Proton inelastic scattering to the dilute α-cluster condensed 0_2^+ state at $E_x = 7.654$ MeV in ^{12}C

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Differential cross sections for the 0_2^+ state at $E_x = 7.654$ MeV in ^{12}C were measured with the (p, p') reaction at an incident energy of $E_p = 300$ MeV, and in an angular range from $\theta_{\rm Lab} = 2.7^\circ$ to 40°. The cross-section data were compared with the distorted-wave Born-approximation calculations employing three types of transition densities obtained in a macroscopic collective model, a microscopic α-cluster model, and a microscopic α-cluster condensation model. It is concluded that the measured angular distribution of the differential cross sections for the ^{12}C(p, p') reaction at 300 MeV is consistently described with the assumption that the 0_2^+ state at $E_x = 7.654$ MeV is the dilute α-cluster condensed state.

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I. INTRODUCTION

The second 0_2^+ state at $E_x = 7.654$ MeV in ^{12}C has been studied for an extended period of time with great interest from the viewpoints of not only nuclear synthesis but also nuclear structure and reaction. Hoyle predicted that a three-α resonance, a 0^+ state, just above the three-α threshold in ^{12}C should play an important role on the routes of nuclear synthesis [1] in stars, explaining the existence of elements heavier than helium in the universe. Dunbar *et al.* observed such a state at the exactly predicted excitation energy [2]. This state is now well known to be the 7.654-MeV 0_2^+ state in ^{12}C, which locates only 287 and 379 keV above the $\alpha + {}^8$Be and three-α thresholds, respectively [3,4].

On the other hand, the presence of this state could not be explained in the framework of the shell model [5]. Morinaga proposed that the 7.654-MeV 0_2^+ state has a linear chain structure of three α-clusters [6]. Horiuchi successfully explained via a semimicroscopic model that the 0_2^+ state has a three-α cluster structure [7]. Uegaki *et al.* [8], Fukushima *et al.* [9], and Kamimura [10] showed from the microscopic α-cluster (AC) model that the 7.654-MeV 0_2^+ state has not a linear chain structure but a gaslike α-cluster structure. It was also confirmed via the antisymmetrized molecular dynamics calculation that many excited states in ^{12}C have a well-developed α-cluster structure [11]. Recently, Tohsaki *et al.* explained that the 7.654-MeV 0_2^+ state is a dilute α-cluster condensed (ACC) state [12], and that the nuclear radius of ^{12}C for this state is larger than that for the ground state because of the low density of the 0_2^+ state.

Because the 7.654-MeV 0_2^+ state in ^{12}C is considered to be the simplest example of the ACC state in nuclei, the search for experimental evidence for the ACC state is a challenging subject. Kokalova *et al.* observed enhanced emission of ^{12}C in the 7.654-MeV state from the compound nuclear reaction of the ^{28}Si + ^{24}Mg, and they have interpreted that this type of enhancement happens because the Coulomb barrier becomes lower when the size of the state is enlarged [13]. Ohkubo and Hirabayashi analyzed the differential cross sections of ^{3}He and α inelastic scattering to the 7.654-MeV state in ^{12}C at different incident energies, and found that the shifts of the rainbow minimal point are explained by enlarging the nuclear radius of this state [14]. Takashina and Sakuragi analyzed the ^{12}C(α,α') reaction leading to the 7.654-MeV state in ^{12}C with the microscopic coupled channels using the ACC model [15]. They found that one can determine the extension of the transition density rather than the nuclear radius of the excited state from the oscillation pattern of the angular distribution of inelastic scattering, and the nuclear radius of the excited state can be deduced from the absolute value of the differential cross sections through the amplitude of the transition density. Analysis of a form factor for the inelastic electron scattering indicates that the 7.654-MeV state has a radius of ~1.5 times larger than that of the ground state [16–19]. Recently, Danilov *et al.* analyzed the inelastic scattering of *d*, ^{3}He, ^{4}He, ^{6}Li, and ^{12}C on ^{12}C with the diffraction model of scattering [20]. They found that the root mean square (rms) radii for the 7.654-MeV 0^+ and 9.641-MeV 3^- states are a factor of 1.2 larger than the rms radius for the ground state of ^{12}C. Confirmation of the large observed radius is evidence that the 7.654-MeV state is the ACC state.

