Excitations of the α cluster in $A=6$ and 7 nuclei

T. Yamagata,[1,*] S. Nakayama,[2] H. Akimune,[1] M. Fujiwara,[3,4] K. Fushimi,[2] M. B. Greenfield,[5] K. Hara,[3] K. Y. Hara,[1] H. Hashimoto,[3] K. Ichihara,[2] K. Kawase,[3] M. Kinoshita,[1] Y. Matsui,[2] K. Nakanishi,[3] M. Tanaka,[6] H. Utsunomiya,[1] and M. Yosoi[7]

[1]*Department of Physics, Konan University, Kobe 658-8501, Japan*
[2]*Department of Physics, University of Tokushima, Tokushima 770-8502, Japan*
[3]*Research Center for Nuclear Physics, Osaka University, Osaka 567-0047, Japan*
[4]*Advance Science Research Center, JAERI, Ibaragi 319-1195, Japan*
[5]*Department of Physics, International Christian University, Tokyo 113-0033, Japan*
[6]*Kobe Tokiwa College, Kobe 654-0838, Japan*
[7]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

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The isovector giant dipole resonance (GDR) of an α cluster in ^{6}Li and ^{7}Li, and its analogs in ^{6,7}Be and ^{6,7}He were searched for by using the ^{6,7}Li(p,p'), ^{6,7}Li$(^{3}$He$,t)$, and ^{6,7}Li$(^{7}$Li$,^{7}$Be$)$ reactions at the incident energies of 300, 450, and 455 MeV, respectively. New dipole resonances were found at $E_x=27.0\pm1.5$ MeV in ^{6}Li and at $E_x=29.0\pm1.5$ MeV in ^{7}Li, both with widths (full width at half maximum) of 12 ± 2 MeV. In ^{6}He, ^{6}Be, ^{7}He, and ^{7}Be, the dipole resonances with a width of 12 ± 2 MeV were observed at $E_x=24.0\pm1.5, 23.5\pm1.5, 18.0\pm1.5$, and 28.0 ± 1.5 MeV, respectively. The resonance shapes were reproduced well with the GDR shape observed in the ^{4}He(γ,n) reactions. The averaged value for the ratios of the resonance cross section in $A=6$ to that in $A=7$ for each element was 1.2 ± 0.3. The averaged value for the ratios of the resonance cross section to the GDR cross section in the respective target nuclei was 0.44 ± 0.08, which was consistent with the ratios of the GDR cross section in ^{4}He to that in ^{6,7}Li reported in the photonuclear reactions. The excitation energies for the dipole resonances in $A=6$ and 7 nuclei relative to the separation energies of an α particle in ^{6}Li and ^{7}Li, respectively, agreed well with the excitation energy for the GDR in ^{4}He ($\sim$26 MeV). We conclude that the resonances observed in ^{6,7}Li are consistent with the GDR of the α cluster and the resonances in ^{6,7}He and ^{6,7}Be are consistent with the analogs of the GDR in the α cluster. The Q value for the excitation of the GDR of the α cluster in $A=7$ nuclei is deeper by 1.6 ± 0.3 MeV on the average than that in $A=6$.

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I. INTRODUCTION

Clusters in nuclei play an important role in nuclear structure and nuclear reactions. Clusters in nuclear systems are spatially localized subsystems composed of strongly correlated nucleons [1]. Therefore, we can expect two types of excitations in the clustering nuclei. One is the excitation due to an intercluster relative motion. A typical example is the rotational excitation of a clustering nucleus [2]. The other is due to an intrinsic excitation of the cluster itself, which has not been well understood. Such a cluster excitation is very interesting as a new concept of nuclear excitation [3]. The excited cluster may have characteristics different from the excitation of the cluster itself due to the nuclear medium effect.

