

## Search for Alpha Condensed State in $^{24}\text{Mg}$

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The alpha inelastic scattering from  $^{24}\text{Mg}$  was measured to obtain the isoscalar natural-parity excitation strengths and to search for the  $\alpha$ -condensed states. The multipole decomposition analysis for the measured cross sections was performed. The strength distributions for the  $\Delta L = 0-3$  were successfully obtained and the possible candidates for the  $\alpha$ -condensed states around the  $^{16}\text{O}$  core were found.

### §1. Introduction

Alpha particle clustering is an important concept in nuclear physics. On the basis of the Ikeda diagram,<sup>1)</sup> the  $\alpha$  cluster structures are expected to emerge near the  $\alpha$ -decay threshold energies. For instance, it has been suggested that the 7.65-MeV  $0_2^+$  state in  $^{12}\text{C}$ , which locates at an excitation energy higher than the  $3\alpha$ -decay threshold by 0.39 MeV, has a spatially well-developed  $3\alpha$ -cluster structure.

This  $0_2^+$  state is theoretically described by introducing a novel concept of the nuclear structure, i.e., this state has a dilute-gas-like structure where three  $\alpha$  clusters are weakly interacting and are condensed into the lowest  $s$ -orbit.<sup>2)</sup> The next natural question addressed is whether such  $\alpha$  condensed states exist in heavier self-conjugate  $4n$  nuclei.

Such  $\alpha$  condensed states are theoretically predicted up to  $n = 10$ .<sup>3)</sup> The energy of the  $n\alpha$  condensed state relative to the  $n\alpha$ -decay threshold increases with  $n$  due to the short-range nature of the attractive force between  $\alpha$  clusters and the long-range nature of the Coulomb repulsion. Finally  $n\alpha$  condensed state becomes unstable beyond  $n = 10$ .

A recent theoretical work proposed a new conformation of the  $\alpha$  condensed state where  $\alpha$  clusters are condensed into the lowest  $s$ -orbit around a core nucleus.<sup>4),5)</sup> Attractive potential for  $\alpha$  clusters provided by the core nucleus stabilizes the  $\alpha$

condensed state around the core nucleus. Thus, such  $\alpha$  condensed states around core nuclei are expected to appear at excitation energies lower than the corresponding cluster-decay threshold energies.

From the experimental point of view, the  $3\alpha$  and  $4\alpha$  condensed states in  $^{12}\text{C}$  and  $^{16}\text{O}$  were extensively studied in the last decade.<sup>6)–11)</sup> However, the other nuclei heavier than  $^{16}\text{O}$  are still unexplored due to experimental difficulties. Since the fully condensed states in  $^{20}\text{Ne}$  and  $^{24}\text{Mg}$  are expected to appear about 5 MeV above the  $n\alpha$ -decay threshold, these states are obscured by continuum states in the highly excited region. Although the  $\alpha$  condensed states around the core nuclei should appear at relatively low excitation energies, the level densities near these condensed states are still high and the experimental identifications are not easy.

In our previous works,<sup>12),13)</sup> it was demonstrated that spatially well-developed cluster states in light nuclei, whose spins and parities are the same as in the ground state, are strongly excited by isoscalar monopole transitions. The  $0_2^+$  state in  $^{12}\text{C}$ , a typical  $3\alpha$  cluster state, is strongly excited with an isoscalar monopole strength of  $121 \pm 9 \text{ fm}^4$ ,<sup>14)</sup> which is about 3 times larger than the single particle estimation. Besides the  $0_2^+$  state in  $^{12}\text{C}$ , the  $3/2_3^-$  state in  $^{11}\text{B}$  with the well-developed  $2\alpha + t$  structure is also strongly excited by an isoscalar monopole transition. These facts are theoretically explained on the basis of the Bayman-Bohr theorem and the ground-state correlation.<sup>15)</sup> Since ground-state wave functions in light nuclei inherently possess the clustering degrees of freedom, it is naturally expected that spatially developed cluster states are excited by stimulating relative motion between the clusters with the monopole operator  $r^2$ . Therefore, the isoscalar monopole strengths are a key observable to search for the  $\alpha$ -condensed states.