In the present work we took a different approach to search for evidence for the ACC state in ^{12}C; we investigated the ^{12}C(p, p') reaction leading to the ground state, and 4.439-MeV 2_1^+, 7.654-MeV 0_2^+, and 9.641-MeV 3_1^- states at an incident energy of 300 MeV to confirm whether the wave function for

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the ACC and AC models well explain the experimental result or not. Because of the transparency of nuclei to 300-MeV protons, the cross sections are sensitive to the interior as well as the surface of nuclei [21]. This is in sharp contrast to inelastic scattering, wherein ^{3}He and α particles are strongly absorbed on the surface of nuclei. In the analysis of the proton scattering data, we employed the microscopic wave function of the ACC model for the 7.654-MeV 0_2^+ state published by Funaki *et al.*, who provided the transition density in the framework of the ACC model [19], and pointed out that the transition density for the 7.654-MeV 0_2^+ state predicted by Kamimura based on the microscopic AC model [10] was almost equivalent to their transition density.

II. EXPERIMENT

A 300-MeV proton beam from the ring cyclotron at the Research Center for Nuclear Physics (RCNP), Osaka University, bombarded a self-supporting $^{\rm nat}$C target with a thickness of 30 mg/cm^2 or a polyethylene foil of 4.6 mg/cm^2. Because a similar experimental setup has been described in the previous work [22], only the experimental details essential for this experiment are summarized herein. Scattered protons were analyzed by using the magnetic spectrograph "Grand Raiden" and were detected with the focal plane detector system, consisting of two multiwire drift chambers backed by a ΔE-E plastic scintillator telescope [23]. The aperture of the entrance slits of the spectrograph was ± 20 mr horizontally and ± 30 mr vertically. We measured the (p,p') spectra in a wide angular range from $\theta_{\rm Lab} = 2.7^\circ$ to 40° to observe a large momentum transfer domain of the wave function. A Faraday cup mounted in the scattering chamber was used to measure the beam current. In the measurements at forward angles smaller than 6°, we used another Faraday cup behind the Q1-magnet of the Grand Raiden spectrograph [24], and elastically scattered protons were blocked by a lead plate with a thickness of 5 cm located in front of the focal plane detector to reduce the counting rate. Additional measurements for elastic scattering at forward angles were done without the lead plate by using a low-intensity beam. Events were sorted with a 10-mrad horizontal bin by a software gate in a ray-trace method.

Figure 1 shows the two (p,p') spectra at $\theta_{\rm Lab} = 2.7^\circ$ and 15°. We obtained nearly background free spectra. Typical energy resolution was 120 keV, which was mainly from the energy spread of the incident proton beam. At $\theta_{\rm Lab} = 2.7^\circ$, several sharp states have been observed; they are the 4.439-MeV 2_1^+, 7.654-MeV 0_2^+, 12.71-MeV 1^+ (T=0), and 15.11-MeV 1^+ (T=1) states. At $\theta_{\rm Lab} = 15^\circ$, the states excited with low transferred angular momenta are relatively weakly observed. On the other hand, the excitation of relatively high-spin states is enhanced.

