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Cluster structure of broad resonances near threshold in ^{12}C and ^{16}O

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Abstract. We investigated decay properties of the broad resonance around 10 MeV in ^{12}C and measured inelastic scattering of 386 MeV α particles on ^{16}O at extremely forward angles including 0° . We have found that the lower component of the broad 0^+ resonance at 10 MeV in ^{12}C decayed to the $^8\text{Be} + \alpha$ channel, and that the higher component decayed both to the $^8\text{Be} + \alpha$ channel and to the $^8\text{Be}(2^+) + \alpha$ channel. On the ^{16}O nucleus, we have found two 0^+ resonances at 16.7 MeV and 18.8 MeV, which are near the 4α breakup threshold. On the analogy to the broad resonances near the 3α threshold in ^{12}C , they are considered to have the $^{12}\text{C}(0_2^+) + \alpha$ cluster and the $^8\text{Be} + ^8\text{Be}$ cluster structures, respectively. It is consistent with the result of the experiment for the $^{12}\text{C}(^4\text{He}, ^8\text{Be})^8\text{Be}$ and $^{12}\text{C}(^4\text{He}, ^{12}\text{C}^* \rightarrow ^8\text{Be} + \alpha)$ reactions.

1. Introduction

Cluster structure in the nucleus is considered to appear near the threshold energy of disassembling to the constituent clusters, as indicated by Ikeda diagram [1]. The 0_2^+ state at $E_x = 7.65$ MeV in ^{12}C , which is known as the Hoyle state, is a typical 3α cluster state, which is 0.38 MeV above the 3α breakup threshold. However, its configuration of α cluster is still controversial. In 1953, Morinaga proposed it had a linear 3α chain structure [2]. According to the semi-microscopic and microscopic α -cluster models, the linear 3α configuration was found to be energetically unstable and the Hoyle state was considered to have loosely coupled 3α gaslike structure [3, 4, 5]. In 2001, Tohsaki *et al.* presented that this loosely coupled 3α gaslike structure was similar to the Bose-Einstein condensate of the 3α clusters [6], in which the 3α clusters enter into the lowest S-orbit.

Considering the α condensate structure as a special case of the loosely coupled α gaslike structure, many analog states are expected such as the 2^+ and the broad 0^+ states around 10 MeV in ^{12}C [7, 8]. This 2^+ state is considered as the 2^+ excitation of the Hoyle state and also



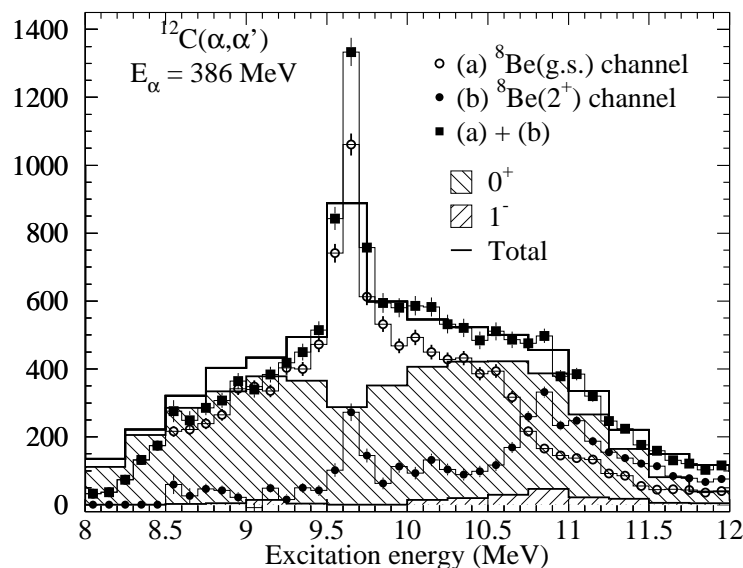


Figure 1. The coincidence energy spectra at 0° in the 10 MeV region is superimposed into the singles energy spectrum of inelastic α scattering of ^{12}C . (Figure adapted from Ref. [18].)

predicted in almost all α cluster models. In the α condensate model [7], it is considered that one of 3α clusters in the 3α condensate state is excited from the lowest S-orbit to the D-orbit. The broad 0 state around 10 MeV predicted in Ref. [8] is considered as the higher nodal state of the Hoyle state, in which one of 3α clusters is excited up to the second S-orbit. On the other hand, in the AMD and FMD calculations [9, 10], the linear-like 3α state is also predicted around 10 MeV, in which the dominant component is the 2^+ state of ^8Be ($^8\text{Be}_{2^+}$) and α cluster structure.

