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Search for alpha inelastic condensed state in ^{24}Mg

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Abstract. The alpha inelastic scattering from ^{24}Mg was measured to obtain the isoscalar natural-parity excitation strengths and to search for α-condensed states. Multipole decomposition analysis was performed for the measured cross sections, and the strength distributions for the ΔL = 0–3 transitions were successfully obtained. The decay particles from the excited states in ^{24}Mg were also measured in concidence with the inelastically scattered alpha particles. Candidates were found for α-condensed states around the ^{16}O core.

1. Introduction

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

This 0_2^+ state is described by introducing a novel concept into nuclear structure. This state has a dilute-gas-like structure, in which three α clusters are weakly interacting and are condensed into the lowest s-orbit [2]. The next natural question addressed is whether such α-condensed states exist in heavier self-conjugate $4n$ nuclei.

Such α-condensed states are theoretically predicted up to $n = 10$ [3]. 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 α clusters and the long-rage nature of the Coulomb repulsion. Finally, the $n\alpha$ condensed state becomes unstable beyond $n = 10$.

A recent theoretical work proposed a new conformation of the α-condensed state: α clusters may be condensed into the lowest s-orbit around a core nucleus [4]. The attractive potential for α clusters provided by the core nucleus stabilizes the α-condensed state around the core. Thus, such α-condensed states around core nuclei are expected to appear at excitation energies lower than the corresponding cluster-decay threshold energies.

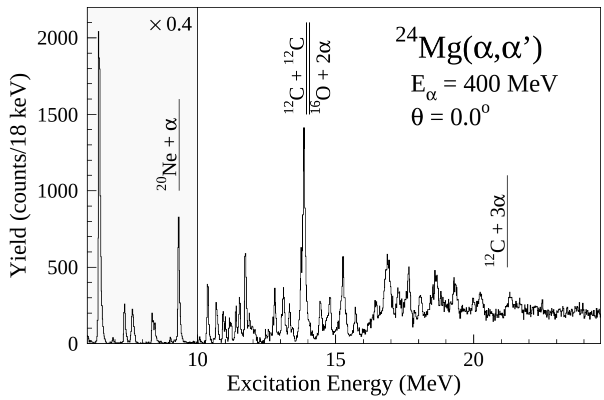

Figure 1. Typical spectrum for the ^{24}Mg(α,α') reaction measured at 0°. The excitation spectrum below $E_x = 10$ MeV is downscaled by a factor of 0.4.

From the experimental point of view, the 3α- and 4α-condensed states in ^{12}C and ^{16}O were extensively studied in the last decade [5, 6, 7, 8, 9]. However, the other nuclei heavier than ^{16}O are still unexplored due to experimental difficulties. Since the fully condensed states in ^{20}Ne and ^{24}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 α-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 [10, 11], it was demonstrated that, in light nuclei, spatially well-developed cluster states 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}C, a typical 3α cluster state, is strongly excited with an isoscalar monopole strength of 121$\pm$9 fm^4, which is about 3 times larger than the single particle estimate. Besides the 0_2^+ state in ^{12}C, the $3/2_3^-$ state in ^{11}B with a 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 [12]. Since the 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 perturbing the relative motion between the clusters with the monopole operator r^2. Therefore, the isoscalar monopole strengths are key observables in searching for the α-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}Mg was previously measured at Texas A&M University [13, 14]. However, these measurements were devoted to studying giant resonances in ^{24}Mg, and the excitation-energy resolution was not good enough to separate the α-condensed states from the other states.

In the present work, we performed high-resolution measurement of alpha inelastic scattering from ^{24}Mg and obtained the isoscalar natural-parity excitation strengths to search for the α-condensed states in ^{24}Mg. Since the α-condensed states are expected to have large branching ratios to the α-decay channels, the particles emitted from the decaying excited states were also measured in coincidence with the inelastically scattered alpha particles.