In the photonuclear reaction Costa *et al.* suggested a possible excitation of the α cluster. They observed two resonances at excitation energies of $E_x=11.5$ and 26 MeV in the ^{6}Li(γ,n) spectra [4]. They concluded that the resonance at 11.5 MeV was the isovector giant dipole resonance (GDR) in ^{6}Li and the resonance at 26 MeV was due to the excited α cluster; namely, the GDR of ^{4}He in the ^{6}Li nucleus. However, no such evidence for the GDR in the α cluster has been obtained in other ^{6}Li(γ,n) reactions [5–7]. In the ^{nat}Li(γ,n) spectrum a peak at $E_x=30$ MeV was reported [8] in addition to the GDR peak at $E_x=17$ MeV. However, this 30-MeV peak was not observed in other ^{7}Li(γ,n) work [5,6]. Existence of the excited α cluster is not conclusive in the photonuclear reactions.

On the other hand, in the nuclear reaction the GDR in the α cluster seems to have been observed by Brady *et al.* at $Q\sim-30$ MeV in the ^{6,7}Li$(n,p)^{6,7}$He reaction [9]. Jänecke *et al.* reported a structure similar to that observed in the (n,p) reaction [9] by the ^{6}Li$(^{7}$Li$,^{7}$Be$)$ reaction [10]. In the ^{6,7}Li(p,n) reaction, Yang *et al.* reported the high-lying dipole resonances at $E_x=25$ MeV in ^{6}Be and at $E_x=30$ MeV in ^{7}Be [11]. The excitation energies and widths for the resonances observed in the nuclear reactions are very similar to those for the GDR in ^{4}He reported in the ^{4}He(γ,n) reaction [5].

We inferred that the resonances observed in the nuclear reactions are the analogs of the GDR in α clusters. Based on the excitation energies, widths, and cross sections observed with the $(^{7}$Li$,^{7}$Be$)$ reaction, we demonstrated, for the first time, that the resonances at $E_x\sim24$ MeV in ^{6}He and at 20 MeV in ^{7}He stem from the α cluster excitation, i.e., the analogs of the GDR in ^{4}He in nuclei [12]. From this result, the next questions were addressed: The resonances observed

*Electronic address: yamagata@center.konan-u.ac.jp

in ^{6}Be at $E_x=25$ MeV and in ^{7}Be at $E_x=30$ MeV in the (p,n) reactions [11] might also be the analogs of the GDR in an α cluster. By taking into account the Coulomb displacement energies, the GDR in an α cluster should be observed, if it exists, at $E_x\sim 26-30$ MeV in ^{6}Li and ^{7}Li, though there had been no report on such highly excited dipole resonances in ^{6,7}Li [13,14].

The ground states in ^{6}Li and ^{7}Li are known to have the large $d+\alpha$ and $t+\alpha$ components, respectively [13]. The excited α cluster, the GDR in ^{4}He, was searched for in ^{6,7}Li by using the ^{6,7}Li(p,p') reaction at 300 MeV, and the analogs in ^{6,7}He and ^{6,7}Be by the ^{6,7}Li(^{7}Li,^{7}Be) reaction at 455 MeV [12] and ^{6,7}Li(^{3}He,t) reaction at 450 MeV, respectively. These reactions were considered to be suitable for excitation of isovector resonances [15,16]. The GDR in an α cluster may be commonly identified by investigating the excitation energies, resonance shapes, cross sections of the resonances excited via the three different reactions.

The GDR in ^{4}He is a strongly excited resonance on the underlying continuum. Its excitation energy is about 26 MeV and is much higher than the excitation energies of the GDR in the target nuclei, $E_x\sim 12$ and 17 MeV in ^{6}Li and ^{7}Li, respectively [5]. In the nuclear reaction the spin dipole resonance (SDR) is also excited at the excitation region of the GDR. The SDR in the light nuclei has been observed to be similar to the GDR in terms of both excitation energy and the resonance shape [17]. Thus, a single-resonance-like peak composed of the GDR and SDR is observed. The existence of the GDR in an α cluster should be clearly distinguishable as a compact resonance on top of the underlying continuum at an excitation energy much higher than the GDR in the target nuclei.

The cross sections depend strongly on both the reaction mechanism and nuclear structure. However, the ratio of the cross sections deduced from the same reaction does not depend strongly on the reaction mechanism. Therefore, the cross-section ratio of the GDR in an α cluster in $A=6$ nucleus to that in $A=7$ nucleus for each element should be nearly unity, since the same GDR in the α cluster is excited in the same reaction. The cross-section ratio of the GDR in an α cluster to the GDR in the target nucleus deduced in these reactions should be nearly equal to the cross-section ratio, $\sigma(^4\mathrm{He})/\sigma(^{6,7}\mathrm{Li})$ obtained for the GDR in the photonuclear reactions [5,18] for all reaction channels.