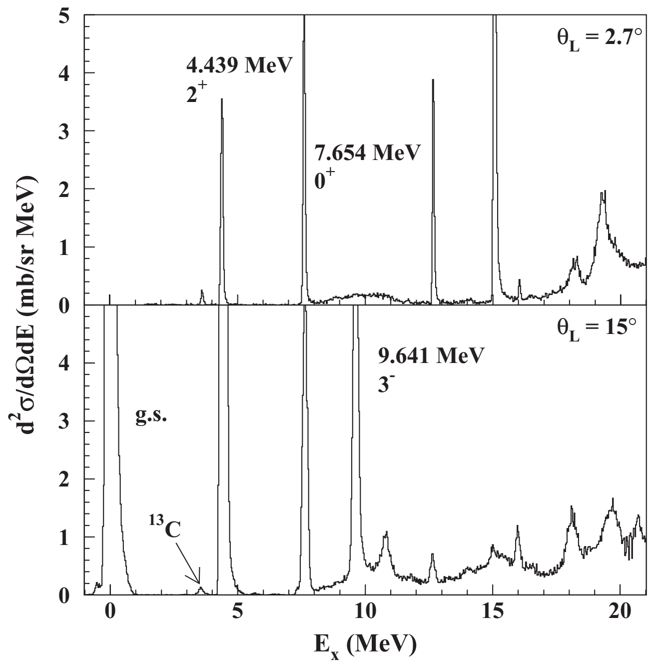

FIG. 1. The ^{12}C(p,p') spectra at $E_p = 300$ MeV and at $\theta_{\rm Lab} = 2.7^\circ$ and 15°. The events corresponding to proton elastic scattering at 2.7° were not measured because elastically scattered protons were blocked in front of the focal plane detector at the high-momentum side.

III. RESULTS AND ANALYSIS

The optical potential parameters were derived by fitting the measured cross sections for proton elastic scattering with the code ECIS95 [25]. Because we did not measure the polarization observables, the spin-orbit potentials were deemed to be irrelevant in the present potential parameters. The contribution of the spin-orbit potentials to the differential cross sections were confirmed to be small by artificially introducing a spin-orbit potential. Two sets of the potential parameters, Set 1 and Set 2, which gave different local minimum χ^2 values, were obtained. The results are listed in Table I. Figure 2 shows the measured differential cross sections for the 0^+ ground state, 2_1^+ state at $E_x = 4.439$ MeV, 3_1^- state at $E_x = 9.641$ MeV, and 0_2^+ state at $E_x = 7.654$ MeV. Because the cross sections at forward angles for the 7.654-MeV state have been reported by Tamii *et al.* at $E_p = 300$ MeV [26], their data are also presented in Fig. 2. Their data are in good agreement with the present data.

We analyzed the inelastic scattering data with the distorted-wave Born approximation (DWBA) employing a macroscopic collective model [27,28], and the microscopic AC model [10]. For the 7.654-MeV 0_2^+ state, the microscopic ACC model

TABLE I. Optical potential parameters.

	V (MeV)	r (fm)	a (fm)	W (MeV)	r_W (fm)	a_W (fm)	V_s (MeV)	r_s (fm)	a_s (fm)
Set 1	30.78	1.16	0.55	21.18	1.19	0.53	−10.47	1.18	0.56
Set 2	29.68	1.10	0.30	28.21	1.10	0.49	−13.40	0.90	0.47