The alpha inelastic scattering at intermediate energies and at forward angles is one of the most useful probes to measure the isoscalar monopole strengths because its reaction mechanism is simple. It has a selectivity for isoscalar natural-parity transitions and there is a good linear relation between the reaction cross sections and the relevant nuclear transition matrix elements. The alpha inelastic scattering from  $^{24}\text{Mg}$  was previously measured at Texas A&M University.<sup>16)–18)</sup> However, these measurements were devoted to studying giant resonances in  $^{24}\text{Mg}$  and the excitation-energy resolution was not good enough to separate the  $\alpha$ -condensed states from the other states.

In the present work, we performed the high resolution measurement of the alpha inelastic scattering from  $^{24}\text{Mg}$  and obtained the isoscalar natural-parity excitation strengths to search for the  $\alpha$ -condensed states in  $^{24}\text{Mg}$ .

## §2. Experiment

The experiment was performed at the Research Center for Nuclear Physics, Osaka University, using a 400-MeV alpha beam. The halo-free alpha beam extracted from the ring cyclotron was transported to the  $^{24}\text{Mg}$  target. Scattered alpha particles were momentum analyzed by the high-resolution spectrometer Grand Raiden.<sup>19)</sup> The focal-plane detector system of Grand Raiden consisting of two multi-wire drift chambers and plastic scintillation detectors allowed the reconstruction of the scat-

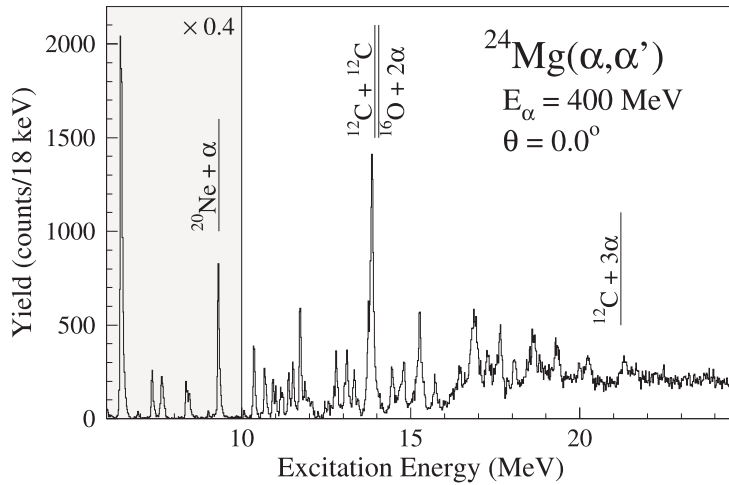


Fig. 1. Typical spectrum for the  $^{24}\text{Mg}(\alpha, \alpha')$  reaction measured at  $0^\circ$ . The excitation spectrum below  $E_x = 10$  MeV is downscaled by a factor of 0.4.

tering angle at the target via ray-tracing techniques.

A typical spectrum for the  $^{24}\text{Mg}(\alpha, \alpha')$  reaction measured at  $0^\circ$  is shown in Fig. 1. An energy resolution of 80 keV full width at half maximum was obtained.

### §3. Result and discussion

The measured cross sections for the  $^{24}\text{Mg}(\alpha, \alpha')$  reaction exciting the prominent low-lying states are compared with the distorted-wave Born-approximation (DWBA) calculation in Fig. 2. The transition potentials used in the DWBA calculation were obtained by folding the macroscopic form factors with the phenomenological  $\alpha N$  interaction  $V_{\alpha N}$  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  $V = 13.1$  MeV,  $W = 8.8$  MeV, and  $\alpha_V = \alpha_W = 5.0$  fm were determined to reproduce the cross section for the  $\alpha + ^{24}\text{Mg}$  elastic scattering.

The normalization factors for the macroscopic form factors were determined to give the known electromagnetic transition strengths except for the  $0_3^+$  state at  $E_x = 9.305$  MeV. The hatched bands in Fig. 2 show uncertainties of the calculated cross sections due to the errors in the electromagnetic transition strengths. The normalization factor for the  $0_3^+$  state was determined to fit the present data. As seen in Fig. 2, the DWBA calculation reasonably well-describes the measured cross sections. It should be noted that all the parameters in the present DWBA calculation are determined from the previous experimental data and no parameters are tuned to reproduce the present result except for the normalization factor for the  $0_3^+$  state.

