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Search for α-cluster States in ^{13}C

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The cluster structures in ^{13}C were discussed by measuring the isoscalar transition strengths in the ^{13}C(α, α') reaction at forward angles at $E_\alpha = 388$ MeV. We found two excited states at $E_x = 11.08$ and 12.5 MeV near the ^{9}Be + α and $3\alpha + n$ decay thresholds are strongly excited by the isoscalar monopole transitions. We also observed bump structures around $E_x = 15$ MeV in the isoscalar dipole strength distribution. These states are proposed to be candidates for spatially developed cluster states from the consideration of the threshold-rule presented in the Ikeda diagram and the comparison with the $3\alpha + n$ orthogonality condition model calculation.

KEYWORDS: cluster state, inelastic alpha scattering, isoscalar transition strength

1. Introduction

Alpha clustering is an important concept in describing the nuclear structure. On the basis of the threshold rule presented in the Ikeda diagram [1], the α-cluster states emerge near the cluster-decay thresholds in self-conjugate $A = 4n$ nuclei. One of the most well-known α cluster states is the 0_2^+ state in ^{12}C at $E_x = 7.65$ MeV only 0.38 MeV above from the 3α-decay threshold. The excitation energy of the 0_2^+ state is reproduced in 3α cluster models [2–4], but cannot be explained by shell-model calculations. Therefore, it is widely believed that the 0_2^+ state has a spatially well-developed structure consisting of 3α clusters. Recently, the 0_2^+ state has attracted attention as the 3α condensed state where the 3α clusters are condensed into the lowest-energy orbit [5–8]. According to the 3α orthogonality condition model (OCM) calculation by Yamada and Schuck [6], the 3α clusters in the 0_2^+ state occupy the $0s$ orbit with a high probability of 70%, and thus the momentum distribution of the α clusters has a sharp peak like a δ-function in the $k \sim 0$ fm^{-1} region. Reflecting this momentum distribution, the

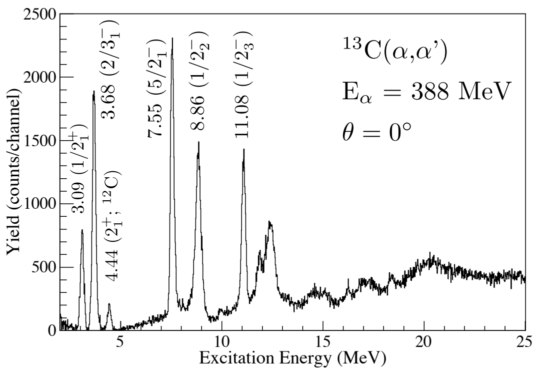

Fig. 1. Excitation-energy spectrum for the ^{13}C(α, α') reaction measured at 0°.

0^+_2 state has a spatially expanded and low-density dilute cluster structure. The α condensed states with exotic properties like low-density dilute gas are theoretically proposed to exist in self-conjugate $A = 4n$ nuclei up to $n = 10$, namely ^{40}Ca [9].

It is a very interesting question of how cluster structures develop in $A \neq 4n$ nuclei such as ^{13}C. In the recent theoretical and experimental studies [10, 11], it is pointed out that the cluster states are strongly excited by the isoscalar monopole transitions and its transition strengths are key observables to identify the cluster states. In the case of ^{13}C, Yamada and Funaki investigated the structure of the excited states up to around $E_x \sim 16$ MeV with the full four-body $3\alpha + n$ OCM calculation [12]. According to their calculation, it is suggested that the $1/2^-$ states with well-developed cluster structures are excited by the isoscalar monopole ($\Delta L = 0$) transitions although the ground state has a shell-model-like structure. In addition to the $1/2^-$ states, they predicted the $1/2^+_5$ state around $E_x \sim 15$ MeV excited by the isoscalar dipole ($\Delta L = 1$) transition is a strong candidate for the $3\alpha + n$ condensed-like state where the 3α clusters and the excess neutron occupy the $(0s)^{3\alpha}(0s)^{\nu}_{1/2}$ orbits.

In this work, we measured the ^{13}C(α, α') reaction at $E_\alpha = 388$ MeV and extracted the isoscalar monopole and dipole transition strengths in order to search for the α-cluster states in ^{13}C.