In this paper, the details of our experimental study on the excited α clusters in ^{6,7}Li target nuclei are presented. Since the experimental details of the ^{6,7}Li(^{7}Li,^{7}Be) reaction are similar to those reported by Nakayama *et al.* [12], the present paper will focus only on the results of this reaction and will compare the results with those obtained in the (p,p') and (^{3}He,t) reactions.

II. EXPERIMENT

The experiment was carried out by using the 300-MeV proton, 450-MeV ^{3}He, and 455-MeV ^{7}Li beams from the ring cyclotron at the Research Center for Nuclear Physics (RCNP), Osaka University. Targets used were self-supporting metallic foils of enriched ^{6}Li (95.4%) and ^{7}Li (99.9%). Reaction particles were analyzed by using the magnetic spectrometer "Grand Raiden," and were detected with the focal plane detector system, which consisted of two multiwire drift chambers backed by a $\Delta E-E$ plastic scintillator telescope [19]. The typical values of the thickness of the targets used and energy resolution were 15, 20, and 1.0 mg/cm^2 and 120, 340, and 800 keV for the (p,p'), (^{3}He,t), and (^{7}Li,^{7}Be) reactions, respectively. The energy resolution for the (p,p') and (^{3}He,t) reactions were mainly due to the energy spread of the incident beams, while that for the (^{7}Li,^{7}Be) reaction was mainly due to both the energy spread of the incident beam and the ^{7}Be-particle excitation ($E_x=0.43$ MeV).

Energy spectra were measured in the angular ranges of $\theta_L=2.5°-16°$ for the (p,p') reaction, $\theta_L=0°-4.1°$ for the (^{3}He,t) reaction, and $\theta_L=0°-2.3°$ for the (^{7}Li,^{7}Be) reaction where the cross sections with a $\Delta L=1$ were expected to have the first maximum. The aperture of the entrance slits of the spectrometer was ±20 mrad horizontally and were ±15, ±10, and ±15 mrad vertically for the (p,p'), (^{3}He,t), and (^{7}Li,^{7}Be) reactions, respectively. In each reaction, events were sorted with a 10-mrad horizontal bin by a software gate in a ray-trace method. Since the momentum range covered with this spectrometer was about 5%, the measurements were done with several different settings of the magnetic field to cover a wide excitation-energy range of interest. In the measurement for the (p,p') reaction at forward angles $\theta_L\leqslant 10°$, the elastically scattered protons were blocked by a thick lead plate in front of the focal plane detector to reduce the counting rate. Additional measurements for the ground state and the low-lying discrete states were done without the plate by using a low intensity beam. The calibration of the excitation energies was carried out by observing known states with ^{12}C targets. The uncertainty in the excitation energies was about 0.15 and 0.3 MeV at the excitation-energy regions below $E_x=15$ MeV and above 15 MeV, respectively. The experimental details are presented elsewhere [12,20].

III. RESULTS AND ANALYSIS

A. Energy spectra

Figure 1 shows typical energy spectra for the ^{6,7}Li(p,p'), ^{6,7}Li(^{3}He,t), and ^{6,7}Li(^{7}Li,^{7}Be) reactions at $\theta_L=8°$, 2.7°, and 0°, respectively. The state at $E_x=3.56$ MeV in ^{6}Li and the ground states in ^{6}He and ^{6}Be are the isobaric analogs of the 0^+, $T=1$ state. The ground state in ^{7}He and the states at $E_x=11.25$ MeV in ^{7}Li and at $E_x=11.01$ MeV in ^{7}Be are the isobaric analogs of the $3/2^-$, $T=3/2$ state [14]. The 11.25 MeV state in ^{7}Li and the 11.01 MeV state in ^{7}Be were not identified in the present work. To clearly show the relationship between the analog states excited in these nuclei, each spectrum in Fig. 1 is shifted such that the location of the analog states coincides horizontally.