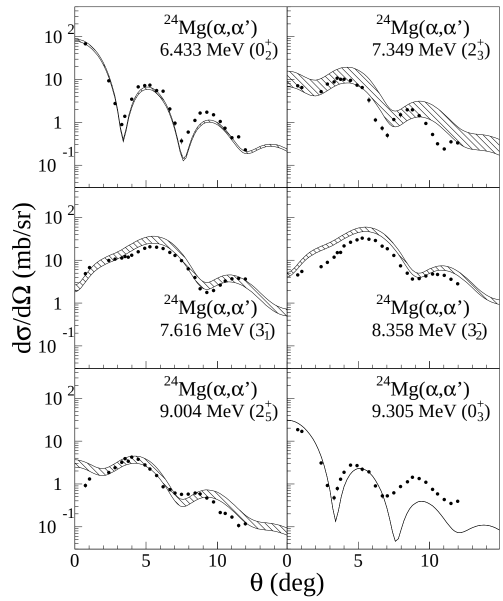

Figure 2. Cross sections for the prominent low-lying states in ^{24}Mg compared with the DWBA calculation. The hatched bands show uncertainties of the calculated cross sections due to the errors of the electromagnetic transition strengths.

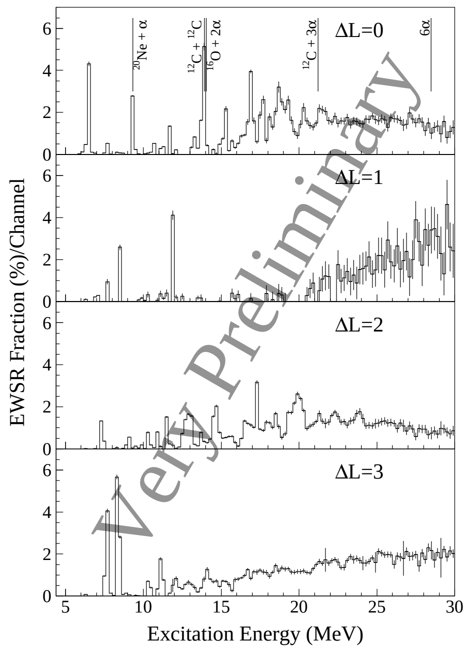

Figure 3. Strength distributions for $\Delta L =$ 0–3 transitions obtained from the multipole decomposition analysis for the ^{24}Mg(α,α') reaction.

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}Mg target. The scattered alpha particles were momentum-analysed by the high-resolution spectrometer Grand Raiden [15]. 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. A typical spectrum for the ^{24}Mg(α,α') reaction measured at 0° is shown in Fig. 1. An energy resolution of 80 keV full width at half maximum was achieved.

Six silicon counter telescopes were installed at a distance of 200 mm from the target in the scattering chamber to measure decay particles from excited states. Each telescope consists of 4 silicon detectors with a sensitive area of 50 mm × 50 mm. The thickness of the first silicon detector, nearest to the target, was 65 μm, while those of the other silicon detectors were 525 μm. The sensitive area of the first silicon detector was segmented into four strips, and the dimension of each strip was 12.5 mm in width and 50 mm in height.

3. Result and Discussion

The measured cross sections for the ^{24}Mg(α,α') reaction exciting the prominent low-lying states are compared with a 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 αN 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^2 were determined so as to reproduce the cross section for the α+^{24}Mg elastic scattering.

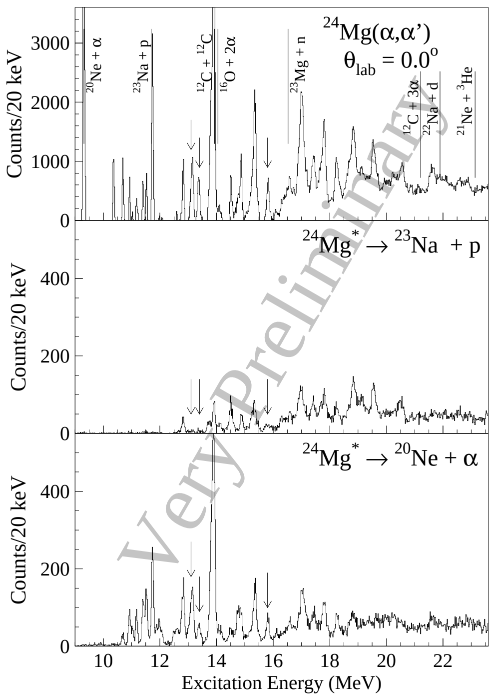

Figure 4. Excitation energy spectra in the ^{24}Mg(α,α') reaction at E_x = 9–23.6 MeV taken from the singles measurement (top) and from the coincidence measurements with decay protons (middle) and α particles (bottom). The vertical arrows show the 0^+ states at 13.1, 13.4, and 15.8 MeV.

