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

T. Kawabata$^1$, T. Adachi$^2$, M. Fujiwara$^2$, K. Hatanaka$^2$, Y. Ishiguro$^1$, M. Itoh$^3$, Y. Maeda$^4$, H. Matsubara$^6$, H. Miyasako$^1$, Y. Nozawa$^1$, T. Saito$^4$, S. Sakaguchi$^6$, Y. Maeda$^4$, H. Matsubara$^6$, H. Miyasako$^1$, Y. Nozawa$^1$, T. Saito$^4$, S. Sakaguchi$^6$, Y. Maeda$^4$, H. Matsubara$^6$, H. Miyasako$^1$, Y. Nozawa$^1$

$^1$Department of Physics, Kyoto University
$^2$Research Center for Nuclear Physics, Osaka University
$^3$Cyclotron and Radioisotope Center, Tohoku University
$^4$Faculty of Engineering, University of Miyazaki
$^5$Center for Nuclear Study, University of Tokyo
$^6$RIKEN (The Institute for Physical and Chemical Research)
$^7$Department of Physics, Tokyo Institute of Technology

E-mail: kawabata@scphys.kyoto-u.ac.jp

Abstract. 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 [1], 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 [2]. 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 $n = 10$ [3]. The energy of the $na$ condensed state relative to the $na$-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 [4]. 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 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 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 $^{12}$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 estimation. Besides the $0^+_2$ state in $^{12}$C, the $3/2^-$ state in $^{11}$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 [12]. 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 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 study 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 the high resolution measurement of the alpha inelastic scattering from $^{24}$Mg and obtained the isoscalar natural-parity excitation strengths to search for the α-condensed states in $^{24}$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 $^{24}$Mg target. Scattered alpha particles were momentum analyzed by

**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.
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 $^{24}\text{Mg}(\alpha,\alpha')$ 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 $V_{\alpha N}(r) = -V \exp(-r^2/\alpha V) - iW \exp(-r^2/\alpha W)$. 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

**Figure 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.

**Figure 3.** Strength distributions for the $\Delta L = 0$–3 transitions obtained from the multipole decomposition analysis for the $^{24}\text{Mg}(\alpha,\alpha')$ reaction.
component 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 the fine structures are observed in the $\Delta L = 0$ strength distribution and some of them are located near the $\alpha$-decay threshold energies. Although no prominent structure is found near the $6\alpha$-decay threshold, a narrow peak at $E_x = 21.5$ 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, thus, might be attributed to the GMR instead of the $\alpha$-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 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, provide 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.

Acknowledgments
The authors acknowledge the effort of the RCNP cyclotron crew for providing the stable and clean beam. This research was supported in part by the Nogami memorial fund for young nuclear physicists, the Grant-in-Aids for Scientific Research No. 21740171 and for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence” from the Japan Ministry of Education, Sports, Culture, Science, and Technology.

References
[1] Ikeda K, Takigawa N and Horiuchi H 1968 Prog. Theor. Phys. Suppl., Extra Number 464–475
[2] Tohsaki A, Horiuchi H, Schuck P and Röpke G 2001 Phys. Rev. Lett. 87 192501
[3] Yamada T and Schuck P 2004 Phys. Rev. C 69 024309
[4] Itagaki N, Kimura M, Kurokawa C, Ito M and von Oertzen W 2007 Phys. Rev. C 75 037303
[5] Itoh M et al. 2004 Nucl. Phys. A 738 268–272
[6] Chernykh M, Feldmeier H, Neff T, von Neumann-Cosel P and Richter A 2007 Phys. Rev. Lett. 98 032501
[7] Freer M et al. 2009 Phys. Rev. C 80 041303
[8] Belyaeva T L et al. 2010 Phys. Rev. C 82 054618
[9] Wakasa T et al. 2007 Phys. Lett. B 173–177
[10] Kawabata T et al. 2007 Phys. Lett. B 646 6–11
[11] Kawabata T et al. 2004 Phys. Rev. C 70 034318
[12] Yamada T, Funaki Y, Horiuchi H, Ikeda K and Tohsaki A 2008 Prog. Theor. Phys. 120 1139–1167
[13] Youngblood D H, Lui Y W, Chen X F and Clark H L 2009 Phys. Rev. C 80 064318
[14] Youngblood D H, Lui Y W and Clark H L 1999 Phys. Rev. C 60 014304
[15] Fujiiwa M et al. 1999 Nucl. Instrum. Methods Phys. Res. A 422 484–488