Nature of 10 MeV state in $^{12}$C

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Abstract. We performed a coincidence measurement of decay-$\alpha$ particles by using inelastic scattering of 386 MeV $\alpha$ particles on $^{12}$C. We obtained further evidence for the second $2^+$ state at 9.84 MeV, which we found in previous work, from angular correlation functions for decay-$\alpha$ particles. The coincidence energy spectra with the $\alpha$-decay to the ground state and the first excited $2^+$ state in $^8$Be from the 10 MeV states in $^{12}$C were obtained. They indicated the broad $0^+$ state at 10 MeV consists of two components. The lower $0^+$ state do $\alpha$ decay to the ground state of $^8$Be only. The higher $0^+$ state has a distinct peak at 10.8 MeV with a width of 0.4 MeV in the coincidence spectrum for the first excited state of $^8$Be channel. They have consistent properties predicted for a higher nodal state of the Hoyle state and a linear-like $3\alpha$ state, respectively.

1. Introduction

The $0^+_2$ state at $E_x = 7.65$ MeV in $^{12}$C known as Hoyle state plays important role of a nucleosynthesis in the universe and is considered to have a typical $3\alpha$ cluster structure. In an early stage of the study on the structure of Hoyle state, Morinaga proposed it had a linear $3\alpha$ chain structure [1]. However, this configuration of the $3\alpha$ clusters was unstable energetically. According to the microscopic $\alpha$-cluster models such as $3\alpha$-GCM [2] and $3\alpha$-RGM [3], this state is considered to have a $3\alpha$ gas-like structure in which $3\alpha$ clusters are weakly coupled. About ten years ago, Tohsaki et al showed this $3\alpha$ gas-like structure was similar to the Bose-Einstein condensate of the $3\alpha$ clusters by using the condensate model wave function [4]. In this new concept, the $3\alpha$ clusters entered into the lowest S orbit.

These $\alpha$ cluster models also predicted the $2^+$ state at around 10 MeV. In the previous experiment, we have found the $2^+_2$ state at 9.84 MeV with the width of 1.0 MeV by inelastic $\alpha$ scattering [5]. The $2^+$ state at 9.6 MeV was also found in the $(p,p')$ experiment [6]. From the combined analysis of the $(\alpha,\alpha')$ and $(p,p')$ reactions, the $2^+$ states at 9.84 and 9.6 MeV are
confirmed to be identical [7]. Recently, M. Gai et al performed the $^{12}$C($\gamma$,3$\alpha$) experiment at High Intensity Gamma-Ray Source (HIGS) facility in the Duke University [8]. They also measured the $2^+$ strength at around 10 MeV. In this way, the $2^+_2$ state at 10 MeV was established. This result supports the $3\alpha$ gas-like structure of the Hoyle state. The next problem is the structure of the broad $0^+$ state at 10 MeV. This broad $0^+$ state is also considered to have a $3\alpha$ cluster structure. Kurokawa and Katō claimed the broad $0^+$ state at 10 MeV was a higher nodal state of the Hoyle state by using the Complex Scaling Method [9]. Kanada-En’yo predicted the $0^+$ state of the linear-like $3\alpha$ structure appeared at around 10 MeV in the framework of AMD [10]. In our previous study, we have obtained the $0^+$ strength distribution at around 10 MeV. It was almost consistent with the excitation energy and the width of the broad $0^+$ state, if it consisted of a single $0^+$ state. However, our result indicated it consists of two $0^+$ components at 9.04 MeV and 10.56 MeV, as shown in Ref. [5] Fig.8(a).

In this report, we present results of the coincidence measurement of the $^{12}$C($\alpha,\alpha'\alpha$) reaction. We obtained angular correlation functions (ACFs) for the $\alpha_0$ decay to the ground state of $^8$Be and further evidence for the existence of the $2^+_2$ state at 9.84 MeV. We also found a new peak at 10.8 MeV in the coincidence energy spectrum for the $\alpha_1$ decay to the first excited $2^+$ state of $^8$Be at 0°. This is additional evidence for consisting of two $0^+$ components in the broad $0^+$ state at 10 MeV. By using the coincidence energy spectrum, natures of the 10 MeV state including this new peak are discussed.

