay mechanism of the Hoyle state.

In the measurement of the broad 10 MeV state, recoil \(^{12}\text{C}\) particles were not measured because their energies were too small to be measured at the forward scattering angle of the \(^{12}\text{C}\) beam. Two DSSDs were set at extremely forward angles for the detection of the decay α particles. Since the beam was stopped just in front of the DSSD, background events were much larger than the measurement of the Hoyle state. Therefore, the trigger signal was made from the event of the multiplicity 2 and over. Aluminum plates with a thickness of 200 \(\mu \text{m}\) were installed in front of the DSSDs to stop \(^{12}\text{C}\) particles of the beam halo and elastic scattering, which became main background particles without them. In this measurement, the excitation energy of \(^{12}\text{C}\) was determined from the relative kinetic energies between decay 3-α particles. Figure 1 shows the excitation energy spectrum of \(^{12}\text{C}\) obtained the measurement of the broad 10 MeV state.

3. The 3-α decay from the Hoyle state

To visualize the energy correlation of the decay 3-α particles, the symmetric Dalitz plot is adopted in the analysis of the Hoyle state. Figure 2 shows the symmetric Dalitz plots obtained in the present measurement and the Monte Carlo simulation. The number of events in each simulation plot in Fig. 2 was same as that of the experimental plot. Three decay mechanisms were
Figure 1. The excitation energy spectrum of $^{12}$C obtained in the measurement of the broad 10 MeV state. The broad 10 MeV state were divided into 4 regions (a, b, c, d). See text.

Figure 2. The symmetric dalitz plot of the decay 3-$\alpha$ particles from the Hoyle state. (a) Experimental data, (b) Monte Carlo simulation of the sequential decay (SD), (c) the direct decay with an equal energy of 3-$\alpha$ particles (DDE), (d) the direct decay to the phase space uniformly (DD\Phi).

compared with the result of the experiment. The first is the sequential decay (SD) mechanism, in which the Hoyle state decay to three $\alpha$ particles through the ground state of $^8$Be + $\alpha$ channel. The second is the direct decay with an equal energy of 3-$\alpha$ particles (DDE). The third is the direct decay to the phase space uniformly (DD\Phi). The experimental plot seems to be almost same as that of the SD mechanism.

In order to obtain the branching ratio for each decay mechanism, we fitted the energy distribution for the highest energy among the decay 3-$\alpha$ particles with those obtained in the simulation. The decay branch of the SD mechanism was 100%. After statistical treatment, the upper limit of 0.2% for the direct decay mechanisms (DDE + DD\Phi) was obtained.

Recently, Ishikawa predicted the branching ratio of the direct decay from the Hoyle state in the framework of the 3-$\alpha$ model [13]. In his result, the direct decay branch was an order magnitude less than our obtained upper limit of 0.2%. We need to improve the sensitivity of the detection of the direct 3-$\alpha$ decay by an order better than this experiment.

4. The 3-$\alpha$ decay from the broad 10 MeV state

Obtained data were analyzed by dividing the excitation energy spectrum into the following 4 regions, (a) 7.8 - 9.3 MeV, (b) 10.0 - 10.8 MeV, (c) 10.8 - 11.8 MeV, (d) 11.8 - 14.2 MeV, as shown in Fig. 1. To investigate the decay mechanism of the broad 10 MeV state, we also carried out the Monte-Carlo simulation for two decay mechanisms, the decay through the ground state of $^8$Be, $^8$Be(g.s.), and that through the $2^+$ state of $^8$Be, $^8$Be($2^+$), in each energy region. In the decay from the broad 10 MeV state, the direct 3-$\alpha$ decay could not be distinguished from the $^8$Be($2^+$) channel. Therefore, the energy distributions were fitted with these two decay channels, $^8$Be(g.s.) and $^8$Be($2^+$). Figure 3 shows the preliminary result for the energy distributions of decay $\alpha$ particles in the c.m. frame. They are reproduced well with the sum of the energy distributions.
Figure 3. The energy distributions of decay 3-\(\alpha\) particles in the energy regions, (a) 7.8 - 9.3 MeV, (b) 10.0 - 10.8 MeV, (c) 10.8 - 11.8 MeV, (d) 11.8 - 14.2 MeV, which correspond to those in Fig. 1.

5. Summary
We performed two measurements of the 3-\(\alpha\) decay via the \(^{12}\text{C}(^{12}\text{C},3\alpha)^{12}\text{C}\) reaction at 110 MeV. The first is the Hoyle state, the second is on the broad 10 MeV state. In the measurement of the Hoyle state, we measured all particles participated in the reaction and obtained the upper limit of the direct decay branch as 0.2 % by comparing with the result of the Monte Carlo simulation. This upper limit was further improved than that obtained by Kirsebom \textit{et al.} [9] and excluded the nonzero direct decay branch of 0.9 % obtained by Rana \textit{et al} [10].

In the second measurement of the broad 10 MeV state, we measured the energy distributions of decay \(\alpha\) particles from the broad 10 MeV state. The branching ratios of the sequential decay were acquired in energy regions obtained by dividing the broad 10 MeV state into 4 regions. They were larger than those obtained in the RCNP experiment above 10.8 MeV, although they gradually decreased. The branching ratios of the sequential decay above 10.8 MeV obtained in this experiment included the contributions of higher multipole components. We need to estimate...
Figure 4. Branching ratio of the sequential decay (SD) from the broad 10 MeV state. Open circles show those obtained from the RCNP experiment [12]. Closed circles show preliminary results at CYRIC.

Acknowledgments
Authors wish to thank S Ishikawa for fruitful discussions and the calculation of the decay branch of the Hoyle and broad 10 MeV states. A part of this work is financially supported by JSPS KAKENHI Grant Number 24740139.

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