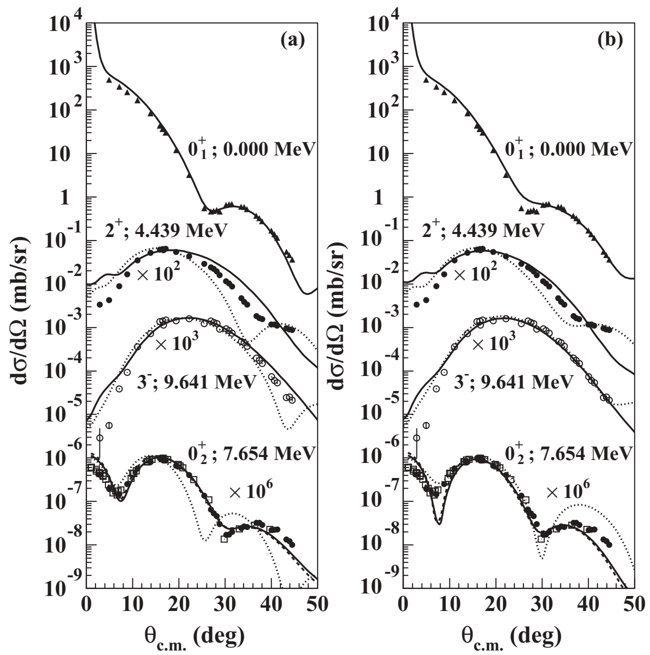

FIG. 2. Experimental and calculated cross sections for the ^{12}C(p,p') reactions at $E_p = 300$ MeV with the optical potential parameters Set 1 (a) and Set 2 (b). The open squares for the 7.654-MeV state show the cross sections taken from Ref. [26]. The DWBA calculations for the inelastic scattering with the macroscopic collective model, the microscopic α-cluster model by Kamimura [10], and the α-cluster condensation model by Funaki [19] are shown by the dotted, solid, and dashed lines, respectively.

[19] was also applied. In the calculations of the excitation for the 4.439-MeV 2^+ and 9.641-MeV 3^- states, the Coulomb excitation was also included.

Figure 2 shows the measured cross sections in comparison with the results of the DWBA calculations with the optical potential parameters, Set 1 and Set 2. The dotted lines in Fig. 2 correspond to the results of the DWBA calculations with the macroscopic collective model, where the transition potential for a breathing mode was assumed to reproduce the cross sections of the 7.654-MeV 0^+_2 state [28]. The deformation parameters obtained in the present analysis with the optical potentials of Set 1 and Set 2 are found to give almost the same values for each transition, and are listed in Table II together with those published in Refs. [30–33].

In the DWBA calculation with the microscopic AC model, the transition potentials were generated by folding the effective interactions given by Franey and Love [21] at 270 and 325 MeV to the transition densities published by Kamimura [10] according to prescription by Satchler [29]. The knock-on

TABLE II. Deformation parameters, β_λ.

States	Present work	Ref. [30]	Ref. [31]	Ref. [32]	Ref. [33]
2^+_1	0.55 ± 0.11	0.753 ± 0.049	0.41	0.3	0.46
0^+_2	0.15 ± 0.03	0.187 ± 0.013			
3^-_1	0.39 ± 0.08	0.556 ± 0.066	0.26	0.18	0.24

TABLE III. Renormalization factors.

States	AC model	ACC model
2^+_1	0.64 ± 0.13	
0^+_2	0.50 ± 0.10	0.67 ± 0.13
3^-_1	0.26 ± 0.05	

exchange effect was also taken into account in the calculations. Because the strength, J_{00}, for the knock-on exchange term [29] was not well known at $E_p = 300$ MeV, it was allowed to vary as a free parameter to fit the calculated cross sections to the data, and we determined its value to be $J_{00} = 138$ MeV. Because the calculated cross sections were very similar to both the effective interactions at 270 and 325 MeV, those at 270 MeV are only shown in Fig. 2 by the solid lines. Because the calculated cross sections were larger than the measured ones by a factor of 1.5∼4, we multiplied the calculated cross sections by the renormalization factors to fit the experimental cross sections, as listed in Table III.

IV. DISCUSSION

Love and Franey [34] analyzed the data of the ^{12}C(p,p') reaction at $E_p = 200$ MeV leading to the 4.439-MeV 2^+ state [35] via the distorted-wave impulse approximation by using the Cohen-Kurath wave function [5] and its effective interactions [21]. The calculated cross section was ∼1.7 times larger than the experimental cross sections as was the case for the calculation herein. Based on the Love and Franey model, renormalization factors could be obtained from isoscalar natural-parity transitions because of the fact that the Pauli correction to nucleon-nucleon scattering is necessary in the presence of other nucleons, and this is not peculiar to ^{12}C [34]. Indeed, for the unnatural-parity transition to the 12.71-MeV 1^+ $(T=0)$ and 15.11-MeV 1^+ $(T=1)$ states in ^{12}C, Tamii *et al.* reproduced experimental cross sections via DWBA calculation without the renormalization factor [26].