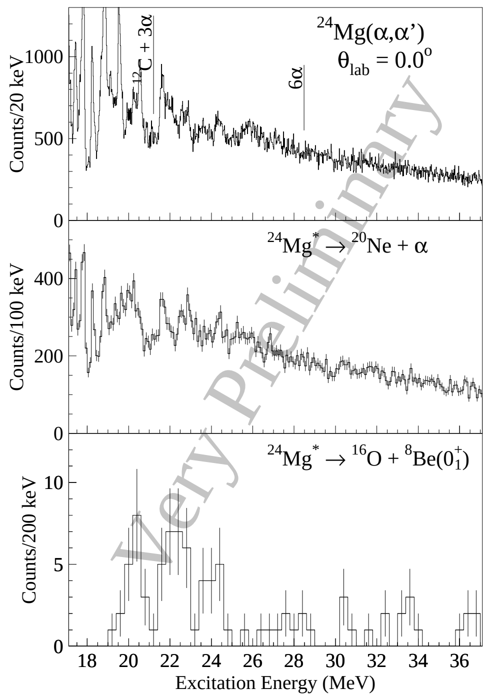

Figure 5. Excitation energy spectra in the ^{24}Mg(α,α') reaction at E_x = 17.1–37.1 MeV taken from the singles measurement (top) and from the coincidence measurements with decay α particles (middle) and ^{8}Be (bottom).

The normalization factors for the macroscopic form factors were determined from the known electromagnetic transition strengths except for the 0_3^+ state at $E_x = 9.305$ MeV. The hatched bands in Fig. 2 show the 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 by fitting to the present data. As seen in Fig. 2, the DWBA calculation describes the measured cross sections reasonably well. It should be noted that all the parameters in the present DWBA calculation were determined from 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 multipole components by fitting the measured angular distribution. In the fitting procedure, the multipole contributions up to $\Delta L = 15$ were taken into 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 validity of the present multipole decomposition analysis.

It is remarkable that 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 6α-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}O + 2α and ^{12}C + 3α threshold energies, respectively. These states are considered to be candidates of the α-condensed states around the core nuclei ^{16}O and ^{12}C predicted in Ref. [4]. However, it is difficult to conclude that these states are indeed the α-condensed states around the core nuclei because the alpha inelastic scattering excites not only α-cluster states but also single-particle states such as giant monopole resonances (GMR). These candidates, thus, might be attributed to the GMR instead of the α-condensed states, and further information is needed to distinguish between the two possibilities.

In order to clarify the microscopic structure of the excited states, we detected the decay particles from the excited states in coincidence with the inelastically scattered α particles. If the excited states above the particle-decay thresholds have spatially well-developed α-cluster structures, these states should dominantly decay into α-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 α-emission channels. The decay branching ratio of the α-emission channels to the proton-emission channels, thus, provide complementary information to identify the α-cluster states.

The excitation energy spectrum in the $^{24}\mathrm{Mg}(\alpha, \alpha')$ reaction from the singles measurement at 0° is compared with those from the coincidence measurements with decay protons and α particles in Fig. 4. It is remarkable that the strong 0^+ state at 13.9 MeV near the $^{16}\mathrm{O} + 2\alpha$ and $^{12}\mathrm{C} +^{12}\mathrm{C}$ decay thresholds has a large decay width to the α-emission channel. This state is considered to be the most probable candidate of the 2α-condensed state around the $^{16}\mathrm{O}$ core predicted in Ref. [4]. The three 0^+ states at $E_x = 13.1$, 13.4, and 15.8 MeV also have large decay widths to the α-emission channel and their proton-decay widths are quite small. This result suggests these three states should also have well-developed alpha-cluster structures.

The excitation energy spectrum in the highly excited region is shown in Fig. 5. The top, middle, and bottom figures present the spectra taken from the singles measurement and the coincidence measurements with the α particles and $^8\mathrm{Be}$. Unfortunately, no significant structures are observed near the 6α decay threshold where the 6α-condensed state is expected. It is still interesting to observe bump structures at 20.5, 22.2, and 24.3 MeV in the coincidence spectrum with $^8\mathrm{Be}$. These states should be attributed to multi-alpha-cluster structures.

The analysis of the decay is still in progress. The results will be presented soon elsewhere.

Acknowledgments

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