In the experimental side, recently, the 2^+ state at 10 MeV in ^{12}C has been established [11, 12, 13, 14]. Although the broad 0^+ states at 10 MeV was also observed in Ref [12], their $E0$ strength distribution around 10 MeV indicated the possibility of consisting of two components. These two components may correspond to the higher nodal state of the Hoyle state and the linear-like 3α state described above.

As for the ^{16}O nucleus, the 4α condensate state is predicted at 15.1 MeV 0^+ state, which is 0.66 MeV above the 4α breakup threshold [15]. The 4α linear chain structure is also proposed around 16 MeV from the measurement of the $^{12}\text{C}(^4\text{He}, ^8\text{Be})^8\text{Be}$ reaction [16]. Ohkubo and Hirabayashi predicted the band head 0^+ state of the Hoyle state ($^{12}\text{C}[0_2^+]) + \alpha$ cluster structure appeared at 16.9 MeV in ^{16}O by solving the coupled channel scattering equations [17]. Consequently, the situation of the 4α cluster configurations at above 4α breakup threshold in ^{16}O is very similar to that of the 3α cluster states in ^{12}C .

In this contribution, we report two studies on the α gaslike structure of broad resonance states near $N\alpha$ breakup thresholds in ^{12}C and ^{16}O .

2. Experiments

The experiments were performed at the ring cyclotron facility in the Research Center for Nuclear Physics (RCNP), Osaka University. In the ^{12}C experiment, the coincidence measurement of a decay α particle via the $^{12}\text{C}(\alpha, \alpha')^{12}\text{C}^*[\alpha + X]$ reaction at $E_\alpha = 386$ MeV was carried out. Details of the experimental setup and procedure are described in Refs. [18, 19]. Only a brief

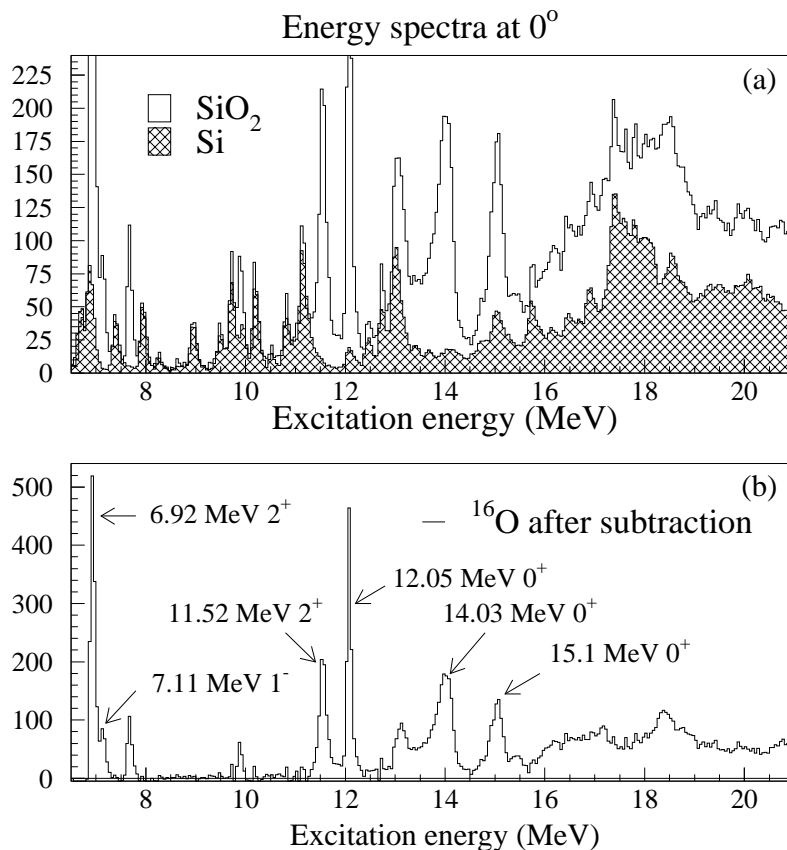


Figure 2. (a) The energy spectra of inelastic α scattering on SiO_2 and Si at 0° (b) The energy spectrum on ^{16}O obtained by subtracting the Si contaminant from the SiO_2 spectrum.