2. Experiment
The experiment was performed at the ring cyclotron facility of Research Center for Nuclear Physics (RCNP), Osaka University. The $^4$He$^{++}$ beam was accelerated up to 386 MeV by using both of the AVF cyclotron and the ring cyclotron, and bombarded to the self-supporting natural Carbon foil target with a thickness of 100 $\mu$g/cm$^2$. The size of the beam spot was less than a diameter of 1 mm. The target was rotated by 10 degrees in order to optimize the energy loss of decay-$\alpha$ particles for the detectors configuration.

The scattered $\alpha$ particles were momentum-analyzed in the Grand Raiden spectrometer and detected in the focal-plane detectors system comprised of two multi-wire drift chambers and two plastic scintillators, which provided both the horizontal and vertical trajectories. The measurement angles ($\theta_{GR}$) were 0° and 4° in the laboratory frame, which correspond to those of the cross section maximum for the $0^+$ and $2^+$ states, respectively. The angles inside the opening angle and momentum of scattered particles were determined by the ray-tracing method.

Decay-$\alpha$ particles were detected by the silicon detectors array, which was composed of fourteen silicon detectors of the surface-barrier type and installed into the scattering chamber at backward angles from 115° to 255° by the 10° step. A 2 mm thick brass collimator with a circular opening of 22 mm diameter was mounted at 250 mm from the target center in front of each silicon detector to define the solid angle. The defining solid angle was about 6 msr, which correspond to the opening angle of 5°. In front of the collimator, a pair of small magnets was attached in order to reduce the background noise due to electrons ejected out of the target. Thickness of silicon detectors were 300 $\mu$m (four silicon detectors) and 500 $\mu$m (the others), which were enough to measure energies of decay-$\alpha$ particles from the 10 MeV state in $^{12}$C. The identification of decay particles was done by the time of flight method, although the excited states at around 10 MeV in $^{12}$C decay essentially only by $\alpha$ particles except very small $\gamma$-decay.

Figure 1 shows the two-dimensional coincidence energy spectrum. The locus corresponding to the decay channel of $^{12}$C$^*\rightarrow ^8$Be + $\alpha_0$ is clearly observed.
3. Analysis and Results
The coincidence energy spectra with the ground state (g.s.) and the $2^+_1$ state of $^8$Be decay channels were obtained. The excitation energy of $^{12}$C* was determined by the missing mass method of inelastically scattered $\alpha$ particles. The excitation energy of $^8$Be was obtained from the kinematics by assuming the recoil $^{12}$C* decay to $^8$Be and $\alpha$ particles. In Fig. 2, open circles
and open squares show coincidence energy spectra at $\theta_{GR} = 0^\circ$ for the $^8$Be(g.s.) and the $^8$Be$(2^+_1)$ decay channels, respectively. Decay-$\alpha$ particles for the excitation energy of $^8$Be from 0.5 to 5 MeV were identified to be those from the $2^+_1$ state at 3.0 MeV with the width of 1.5 MeV. However, that of the $^8$Be$(2^+_1)$ channel contains decay-$\alpha$ particles from $^8$Be(g.s.) and $^8$Be$(2^+_1)$. The contribution from the decay of $^8$Be(g.s.), which is shown by closed triangles, was estimated from the coincidence energy spectrum with the $^8$Be(g.s.) channel and subtracted from that with the $^8$Be$(2^+_1)$ channel. The contribution from the decay of $^8$Be$(2^+_1)$ was estimated by the Monte-Carlo simulation, which is displayed as the detection efficiency (closed stars) for the $^8$Be$(2^+_1)$ decay channel. The real coincidence energy spectrum with the $^8$Be$(2^+_1)$ channel, which is shown by closed circles in Fig. 2, was obtained by multiplying this efficiency to the raw spectrum. A distinct peak at about 10.8 MeV with the width of 0.4 MeV still remains in the coincidence energy spectrum for the $^8$Be$(2^+_1)$ channel.

