Cluster states in \(^{11}\)B and \(^{13}\)C

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Abstract. The cluster structures of the excited states in \(^{11}\)B and \(^{13}\)C were discussed by measuring the isoscalar monopole strengths in the inelastic \(\alpha\) scattering at \(E_\alpha = 388\) MeV. It was found that the \(1^+_2\), \(2^-_2\), and \(2^+_3\) states in \(^{13}\)C are candidates for the \(\alpha\) cluster states with a \(3\alpha + n\) molecular configuration.

1. Introduction

Alpha particle clustering is an important concept in nuclear physics for light nuclei. On the basis of the Ikeda diagram [1], the \(\alpha\) cluster structure is expected to emerge near the \(\alpha\)-decay threshold energy in self-conjugate \(A = 4n\) nuclei. For example, it has been suggested that the 7.65-MeV \(0^+_2\) state in \(^{12}\)C, which locates at an excitation energy higher than the \(3\alpha\)-decay threshold by 0.39 MeV, has a \(3\alpha\)-cluster configuration [2]. Recently, the cluster models have been applied to the neutron-rich nuclei, and the molecular structures where the excess neutrons act as the covalent particles have been discussed.

Milin and von Oertzen proposed \(\alpha\) cluster states in \(^{13}\)C with one covalent neutron based on the compiled experimental data, and proposed \(K = 3/2^-\) and \(K = 3/2^+\) molecular bands [3]. They also pointed out that the \(1/2^-_2\) state at \(E_x = 8.86\) MeV and the \(1/2^+_2\) state at \(E_x = 10.996\) MeV in \(^{13}\)C are considered to have a neutron in the \(1p_{1/2}\) and \(2s_{1/2}\) orbits, respectively, coupled to the \(0^+_1\) state in \(^{12}\)C. They suggested that the \(1/2^-_2\) and \(1/2^+_2\) states in \(^{13}\)C may have the triangular three \(\alpha\)-particle structure since the covalent neutron plays a role to stabilize the three \(\alpha\)-particle structure to a triangular shape in these states. Thus, a comparative study between the \(0^+_1\) state in \(^{12}\)C and the two states in \(^{13}\)C is interesting, and it is meaningful to examine a role of the covalent neutron in the molecular state and to test the molecular orbital model. Although the \(0^+_3\) state of \(^{12}\)C is known at \(E_x = 10.3\) MeV with a width of 3.0 MeV, no candidate for the molecular state in which an excess neutron is coupled to the \(0^+_3\) state has been observed in \(^{13}\)C. The search for such unknown states is also important.
A cluster state relevant to the $0^+_3$ state in $^{12}$C was suggested in $^{11}$B as well as $^{13}$C [4]. The $3/2^-_3$ state at $E_x = 8.56$ MeV, which is not predicted by the shell-model calculation by Cohen and Kurath [5], is predominately excited by the $\Delta J^z = 0^+$ transition in the $^{11}$B($d, d'$) reaction. The angular distribution of the ($d, d'$) cross section for the $3/2^-_3$ state in $^{11}$B is very similar to that for the $0^+_3$ state in $^{12}$C. This fact indicates that the $3/2^-_3$ state is considered to be an $\alpha$ cluster state with a proton hole in the $1p_{3/2}$ orbit coupled to the $0^+_3$ state in $^{12}$C, while the ground state in $^{11}$B is considered to have a proton hole in the $1p_{3/2}$ orbit coupled to the ground state in $^{12}$C.

For clarification of the cluster structure in $^{13}$C and $^{11}$B, further information on the natural-parity excitation strengths is necessary. Especially, the isoscalar monopole strength is a key ingredient because it is expected that the $\alpha$ cluster states are excited from the ground state by the monopole transitions [4, 6].

In the present study, the isoscalar monopole strengths in $^{13}$C and $^{11}$B were obtained by measuring the inelastic $\alpha$ scattering at $E_\alpha = 388$ MeV, and the $\alpha$ cluster structure in $^{13}$C and $^{11}$B was discussed.

2. Experiment
The experiment was performed at the Research Center for Nuclear Physics, Osaka University, using a 388-MeV $\alpha$ beam. The $\alpha$ beam extracted from the ring cyclotron was achromatically transported to self-supporting $^{11}$B and $^{13}$C targets with the thicknesses of 16.7 mg/cm$^2$ and 1.5 mg/cm$^2$. Scattered $\alpha$ particles were momentum analyzed by the high-resolution spectrometer Grand Raiden [7]. The focal-plane detector system of Grand Raiden consisting of two multi-wire drift chambers and plastic scintillation detectors allowed the reconstruction of the scattering angle at the target via ray-tracing techniques.

Typical spectra for the $^{11}$B($\alpha, \alpha'$) and $^{13}$C($\alpha, \alpha'$) reactions are shown in Fig. 1. Energy resolutions of the excitation energy spectra were 250 keV and 180 keV for $^{11}$B and $^{13}$C at full width at half maximum, respectively. The energy resolution for $^{13}$C was dominated by the energy spread of the cyclotron beam, whereas that for $^{11}$B was deteriorated by the energy straggling in the thick $^{11}$B target.