The present calculation of the differential cross sections at very forward angles ($\theta_{\text{c.m.}} \leqslant 5^\circ$) overestimates (∼2 times) the inelastic cross sections. The Coulomb excitation is known to affect the cross sections at forward angles. However, the Coulomb excitation is not found to be so important in the present ^{12}C(p,p') reaction at 300 MeV, and does not explain the magnitude of the calculated cross sections. For the 2^+ state, the nuclear and Coulomb interactions destructively interfere with each other, and the calculated cross sections are slightly less than those without Coulomb excitation. The calculated cross sections are still ∼2 times larger than the experimental cross sections, as shown in Fig. 2. For the 3^- state, the Coulomb excitation has no noticeable effect upon the differential cross sections because of the high multiporarity of the state. On the other hand, only the nuclear excitation is involved for the 0^+_2 state. The fact that the present calculation overestimates the cross sections at the forward angles might be from the detailed shapes in the tails of the transition potentials. Hereafter, we restrict our discussion on the cross sections at $\theta_{\text{c.m.}} \geqslant 5^\circ$.

In the macroscopic collective model, the measured angular distributions of the differential cross sections for the 2^+ and 3^- states are well reproduced by the calculations with the optical potential parameters of Set 2. The calculated cross sections with Set 1 give a rather poor fit of the experimental data, especially for the 7.654-MeV 0_2^+ state. The deformation parameters obtained from the present analysis are consistent with the values reported in Refs. [30–33]. The measured cross sections for the 0_2^+ state are not well reproduced with the breathing mode calculation, particularly at backward angles, suggesting that the breathing mode does not well describe the transition potential inside the nucleus.

In the microscopic AC model, the DWBA calculations well reproduced the experimental cross sections for the 2^+ and 3^- states, irrespective of the optical potential parameters, Set 1 and Set 2. As pointed out by Funaki *et al.* [19] for the 0_2^+ state, the transition density for the ACC model is almost equivalent to that for the AC model by Kamimura [10]. As a result, both calculated cross sections for the 0_2^+ state with the ACC and AC models are very similar to each other, and are in good agreement with the experimental data even at backward angles, as shown in Fig. 2. This fact shows that the microscopic transition potentials employed with the ACC and AC models for the 0_2^+ state are reasonable. On the other hand, it has been theoretically shown that the exact 3α-cluster model wave functions (AC model) for the 0_2^+ state can definitely be interpreted as the 3α-condensed state (ACC model) [36]: The transition density with the AC model for the 0_2^+ state is equivalent to that with the ACC model. Thus, the present result is consistent in supporting the idea that the 7.654-MeV 0_2^+ state in ^{12}C is the dilute α-condensed state.

V. SUMMARY

We studied the ^{12}C(p,p') reaction at 300 MeV. The observed differential cross sections for the 0_2^+ state at $E_x =$ 7.654 MeV are well reproduced by the α-cluster condensation model, but not by the collective model. The present result supports that this state has the wave function of the α-cluster condensation. However, a remaining question should be addressed concerning the difference between the experimental and calculated cross sections at $\theta_{\rm c.m.} \leqslant 5°$. This difference can be caused from the fact that the wave function of the 7.654-MeV 0_2^+ state may have a long tail at the outside of the ^{12}C nucleus. More theoretical efforts in obtaining the 0_2^+ wave function for the skin or hallo part would be necessary to improve the fit of the DWBA calculation to the experimental data at $\theta_{\rm c.m.} \leqslant 5°$.

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