The ACF for decay-$\alpha$ particles from the intermediate state to the final $0^+$ state is proportional to $|P^L_0(\cos \theta)|^2$ in the PWBA calculation. $L$ is the angular momentum of the intermediate state. $\theta$ is the angle of the decay-$\alpha$ particle with respect to the recoil particle. This is a good approximation in the $0^+$ measurement, since there are no m-substate populations except $m = 0$ at $\theta_{GR} = 0^\circ$. If resonances overlapped in the same excitation energy, the ACF is expressed as a coherent summation of the square of Legendre functions. Therefore, the ACF in an energy interval is expressed as,

$$W(\theta) \propto \left( \sum_L a_L P_L(\cos \theta) \right)^2 + \left( \sum_L b_L P_L(\cos \theta) \right)^2.$$  

(1)

$a_L$ and $b_L$ are amplitudes of states for angular momentum $L$ in coherent and incoherent parts, respectively. Figure 3 shows the ACFs for decay-$\alpha$ particles of the $^{12}$C$(^{12}$C) + $^8$Be(g.s.) + $\alpha$ channel at $\theta_{GR} = 0^\circ$. Dashed-lines show incoherent calculations in the PWBA. On the other hand, solid lines show calculations taken into account for overlapping of resonances. Since the intrinsic width of the $3^-_1$ state at 9.64 MeV is much smaller than the broad $0^+$ state and the second $2^+$ state, the ACF was almost same as the incoherent summation of the $0^+$ and $3^-$ states. In Fig. 3(b), 3(d), and 3(c), ACFs summed $0^+$ and $2^+$ states coherently reproduce experimental data better than incoherent summed ACFs. Figure 3(a) and 3(f) show the ACF for only the $0^+$ state.

Figure 4 shows ACFs at $\theta_{GR} = 4^\circ$. The $0^+$ contributions are almost disappeared at this angle due to the angular distribution of inelastic $\alpha$ scattering. Therefore, we calculated ACFs by assuming resonance was not overlapped with each other. ACFs were generally written as,

$$W(\theta) \propto \sum_\nu G_\nu C(LLL; 00)W(j_i j_i LL; \nu jj_f)P_\nu(\cos \theta).$$  

(2)

$C(LLL; 00)$ and $W(j_i j_i LL; \nu jj_f)$ are a Clebsch-Gordan coefficient and a Racah coefficient, respectively. $G_\nu$, which is a statistical tensor, was calculated by ECIS95 [11]. The ACFs calculated in the DWBA were shifted by $10^\circ$ in order to reproduce experimental data. This effect was reported in the measurement of decay-$\alpha$ particles from giant resonances in $^{24}$Mg and $^{40}$Ca on inelastic $\alpha$ scattering at 120 MeV [12]. Figure 4(a) shows the ACF for the excitation energy range from 9.55 MeV to 9.75 MeV which corresponds to the $3^-_1$ state at 9.64 MeV. Since the calculated ACF (solid line) reproduces experimental data well, a contribution from the $2^+$ state may be small in this energy region. ACFs calculated for the $2^+$ state were in agreement with experimental data in energy regions from 9.8 to 10.2 MeV and from 10.2 to 10.6 MeV except at around $100^\circ$, as shown in Fig. 4(b) and 4(c). On the other hand, the ACF in the region from 10.6 to 11.0 MeV was failed to describe experimental data. It was not a simple ACF for the $1^-_1$ state at 10.84 MeV.
Figure 3. Angular correlation functions for decay-α particles to the $^{8}\text{Be}(\text{g.s.}) + \alpha$ channel in the $^{12}\text{C}(\alpha,\alpha')^{12}\text{C}^*\text{ reaction at } \theta_{GR} = 0^\circ$. Vertical axis means counts normalized by solid angles in the c.m. frame.

Figure 4. Angular correlation functions for decay-α particles to the $^{8}\text{Be}(\text{g.s.}) + \alpha$ channel in the $^{12}\text{C}(\alpha,\alpha')^{12}\text{C}^*\text{ reaction at } \theta_{GR} = 4^\circ$.