A common feature of the spectra for $A=6$ is the appearance of two resonances at $E_x\sim 27$ MeV and ~ 18 MeV, as typically seen in the ^{6}Li(p,p') spectrum (denoted herein as G1 and G2, respectively). The resonance at $E_x=27$ MeV in ^{6}Li was found in the present work. In the spectra for $A=7$

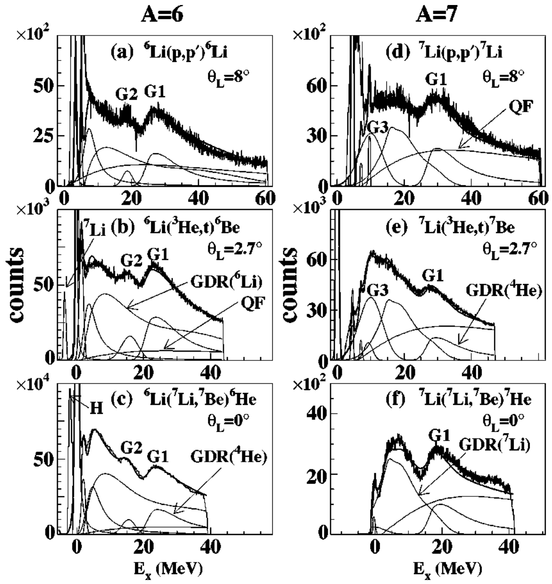

FIG. 1. Energy spectra for the reactions of (p,p') at $\theta_L=8°$, $(^3\mathrm{He},t)$ at 2.7°, and $(^7\mathrm{Li},^7\mathrm{Be})$ at 0°. The solid lines show the peak fitting results. See the text.

nuclei, resonances similar to those observed in $A=6$ nuclei are evident at $E_x\sim30$ MeV in ^{7}Li and ^{7}Be and at 20 MeV in ^{7}He. The resonance at $E_x\sim30$ MeV in ^{7}Li was found in the present work. The resonances in $A=7$ nuclei were recognized to be the G1-type resonances. Based on the fact that the excitation energies of the G1's measured with respect to the excitation energies of ^{6}Li and ^{7}Li are in close agreement with the excitation energy of the GDR in ^{4}He reported at $E_x\sim26$ MeV in the (γ,n) reaction [5], the G1's are the candidates for the GDR in an α cluster.

On the other hand, not only the GDR in the α cluster, but also those in d and/or t clusters should also be present in the spectra. In the $^2\mathrm{H}(\gamma,n)$ reactions, an asymmetric Lorentz-shape peak has been observed at $E_x\sim4$ MeV [21]. Since the excitation energy of 4 MeV in ^{6}Li is slightly below the neutron threshold energy ($E_x=5.4$ MeV), the peak due to the $^2\mathrm{H}(\gamma,n)$ reactions might not be observed in the spectra obtained by the $^6\mathrm{Li}(\gamma,n)$ reactions but in those by the nuclear reactions. Therefore, we took into account the 4-MeV peak in the analysis, as mentioned below. The excitation energy for the GDR in triton, on the other hand, is very similar to that for the GDR in ^{7}Li [6]. Since the GDR peak for the t clusters should be included in the $^7\mathrm{Li}(\gamma,n)$ spectra, it could not be separately observed.

To obtain the excitation energies, widths, and cross sections for the resonances, the measured spectra were decomposed into various peaks and underlying continuum. We restrict our attention to the excitation-energy region above $E_x\geqslant10$ MeV in ^{6,7}Li except for some discrete states in the low-excitation-energy region where the presence of the soft-dipole resonance has been observed [22].