2. Experiment

The experiment was performed at Research Center for Nuclear Physics at Osaka University. A 388-MeV α beam extracted from the ring cyclotron was transported to a self-supporting ^{13}C target with a thickness of 1.5 mg/cm^2. The scattered α particles were momentum analyzed by the high-resolution magnetic spectrometer Grand Raiden [13] and the cross section of the elastic and inelastic α scatterings off ^{13}C were measured at scattering angles between 0°–19.4°. A background measurement using a $^{\mathrm{nat}}$C target with a thickness of 0.5 mg/cm^2 was also performed to subtract contribution due to ^{12}C contained in the ^{13}C target as a contaminant. A typical excitation-energy spectrum for the ^{13}C(α, α') reaction measured at 0° is shown in Fig. 1. Several known discrete states at $E_x \leqq 11.08$ MeV in ^{13}C were clearly observed. The excitation-energy resolution for the 3.09-MeV state was 140 keV at full width at half maximum, which was dominated by the energy spread of the α beam from the cyclotron.

3. Results and discussion

We performed the distorted-wave Born-approximation (DWBA) calculation to obtain transition strengths from the measured differential cross section for the ^{13}C(α, α') reaction. The transition potentials used in the DWBA calculation were obtained by folding the macroscopic transi-

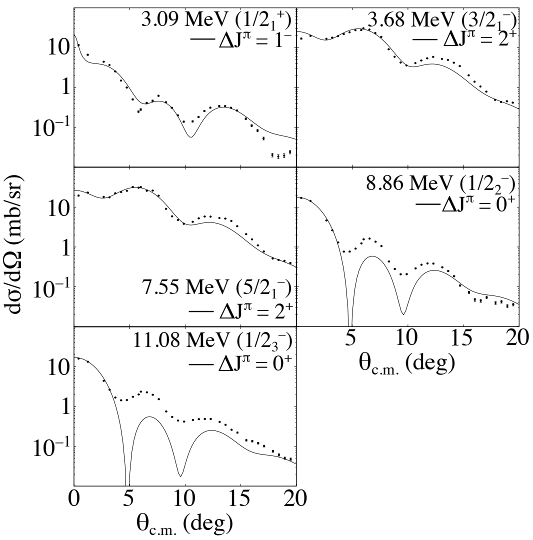

Fig. 2. Angular distributions of cross sections for several discrete states in the ^{13}C(α,α') reaction. The solid circles show the experimental cross sections and the solid lines show those calculated by the DWBA.

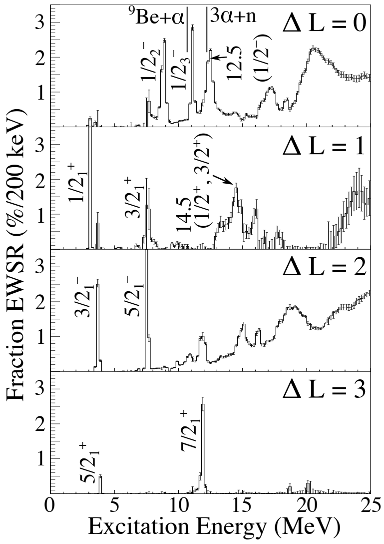

Fig. 3. Strength distributions for the ΔL = 0–3 transitions in ^{13}C obtained by the MDA. The threshold energies to decay into the ^{9}Be + α and $3\alpha + n$ channels are shown by the vertical lines in the top panel.

tion densities [14] with the effective αN interaction potential $V_{\alpha N}(r)$ parameterized by $V_{\alpha N}(r) = -V\exp(-r^2/\alpha_V^2) - iW\exp(-r^2/\alpha_W^2)$. The interaction strengths and range parameters of $V = 18.4$ MeV, $W = 11.3$ MeV, $\alpha_V = 2.01$ fm, and $\alpha_W = 2.00$ fm were determined to reproduce the measured angular distribution of the elastic α scattering. The amplitudes of the transition densities for the several discrete states were determined from the known electric transition strengths [15]. Figure 2 shows the angular distributions of the measured cross sections for the several discrete states compared with the DWBA calculation. The DWBA calculation reasonably reproduces the measured cross sections.