4. Discussion
Figure 5 shows the comparison of energy spectra in the singles measurement of our previous experiment [5] (thick solid lines) and in the coincidence measurement of the present work
Figure 5. Comparison between the result of the multipole decomposition analysis and the present one at $\theta_{GR} = 0^\circ$.

(symbols). The energy spectrum estimated by summing both decay channels is displayed with closed squares. The ACF for the azimuthal angle was assumed to be uniform. The fact that the summed spectrum is in good agreement with the singles spectrum in $^{12}$C indicates coincidence energy spectra for the $^8$Be(g.s.) and $^8$Be($2^+_1$) decay channels were reasonably obtained. The ratio of energy spectra between these two decay channels is directly related to the branching ratio of the state, although several states are contained in energy spectra. However, in the energy spectrum at $0^\circ$, main parts are $0^+$ states, as shown with the right hatched area in Fig. 5. Although the peak energy at 10.8 MeV in coincidence spectrum for the $^8$Be($2^+_1$) channel appears at the almost same energy as the 10.84 MeV $1^-$ state, the $1^-$ contribution to this peak is very small, as shown with the left hatched area in Fig. 5.

Consequently, following results are obtained. The lower $0^+$ component do $\alpha$-decay only to the $^8$Be(g.s.) channel. This property is consistent with the higher nodal $0^+$ state of Hoyle state predicted by Kurokawa and Katō [9]. On the other hand, the higher $0^+$ component has a large branching ratio to the $^8$Be($2^+_1$) channel and is expected to have a linear-like $3\alpha$ structure, which is dominated by the $^8$Be($2^+_1$) + $\alpha$ component according to the AMD calculation [10].

Figure 6 shows the energies of positive-parity resonances around 10 MeV in relation to this topic. Recently, Freer et al found the $4^+$ state at 13.3 MeV with a width of 1.7 MeV in $^{12}$C [13]. If the $2^+_2$ state at 9.84 MeV has a strong coupling to this $4^+$ state as a member of a rotational band of the $^8$Be + $\alpha$ structure, the band head $0^+$ state appears at around 8.5 MeV, as shown in Fig. 6. For that reason, the band head $0^+$ state of the $^8$Be + $\alpha$ structure is considered to fragment into two parts of the Hoyle state at 7.65 MeV and the lower $0^+$ state at 9.04 MeV.

5. Summary
The decay properties from the 10 MeV states in $^{12}$C have been investigated by the coincidence measurement of the $^{12}$C($\alpha,\alpha'$) reaction. Angular correlation functions for decay-$\alpha$ particles from the 10 MeV states in $^{12}$C were measured and compared with calculations. The results were
Figure 6. The energies of positive-parity resonances around 10 MeV on an $L(L+1)$ scale. The line was drawn for the eye-guide.

consistent with the previous work on the singles measurement of the $^{12}\text{C}(\alpha,\alpha')$ reaction. The existence of the $2^+_2$ state at 9.84 MeV in $^{12}\text{C}$ has been confirmed.

The coincidence energy spectra on $^{12}\text{C}$ for decay channels of $^{8}\text{Be}(\text{g.s.})$ and $^{8}\text{Be}(2^+_1)$ were obtained. In the coincidence spectrum for the $^{8}\text{Be}(2^+_1)$ channel, a distinct peak at 10.8 MeV with a width of 0.4 MeV was observed. It indicates that the broad $0^+$ state at 10 MeV in $^{12}\text{C}$ can consist of two components. The lower $0^+$ state is considered to have the $^{8}\text{Be}(\text{g.s.}) + \alpha$ structure and to be the higher nodal state of the Hoyle state. On the other hand, the higher $0^+$ state can be a linear-like $3\alpha$ structure, which has a large $^{8}\text{Be}(2^+_1) + \alpha$ component.

If the $2^+_2$ state at 9.84 MeV and recently found $4^+$ state at 13.3 MeV have a rotational structure, the band head $0^+$ state can be fragmented into two parts. One is the Hoyle state and another is the lower $0^+$ state at 9.04 MeV.

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