In the analysis of the spectra obtained in the $^6\mathrm{Li}(p,p')$ reaction, the resonances at $E_x=18$ MeV (G2) and 27 MeV (G1), the GDR in ^{6}Li reported in the (γ,n) reaction at $E_x\sim12$ MeV [5] and the quasifree continuum were taken into account. The spectral shapes for the resonances were fitted with a Gaussian shape, the shape for the GDR referred from the $^4\mathrm{He}(\gamma,n)$ reaction [5,23], that for the GDR from the $^6\mathrm{Li}(\gamma,n)$ reaction [5], and that for the quasifree spectra (denoted as QF in Fig. 1) calculated following the prescriptions given by Erell [24] and Jänecke [10], respectively. Since in the (γ,n) reactions the GDR shapes in ^{6}Li and ^{7}Li were reported at $E_x\leqslant32$ MeV [5], we extrapolated smoothly the shapes beyond this energy. The GDR shapes thus employed involved some uncertainties at $E_x\geqslant35$ MeV. In order to reproduce the low-excitation-energy region, an asymmetric Lorentz peak was introduced [22]. This peak might also include the GDR in the d cluster.

In the analysis of the $^7\mathrm{Li}(p,p')$ spectra, the GDR in ^{7}Li reported in the (γ,n) reaction at $E_x\sim17$ MeV [5], a resonance at $E_x=29$ MeV (G1), and a quasifree continuum were also taken into account [10,24]. The peak shapes for the GDR and the resonance at 29 MeV (G1) were taken from the GDR shapes reported in the $^7\mathrm{Li}(\gamma,n)$ [5] and the $^4\mathrm{He}(\gamma,n)$ reactions [5,23], respectively. To reproduce the spectral shape around $E_x=10$ MeV an additional Gaussian peak with a width of 9 MeV was introduced at $E_x=9.5$ MeV.

Since the respective $A=6$ and 7 nuclei exhibited very similar spectra, the spectra for ^{6}He and ^{6}Be, and for ^{7}He and ^{7}Be were analyzed in a similar way to that used for ^{6}Li and ^{7}Li, respectively, by taking into account the differences in the Coulomb displacement energies. In the $(^7\mathrm{Li},^7\mathrm{Be})$ reaction, only the $T=3/2$ analog component of the GDR in ^{7}Li can be excited, while the (γ,n) reaction excites both $T=3/2$ and $1/2$ components. Therefore, only the high excitation side of the GDR shape reported in the (γ,n) reaction [5] was used for fitting the ^{7}He spectral shape.

The fitted curves are shown by the solid lines in Fig. 1. The global shapes of each spectrum were reproduced well by the present simplified analysis. The resonance energies and widths (full width at half maximum, FWHM) are summarized in Table I. The quoted errors in Table I were mainly due to the fitting procedure. The resonances at $E_x=9.5$ MeV in $A=7$ nuclei are assumed to be G3.

B. Differential cross sections

To assign the transferred angular momentum of ΔL to the observed resonances, the differential cross sections in the (p,p') and $(^3\mathrm{He},t)$ reactions were analyzed with the plane-wave Born approximation (PWBA). Figures 2 and 3 compare the experimental data and the results of the PWBA calculations. Error bars are mainly due to the peak fitting procedure. The data for the $(^7\mathrm{Li},^7\mathrm{Be})$ reactions have been reported in Ref. [12]. In Figs. 2 and 3, the cross sections are plotted as a function of momentum transfer q. Since the distortion effect and the Coulomb interaction for the present incident energies are less important, the PWBA calculations were sufficient for a qualitative discussion, as it was well applied for the $(^3\mathrm{He},t)$ reaction at 450 MeV [25] and the $(t,^3\mathrm{He})$ reaction at 350 MeV [26].

In the PWBA the cross section is simply given as $\sigma(q)\approx|j_L(qR)|^2$, where $j_L(qR)$ is the spherical Bessel function with the angular momentum L, and R is the interaction ra-

TABLE I. Excitation energies and widths (FWHM) of the resonances.

	^{6}He	^{6}Li	^{6}Be	^{7}He	^{7}Li	^{7}Be	
E_x (MeV)					9.5±1.0	9.5±1.0	G3
Γ (MeV)					9.0±1.0	9.0±1.0	
E_x (MeV)[a]	8.5±1.0	12.0±1.0	8.5±1.0	5.0±1.0[b]	17.0±1.0	17.0±1.0	GDR
Γ (MeV)[c]	20	20	20	14[b]	14	14	
E_x (MeV)	15.0±1.0	18.0±1.0	15.0±1.0				G2
Γ (MeV)	3.0±1.0	6.0±1.0	4.0±1.0				
E_x (MeV)[a]	24.0±1.5	27.0±1.5	23.5±1.5	18.0±1.5	29.0±1.5	28.0±1.5	G1
Γ (MeV)[d]	12	12	12	12	12	12	

