Alpha Inelastic Scattering and Cluster Structures in Light Nuclei

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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 α scattering at $E_\alpha = 388$ MeV. It was found that the $1/2^-_2$, $1/2^-_3$, and $1/2^-_4$ states in ^{13}C are candidates for the α 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 α cluster structure is expected to emerge near the α-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 3α-decay threshold by 0.39 MeV, has a 3α-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 α cluster states in ^{13}C with one covalent neutron on the basis of the compiled experimental data, and proposed the $K = 3/2^-$ 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 be the $3\alpha + n$ cluster states where an excess neutron behaves as a covalent particle in the $1p_{1/2}$ and $2s_{1/2}$ orbits around the 0^+_2 state in ^{12}C. They suggested that the $1/2^-_2$ and $1/2^+_2$ states in ^{13}C may have the triangular shape since the covalent neutron plays a role to stabilize the three α-particle structure to a triangular shape in these states. Thus, a comparative study between the 0^+_2 state in ^{12}C and the two states in ^{13}C is important to examine the molecular structure in the atomic nuclei.

On the other hand, although the molecular states built on the 0^+_2 states were proposed, no candidate for the molecular state on the 0^+_3 states at $E_x = 10.3$ MeV in ^{12}C has been observed in ^{13}C. It is also important to search for those states from a view of the cluster model.

A cluster state relevant to the 0^+_2 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 $\Delta J^\pi = 0^+$ transition in the ^{11}B(d,d') reaction [6]. 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^+_2 state in ^{12}C. This fact indicates the $3/2^-_3$ state is considered to be an α cluster state with a proton hole in the $1p_{3/2}$ orbit coupled to the 0^+_2 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 indispensable. Especially, the isoscalar monopole strength is a key ingredient because it is expected that the α cluster states are excited from the ground state by the monopole transitions [4, 7].

In the present work, the isoscalar monopole strengths in ^{13}C and ^{11}B were obtained by measuring the inelastic α scattering at $E_\alpha = 388$ MeV, and the α 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 α beam. The α 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 α particles were momentum analyzed by the high-resolution spectrometer Grand Raiden [8]. 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 [9].

Typical spectra for the ^{11}B(α,α') and ^{13}C(α,α') 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.

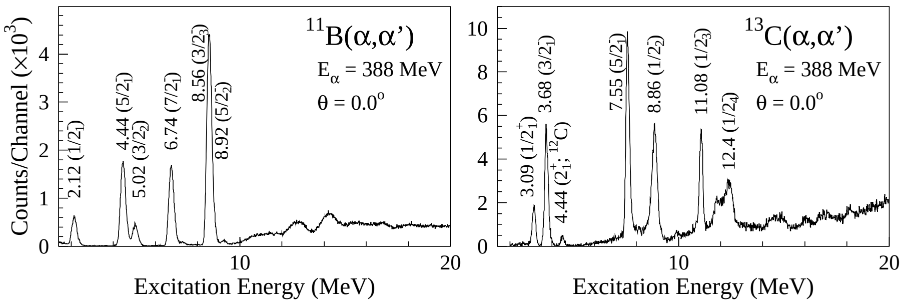

Fig. 1: Excitation energy spectra for the $^{11}\mathrm{B}(\alpha,\alpha')$ (left) and $^{13}\mathrm{C}(\alpha,\alpha')$ (right) reactions measured at $0°$.

3 Result and discussion

The measured cross sections for the $^{13}\mathrm{C}(\alpha,\alpha')$ and $^{11}\mathrm{B}(\alpha,\alpha')$ reactions exciting the several low-lying states are compared with the theoretical predictions by the distorted-wave Born approximation (DWBA) calculation in Figs. 2. The transition potentials in the DWBA calculation were obtained by folding the macroscopic transition densities [10] with the phenomenological αN 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.

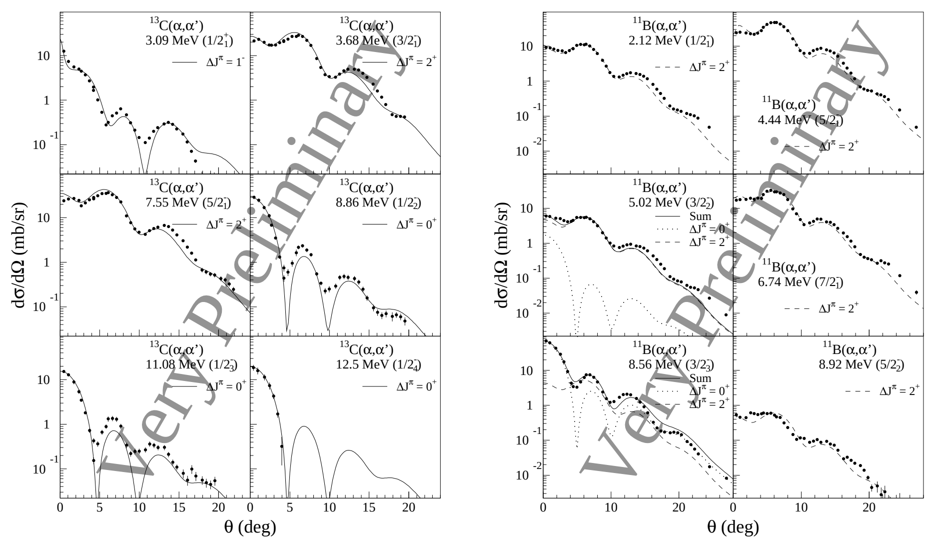

Fig. 2: Preliminary results of the measured cross sections for the several low-lying states in ^{13}C (left) and ^{11}B (right) compared with the DWBA calculation.

The cross sections for the $1/2^-$ and $1/2^+$ states in ^{13}C peak at $0°$, and rapidly decrease with the increasing scattering angle. The allowed transferred spin and parity are uniquely defined in the ^{13}C(α, α') 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 α 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 $0°$ is due to the dipole Coulomb excitation.

On the other hand, several multipole transitions are allowed in the $^{11}\mathrm{B}(\alpha, \alpha')$ reaction. The $^{11}\mathrm{B}(\alpha, \alpha')$ 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 $^{13}\mathrm{C}(\alpha, \alpha')$ and $^{11}\mathrm{B}(\alpha, \alpha')$ 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.

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.

^{13}C			^{11}B		
J^π	E_x (MeV)	$B(E0; IS)$ (fm^4)	J^π	E_x (MeV)	$B(E0; IS)$ (fm^4)
$1/2_2^-$	8.86	41 ± 6	$3/2_2^-$	5.02	5 ± 3
$1/2_3^-$	11.08	23 ± 3	$3/2_3^-$	8.56	88 ± 15
$1/2_4^-$	12.5	29 ± 4			

The three $1/2^-$ states in ^{13}C and the $3/2_3^-$ 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 different from the shell-model picture where each nucleon behaves like an independent particle in the mean-field potential. The non-shell-model-like structure of those states is possibly due to the α-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 [11].

Recently, it is theoretically pointed out that a sizable monopole strength could be a signature of the α cluster states [7]. Thus, it should be noted that the three $1/2^-$ states in ^{13}C are candidates for the α 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 α scattering at $E_\alpha = 388$ MeV was measured to examine the α 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 α 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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