outline is provided below. The excitation energy of ^{12}C was determined from the momentum of a scattered α particle, which was analyzed by the GRAND RAIDEN spectrometer. The decay α particle from the excited ^{12}C was detected by the silicon detectors (SSD) array, which composed of fourteen SSDs installed in the scattering chamber at backward angles from 115° to 255° . The decay α particle was identified by the time of flight method.

From a missing mass spectrum in the $^{12}\text{C}(\alpha, \alpha')^{12}\text{C}^*[\alpha + \text{X}]$ reaction, the decay α particles were classified into two channels. One was the ground state of ^8Be ($^8\text{Be}_{gs}$) channel. The other was the $^8\text{Be}_{2+}$ channel, although it included the direct 3α decay. Figure 1 shows the coincidence energy spectrum at 0° in the $^{12}\text{C}(\alpha, \alpha')^{12}\text{C}^*[\alpha + \text{X}]$ reaction. The singles energy spectrum (solid line) in the $^{12}\text{C}(\alpha, \alpha')$ and 0^+ (right hatched area) and 1^- (left hatched area) components obtained from the multipole decomposition analysis (MDA) in Ref. [12] are superimposed onto the coincidence energy spectra. Open and closed circles show the coincidence energy spectra with the $^8\text{Be}_{gs}$ and the $^8\text{Be}_{2+}$ channels, respectively. The solid triangles show the sum of these two coincidence spectra. Since the scattering plane can not be defined in the 0° scattering, the ϕ -angle distribution of the α -decay is uniform. Furthermore, assuming the detectors for decay α particles covered the whole angles, this summed spectrum can reproduce a inclusive spectrum of the $^{12}\text{C}(\alpha, \alpha')$ reaction at 0° . This means the validity that the energy spectrum at 0° is considered to consist of these two components.