[a]Peak energy.
[b]See text.
[c]Taken from the ^{6,7}Li(γ,n) reactions, Ref. [5]. Fixed in the fitting.
[d]Taken from the ^{4}He(γ,n) reaction, Refs. [5,23]. Fixed in the fitting.

dius. The values for R were chosen to be $1.4A^{1/3}$ and $1.2A^{1/3}$ fm for the (p,p') and $(^3\mathrm{He},t)$ reactions, respectively. The typical angular distributions for $\Delta L=0,1$, and 2 are shown by the dotted, solid, and dotted-chain lines, respectively, in Figs. 2 and 3.

The differential cross sections for the ^{6,7}Li(p,p') reactions are shown in Fig. 2. The observed angular distribution for the 3.562 MeV, 0^+ state in ^{6}Li peaked sharply at 0°. The PWBA calculation with a $\Delta L=0$ roughly reproduced this forward peaking shape. The angular distributions for the 2.186-MeV, 3^+ state in ^{6}Li, and 0.48-MeV, $1/2^-$ and 4.652-MeV, $7/2^-$ states in ^{7}Li have a maximum around $q=1$ fm^{-1}. From the PWBA calculations we can infer that these states are excited with $\Delta L=2$. But, the corresponding fit to the observed angular distributions is marginal. The angular distributions for the GDR in ^{6}Li and ^{7}Li were better reproduced with a $\Delta L=1$. We assigned the resonances at 18 MeV (G2) and 27.0 MeV (G1) in ^{6}Li and at 9.5 MeV (G3) and 29.0 MeV (G1) in ^{7}Li to the dipole resonance, because the PWBA calculation for $\Delta L=1$ was in agreement with the observed angular distributions for these resonances.

The differential cross sections for the ^{6,7}Li$(^3\mathrm{He},t)$ reactions are shown in Fig. 3. The PWBA calculation for $\Delta L=0$ reproduced well the observed angular distributions for the ground state (g.s.), 0^+ in ^{6}Be, g.s., $3/2^-+0.43$-MeV, $1/2^-$ state, and the 9.9-MeV, $3/2^-$ state in ^{7}Be. Those for the 4.5-MeV, $7/2^-$ and 7.1-MeV, $5/2^-$ states in ^{7}Be were also qualitatively reproduced by the $\Delta L=2$ calculation. The PWBA calculations are appropriate for determining ΔL's in the analysis of the present $(^3\mathrm{He},t)$ reactions. Furthermore, the angular distributions for the GDR in ^{6}Be and ^{7}Be are

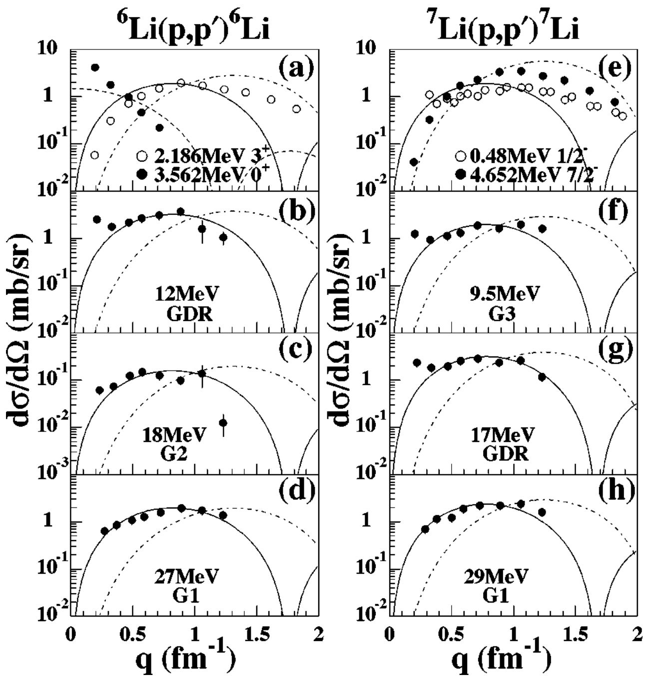

FIG. 2. Differential cross sections for the (p,p') reactions. The dotted, solid, and dotted-chain lines show the PWBA calculations with $\Delta L=0,1$, and 2, respectively.