Since the angular distribution of the cross section for each multipole transition depends on its transferred angular momentum, it is possible to decompose the cross section into each multipole component by fitting the measured angular distribution. In the fitting procedure, the multipole contributions up to  $\Delta L = 15$  were taken into

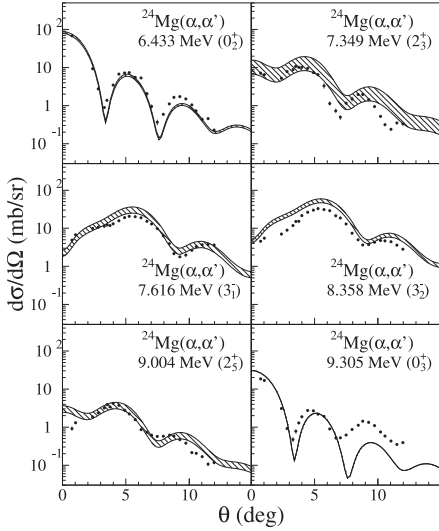


Fig. 2. Cross sections for the prominent low-lying states in  $^{24}\text{Mg}$  compared with the DWBA calculation. The hatched bands show uncertainties of the calculated cross sections due to the errors of the electromagnetic transition strengths.

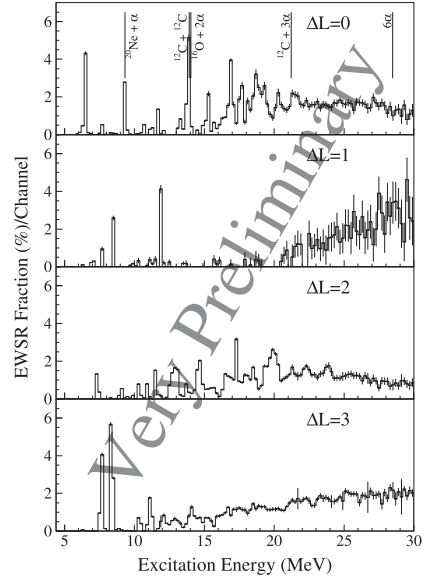


Fig. 3. Strength distributions for the  $\Delta L = 0-3$  transitions obtained from the multipole decomposition analysis for the  $^{24}\text{Mg}(\alpha, \alpha')$  reaction.

account. The strength distributions for the  $\Delta L = 0-3$  transitions obtained from the multipole decomposition analysis are shown in Fig. 3. All the prominent low-lying states shown in Fig. 2 are successfully decomposed into the correct multipole components. This proves the present multipole decomposition analysis is reasonable.

It is remarkable that the fine structures are observed in the  $\Delta L = 0$  strength distribution and some of them are located near the  $n\alpha$ -decay threshold energies. Although no prominent structure is found near the  $6\alpha$ -decay threshold, a narrow peak at  $E_x = 13.8$  MeV and a broad bump at  $E_x = 21.5$  MeV are very close to the  $^{16}\text{O} + 2\alpha$  and  $^{12}\text{C} + 3\alpha$  threshold energies, respectively. These states are considered to be candidates of the  $\alpha$ -condensed states around the core  $^{16}\text{O}$  and  $^{12}\text{C}$  nuclei predicted in Ref. 4). However, it is difficult to conclude that these states are indeed the  $\alpha$ -condensed states around the core nuclei because the alpha inelastic scattering excites not only  $\alpha$ -cluster states but also single-particle states such as giant monopole resonances (GMR). These candidates might be attributed to the GMR instead of the  $\alpha$ -condensed states, thus further information is needed to distinguish between the two possibilities.

In order to clarify the microscopic structure of the excited states, we measured decay particles from the excited states in coincidence with the inelastically scattered  $\alpha$  particles. If the excited states above the particle-decay thresholds have spatially well-developed cluster structures, these states should dominantly decay into  $\alpha$ -emission channels rather than into proton- or neutron-emission channels. On the other hand, single-particle states such as GMR should prefer proton- or neutron-emission channels to  $\alpha$ -emission channels. The decay branching ratio of the

$\alpha$ -emission channels to the proton-emission channels, thus, provides complementary information to identify the  $\alpha$  cluster states. The analysis of the decay particle is still in progress. The results will be presented soon elsewhere.

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