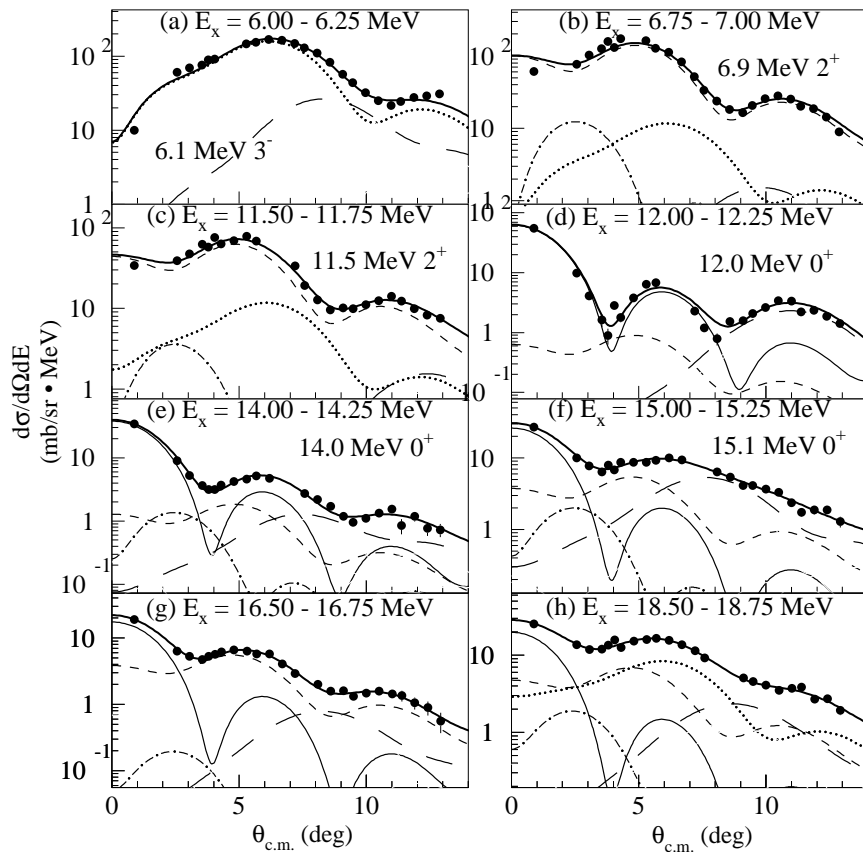


Figure 3. Typical angular distributions of the double-differential cross section for various excitation energy bins in ^{16}O . Thick solid lines show the fits to the data from multipole decomposition. In each panel, the contributions from $L = 0$ (thin solid), $L = 1$ (dot-dashed), $L = 2$ (dashed), $L = 3$ (dotted) and $L \geq 4$ (long-dashed) are also displayed. The excitation energy and J^π value displayed in each panel indicate a dominant component in each excitation energy bin.

In the experiment of ^{16}O , we measured energy spectra of inelastic α scattering at $E_\alpha = 386$ MeV on the SiO_2 and Si targets with thicknesses of 2.0 mg/cm^2 and 2.2 mg/cm^2 , respectively, using the GRAND RAIDEN spectrometer. In order to obtain energy spectra of the $^{16}\text{O}(\alpha, \alpha')$ reaction, the Si contaminant was subtracted from the SiO_2 spectrum. Figure 2 shows the energy spectra of inelastic α scattering at 0° for SiO_2 , Si, and ^{16}O after subtraction. The 2^+ states at 7.42 and 7.93 MeV, and the 1^- state at 8.90 MeV appeared in Fig. 2(a) are completely subtracted in the ^{16}O spectrum in Fig. 2(b). The candidate for the 4α condensate state at 15.1 MeV is clearly seen in Fig. 2(b).

3. Multipole decomposition analysis

In order to identify the multiplicities of the states in ^{16}O , we performed the MDA. In the MDA, the experimentally obtained cross sections are expressed as the sum of the contributions

from the various multipole components as

$$\sigma^{exp}(\theta, E_x) = \sum_L a_L(E_x) \sigma_L^{calc}(\theta, E_x) \quad (1)$$

where θ , E_x are the scattering angle and the excitation energy, respectively. $\sigma_L^{calc}(\theta, E_x)$ is the DWBA cross section for the transferred angular momentum, L . In the present MDA, the energy spectrum at each angle was divided into 0.25-MeV bins. In the DWBA calculation, we adopted a single folding model with the Gaussian form N - α interaction. The interaction parameters were obtained from the fit of the angular distribution of elastic α scattering on ^{16}O , which were taken from Ref. [20].

Figure 3 shows typical results of the MDA. The 6.1 MeV 3^- , 6.9 MeV 2^+ , 11.5 MeV 2^+ , 12.0 MeV 0^+ , 14.0 MeV 0^+ , and 15.1 MeV 0^+ states in ^{16}O are clearly identified. We also found much 0^+ component above the 4α breakup threshold energy at 14.4 MeV as shown in Fig. 3(g) and 3(h). Figure 4(a) shows the obtained $E0$ strength distribution in ^{16}O , which is roughly in agreement with that obtained in Ref. [21] except the high excitation energy region above 25 MeV. In the calculation with the relativistic random-phase approximation, most of the $E0$ strength due to the collective monopole excitation of nucleons appeared at over 20 MeV [22]. On the other hand, according to the 4α -OCM [23] and the AMD + α GCM [24] calculations, the $E0$ strength lower than 16 MeV is dominated by the monopole excitation to cluster states. In our result, two 0^+ bumps are appeared at 16-20 MeV, which corresponds to the region between the cluster excitation and the collective monopole excitation of nucleons. In the next section, we discuss these two 0^+ bumps.