![Figure 1. Excitation energy spectra for the $^{11}$B($\alpha, \alpha'$) (left) and $^{13}$C($\alpha, \alpha'$) (right) reactions measured at $0^\circ$.](image)

3. Result and discussion
The measured cross sections for the $^{13}$C($\alpha, \alpha'$) and $^{11}$B($\alpha, \alpha'$) reactions exciting the several low-lying states are compared with the theoretical predictions by the distorted-wave Born
approximation (DWBA) calculation in Figs. 2 and 3. The transition potentials in the DWBA calculation were obtained by folding the macroscopic transition densities [8] with the phenomenological $\alpha N$ interaction $V_{\alpha N}(r)$ given by:

$$V_{\alpha N}(r) = -V \exp(-r^2/\alpha_V) - iW \exp(-r^2/\alpha_W).$$

The interaction strengths and range parameters of $V = 16.9$ MeV, $W = 11.7$ MeV, and $\alpha_V = \alpha_W = 4.38$ fm$^2$ were determined to reproduce the cross section for the elastic scattering from $^{12}$C.

The cross sections for the $1/2^-$ and $1/2^+$ states in $^{13}$C peak at $0^\circ$, and rapidly decrease with the increasing scattering angle. The allowed transferred spin and parity are uniquely defined in the $^{13}$C$(\alpha, \alpha')$ reaction since the spin-parity of the ground state of $^{13}$C is $1/2^-$ and only the natural-parity transitions are allowed in the inelastic $\alpha$ scattering. Therefore, it is naturally noted that the $1/2^-$ states are excited by the monopole transitions whereas the enhancement of the $1/2^+$ state near $0^\circ$ is due to the dipole Coulomb excitation.

On the other hand, several multipole transitions are allowed in the $^{11}$B$(\alpha, \alpha')$ reaction. The $^{11}$B$(\alpha, \alpha')$ cross sections were analyzed by summing up the calculated cross sections for the allowed multipole transitions with $\Delta J \leq 2$.

The deformation lengths in the macroscopic transition densities were determined to reproduce the measured cross sections for the $^{11}$B$(\alpha, \alpha')$ and $^{13}$C$(\alpha, \alpha')$ reactions, and the isoscalar monopole excitation strengths $B(E0; IS)$ for the $1/2^-$ states in $^{13}$C and the $3/2^-$ states in $^{11}$B were obtained from the deformation lengths as listed in Table 1.

The three $1/2^-$ states in $^{13}$C and the $3/2^-$ state in $^{11}$B are strongly excited by the isoscalar monopole transitions, but those large monopole strengths cannot be explained by the shell-model calculation at all. This fact indicates that the structure of these states is quite far from the shell-model picture where each nucleon behaves like an independent particle in the
Table 1. Preliminary results of the isoscalar monopole excitation strengths for the $1/2^-$ states in $^{13}$C and the $3/2^-$ states in $^{11}$B.

| $J^n$   | $E_x$  | $B(E0; IS)$ | $J^n$   | $E_x$  | $B(E0; IS)$ |
|---------|--------|-------------|---------|--------|-------------|
| 1/2$_2^-$ | 8.86   | 31 ± 3     | 3/2$_2^-$ | 5.02   | 5 ± 3       |
| 1/2$_3^-$ | 11.08  | 18 ± 2     | 3/2$_3^-$ | 8.56   | 88 ± 15     |
| 1/2$_4^-$ | 12.5   | 23 ± 3     |         |        |             |

mean-field potential. The non-shell-model-like structure of those states is possibly due to the $\alpha$-cluster correlation. It is generally difficult to treat the clustering phenomena in the truncated shell-model space since the theoretical description of the clustering phenomena under the shell-model framework requires a huge number of single-particle bases. Actually, the antisymmetrized molecular-dynamics calculation shows the large monopole strength for the $3/2_3^-$ state in $^{11}$B is well described by a spatially well-developed $2\alpha + t$ cluster wave function [9].

Recently, it is theoretically pointed out that a sizable monopole strength could be a signature of the $\alpha$ cluster states [6]. Thus, it should be noted that the three $1/2^-$ states in $^{13}$C are candidates for the $\alpha$ cluster states with a $3\alpha + n$ molecular configuration. For further clarification, a quantitative comparison between the present result and the cluster-model calculations is desired. The results will be reported elsewhere soon.

4. Summary
The inelastic $\alpha$ scattering at $E_\alpha = 388$ MeV was measured to examine the $\alpha$ cluster structures in $^{11}$B and $^{13}$C. The measured cross sections for the low-lying states were compared with the DWBA calculation, and the isoscalar monopole strengths were determined. It was found that the $1/2_2^-$, $1/2_3^-$, and $1/2_4^-$ states in $^{13}$C are candidates for the $\alpha$ cluster states with a $3\alpha + n$ molecular configuration. For further clarification, a quantitative comparison between the present result and the cluster-model calculations is desired. The results will be reported elsewhere soon.

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