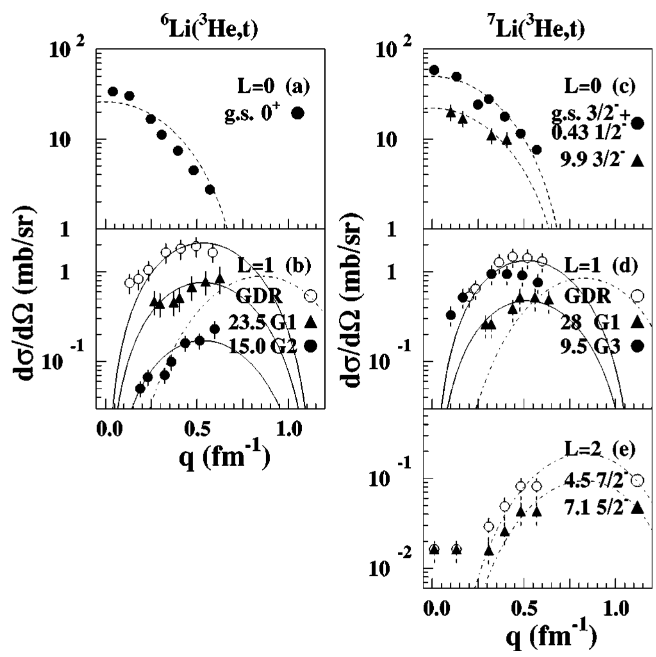

FIG. 3. Differential cross sections for the $(^3\mathrm{He},t)$ reactions. The dotted, solid, and dotted-chain lines show the PWBA calculations with $\Delta L=0,1$, and 2, respectively.

well explained by the $\Delta L=1$ calculations, as shown by the solid lines in Figs. 3(b) and 3(d). Since the angular distributions for the resonances at $E_x=15$ MeV (G2) and 23.5 MeV (G1) in ^{6}Be, and those at 9.5 MeV (G3) and 28 MeV (G1) in ^{7}Be were well reproduced by a $\Delta L=1$ calculation, we assigned these resonances to the dipole resonance.

In the (^{7}Li, ^{7}Be) reaction, in which the $\Delta S=0$ and $\Delta S=1$ cross sections were separately measured, the resonances at $E_x=24$ MeV (G1) in ^{6}He and at $E_x=18$ MeV (G1) in ^{7}He were both assigned to the dipole resonance with the spin-transfer components $\Delta S=0$ and $\Delta S=1$ [12].

IV. DISCUSSION

A. Comparison with other results

1. G1 resonance

In the highly excited energy region of ^{6}Li and ^{7}Li, no resonancelike states have been reported [14], except for three states in ^{6}Li at $E_x=24.779$, 24.890, and 26.590 MeV [14,27]. These three states are assigned to the $t+{}^3$He resonances with the ^3F configuration in the L-S coupling scheme. The excitations of these states are expected to proceed via a $\Delta L=3$. Therefore, all of them are different from the dipole resonance observed in the present work at $E_x=27.0$ MeV in ^{6}Li.

In ^{6}Be and ^{7}Be, Yang *et al.* reported the high-lying dipole resonances at $E_x=25$ MeV ($\Gamma \sim 10$ MeV) and 30 MeV ($\Gamma \sim 10$ MeV), respectively, from the (p,n) reactions at 186 MeV [11]. The excitation energies and widths for the dipole resonances reported in their work agree well with those for the dipole resonances observed in the present work.