4. Discussion

4.1. Analogy to the broad resonance in ^{12}C

Figure 4(b) and 4(c) show the $E0$ strength distributions for ^{16}O and ^{12}C at above the 4α and the 3α breakup thresholds, respectively. The $E0$ strength distribution for ^{12}C is taken from Ref. [12]. In the case of the $E0$ strength distribution in ^{12}C , it is considered to have three resonances, a narrow peak of the Hoyle state at 7.65 MeV, the broad resonance of the higher nodal state of the Hoyle state, and the linear-like 3α cluster state, near the 3α breakup threshold as described in Sec. 2. In the case of ^{16}O , it indicates there are three resonances near the 4α breakup threshold. The lowest narrow resonance is the candidate for the 4α condensate state at 15.1 MeV in ^{16}O . The second broad resonance at 16.7 MeV, which is newly found in the present experiment, is considered to have the $^{12}\text{C}[0_2^+] + \alpha$ cluster structure. Considering in the framework of the α condensate model, the higher nodal state appeared at about 1.5 MeV above the 3α condensate state of the Hoyle state. On the analogy to the higher nodal state in ^{12}C , one of the 4α clusters in the lowest S-orbit may be excited up to the second S-orbit by about 1.5 MeV. The third resonance at 18.8 MeV, which is also newly found in the present experiment, is considered to have the $^8\text{Be} + ^8\text{Be}$ cluster structure due to the following reason.

4.2. Comparison with the resonance scattering experiment

Figure 5 shows the comparison between the $E0$ strength distribution in ^{16}O (the left panel of Fig. 5) and the result of the recent experiment for the $^{12}\text{C}(^4\text{He}, ^8\text{Be})^8\text{Be}$ and $^{12}\text{C}(^4\text{He}, ^{12}\text{C}^* \rightarrow ^8\text{Be} + \alpha)\alpha$ reactions [25] (the right panel of Fig. 5). In the excitation energy at 16.7 MeV in ^{16}O , the cross section for the $^{12}\text{C}(^4\text{He}, ^{12}\text{C}^*[0_2^+])\alpha$ reaction channel is larger than that of other reaction channels. On the other hand, in the excitation energy at 18.8 MeV in ^{16}O , the cross section for the $^{12}\text{C}(^4\text{He}, ^8\text{Be})^8\text{Be}$ reaction channel is relatively large compared to other channels. Therefore, we conclude that the second resonance at 16.7 MeV is considered to have the $^{12}\text{C}[0_2^+] + \alpha$ cluster structure, and that the third resonance at 18.8 MeV is considered to have the $^8\text{Be} + ^8\text{Be}$ cluster structure.

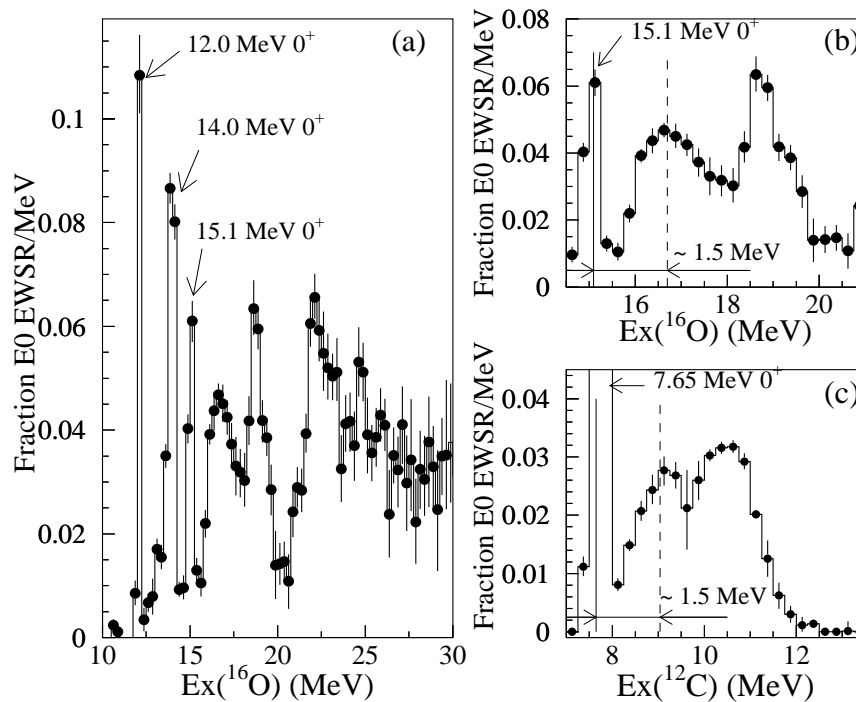


Figure 4. $E0$ strength distributions. (a) A distribution of the $E0$ EWSR fraction in ^{16}O obtained in present work. (b) Enlarged view of the $E0$ EWSR fraction distribution from 14.5 to 21.0 MeV in ^{16}O . (c) The $E0$ EWSR fraction distribution in ^{12}C from 7.0 to 13.5 MeV, which was obtained in Ref. [12], are shown.