The cross sections for each multipole transition in inelastic α scattering have a characteristic angular distribution depending on the transferred angular momentum. Therefore, the multipole transition strengths from the ground state to excited states are obtained by the multipole decomposition analysis (MDA) in which the measured cross sections are fitted by the calculated cross sections by the DWBA as follows:

$$\left[\frac{d\sigma}{d\Omega dE_x}\right]^{\mathrm{exp}} = \sum_{\Delta L} A_{\Delta L}(E_x) \left[\frac{d\sigma}{d\Omega dE_x}\right]^{\mathrm{DWBA}}_{\Delta L}.$$

The strength distributions for the ΔL = 0–3 transitions obtained by the MDA are shown in Fig. 3. The known discrete states in ^{13}C are correctly observed in the ΔL spectra. This result demonstrates the reliability of the present MDA.

3.1 $\Delta L = 0$ *states*

Several prominent peaks are observed in the strength distribution for the $\Delta L = 0$ transitions. The first and second peaks correspond to the $1/2^-_2$ state at $E_x = 8.86$ MeV and the $1/2^-_3$ state at $E_x = 11.08$ MeV, respectively. In this work, we found a new state located at $E_x = 12.5$ MeV which is not listed in the compilation of the experimental data [15]. Since this state is excited by the monopole transition, its spin and parity were determined to be $1/2^-$. According to the $3\alpha + n$ OCM calculation [12], four excited $1/2^-$ states are proposed to exist in a region of $E_x < 16$ MeV and the newly observed $1/2^-$ state at $E_x = 12.5$ MeV is suggested to correspond to the $1/2^-_4$ state.

Considering the cluster states are strongly excited by the isoscalar monopole transitions [10, 11] and emerge near the cluster decay thresholds [1], the two states at $E_x = 11.08$ MeV $(1/2_3^-)$ and 12.5 MeV $(1/2_4^-)$ are inferred to have developed cluster structures. These two states are proposed to have $^9\mathrm{Be}(1/2^-)+\alpha$ and $^9\mathrm{Be}(3/2^-)+\alpha$ cluster structures in the $3\alpha+n$ OCM calculation, respectively.

3.2 $\Delta L = 1$ states

Several peak structures are observed around $E_x = 15$ MeV in addition to peaks corresponding to the $1/2_1^+$ state at $E_x = 3.09$ MeV and the $3/2_1^+$ state at $E_x = 7.68$ MeV in the strength distribution for the $\Delta L = 1$ transitions. A small peak observed at the same energy with the $3/2_1^-$ state at $E_x = 3.7$ MeV is a spurious peak due to errors of the DWBA calculation. Since the DWBA calculation could not completely reproduce the cross section for the $3/2_1^-$ state excited by the $\Delta L = 2$ transition, residues in the MDA were incorrectly decomposed into the $\Delta L = 1$ strength. A large uncertainty was assigned to this peak, and thus its peak height is consistent with zero.

Prominent peaks at $E_x = 14.5$ MeV and 16.1 MeV are observed, which are not listed in Ref. [15]. Since these states are excited by the dipole transition, the spin and parity of these states should be $1/2^+$ or $3/2^+$. The excitation energies of these states are close to that of the $1/2_5^+$ state predicted by the $3\alpha+n$ OCM calculation, therefore, these might be candidates for the $3\alpha+n$ condensed-like state proposed in Ref. [12].

4. Summary

The cross sections of the $^{13}\mathrm{C}(\alpha,\alpha')$ reaction was measured at forward angles including 0° and the MDA was performed in order to search for the α cluster states in ^{13}C. As a result of the MDA, several states strongly excited by the isoscalar monopole transition were observed and a new state at $E_x = 12.5$ MeV was found which is not listed in the compilation of the experimental data [15]. The spin and parity of this state were determined to be $1/2^-$. Since the $1/2^-$ states at $E_x = 11.08$ MeV and 12.5 MeV are located near the cluster decay thresholds, these states are inferred to have spatially well-developed cluster structures. According to the $3\alpha+n$ OCM calculation, these states are indicated to have $^9\mathrm{Be}(1/2^-)+\alpha$ and $^9\mathrm{Be}(3/2^-)+\alpha$ structures, respectively.

We also found the new structures around $E_x = 15$ MeV in the isoscalar dipole transition strength distribution. Although these states are possible candidates for the $1/2_5^+$ state which is theoretically suggested to be the $3\alpha+n$ condensed-like state, the spin and parity of these states cannot be identified in this experiment. The spin and parity of these states are necessary to be determined by measuring the angular distribution of decay particles from these states in the future work.

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