5. Summary

In summary, we investigated the α gaslike structure of broad resonance states near $N\alpha$ breakup threshold in ^{12}C and ^{16}O . From the coincidence measurement of a decay- α particle via the $^{12}\text{C}(\alpha, \alpha')^{12}\text{C}^*[\alpha + X]$ reaction, the decay property of the broad resonance at 10 MeV is different between the low excitation energy component and the high excitation energy component. They correspond to the higher nodal of the Hoyle state predicted by the CSM calculation and the linear-like 3α state predicted by the AMD calculation. From the measurement of inelastic scattering of 386 MeV α particles on ^{16}O and the multipole decomposition analysis, we have newly found two broad resonances at 16.7 MeV and 18.8 MeV, which are considered to correspond to the $^{12}\text{C}[0_2^+] + \alpha$ cluster and the $^8\text{Be} + ^8\text{Be}$ cluster structures, respectively. It is consistent with the result of the recent experiment for the the $^{12}\text{C}(^4\text{He}, ^8\text{Be})^8\text{Be}$ and $^{12}\text{C}(^4\text{He}, ^{12}\text{C}^* \rightarrow ^8\text{Be} + \alpha)\alpha$ reactions [25].

Acknowledgments

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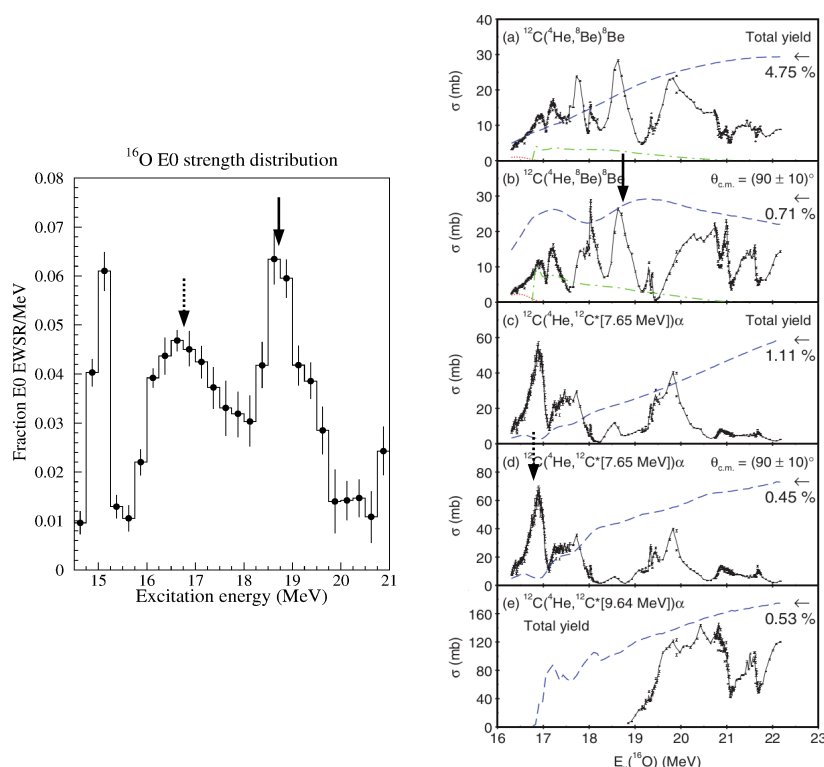


Figure 5. The comparison between the $E0$ strength distribution obtained in present study and the excitation function for the $^{12}\text{C}(^4\text{He},^8\text{Be})^8\text{Be}$ and $^{12}\text{C}(^4\text{He},^{12}\text{C}^* \rightarrow ^8\text{Be} + \alpha)\alpha$ reactions [25]. The solid and dotted arrows indicate peaks of the higher and the lower components of the broad 0^+ resonance in ^{16}O , respectively. The right panel of the excitation functions is taken from Ref. [25].

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