Brady *et al.* reported the dipole resonance in ^{6}He at $E_x=25\pm1$ MeV ($\Gamma=8\pm2$ MeV) and in ^{7}He at $E_x=20\pm1$ MeV ($\Gamma=9\pm2$ MeV) via the (n,p) reaction at an incident energy of 60 MeV [9]. In the (^{7}Li, ^{7}Be) reaction at 350 MeV, Jänecke *et al.* observed the resonance at $E_x=23.3\pm1.0$ MeV ($\Gamma=14.8\pm2.3$ MeV) in ^{6}He [10]. From the measurement of the $\Delta S=0$ and $\Delta S=1$ cross sections, they assigned the 23.3-MeV resonance to a high spin state populated via the $\Delta S=1$ transfer. In the present measurement of the (^{7}Li, ^{7}Be) reaction, the resonances at $E_x=24.0$ MeV in ^{6}He and at $E_x=18.0$ MeV in ^{7}He are excited via both $\Delta S=0$ and $\Delta S=1$ with a $\Delta L=1$ [12].

It is worthwhile to consider the possibility that the G1 peaks may be the two-phonon states of the GDR's in ^{6,7}Li. (a) Since the excitation energies of the GDR's in ^{6}Li and ^{7}Li are 12 and 17 MeV, respectively, resulting excitation energies for the two-phonon states would be about 24 and 34 MeV, respectively. These excitation energies are 3–5 MeV different from the observed excitation energies of 27 and 29 MeV for the G1's in ^{6}Li and ^{7}Li, respectively. (b) The observed width for the G1's is 12 MeV, while the widths for the GDR's in ^{6}Li and ^{7}Li are 20 and 14 MeV, respectively, as listed in Table I. The G1 width is 2–8 MeV less than the GDR widths. (c) Since the two-phonon states would be excited via $\Delta L=0$ and/or 2, and the G1 resonance was observed to have $\Delta L=1$, the G1 resonance is unlikely to consist of the two-phonon states.

TABLE II. Cross-section ratios of the G1 resonance in $A=6$ to that in $A=7$ for each element.

	He	Li	Be
$\sigma(A=6)/\sigma(A=7)$	1.2 ± 0.3	0.8 ± 0.2	1.5 ± 0.7

2. G2 and G3 resonances

In ^{6}Li, a peak with a width of 1–2 MeV has been reported at $E_x=16$ MeV in the ^{6}Li(γ,n) reactions, as a fine structure of the GDR [5,7]. The excitation energy for this peak reported in Refs. [5,7] is lower by 2 MeV than that observed in the present work for the G2 resonance. Hernández *et al.* claimed a resonance at $E_x=17.985$ MeV [14,27] with a pure ^3P $(2^-,T=1)$ $t+{}^3$He-clustering structure. However, Akimune *et al.* [20,28] and Nakayama *et al.* [29] recently observed the isobaric analog triplets of the $^3P,T=1$ state in ^{6}He, ^{6}Be, and ^{6}Li, at higher excitation energies of $E_x=18.0$, 18.0, and 21.5 MeV, respectively. At the excitation energy of $E_x=18$ MeV in ^{6}Li, Nakayama *et al.* observed the $^1P(T=0)$ resonance with a width of $\Gamma=5$ MeV [29]. These experimental results seriously contradict the result by Hernández *et al.* [27]. As discussed below, the G2 resonances observed in the present work are supposed to be an isobaric triplet in $A=6$ nuclei. Therefore, the isoscalar resonance reported by Nakayama *et al.* at 18 MeV [29] is different from the 18 MeV resonance $(T=1)$ observed in the present (p,p') reaction.

In ^{6}Be, Yang *et al.* reported a dipole resonance at $E_x=15$ MeV via the (p,n) reaction. At $E_x \sim 15$ MeV in ^{6}He, the resonance has been observed and assigned to the dipole resonance in the (n,p) reaction ($E_x=15.5\pm0.5$ MeV and $\Gamma=4\pm1.5$ MeV) [9], in the (^{7}Li, ^{7}Be) reaction ($E_x=14.6\pm0.7$ MeV and $\Gamma=7.4\pm1.0$ MeV) [10], in the $(t,{}^3$He)

TABLE III. Cross-section ratios of the G1 resonance to the GDR.

	^{6}He	^{6}Li	^{6}Be	^{7}He	^{7}Li	^{7}Be
σ(G1)/σ(GDR)[a]	0.23 ± 0.10	0.50 ± 0.15	0.40 ± 0.16	0.43 ± 0.20	0.70 ± 0.20	0.36 ± 0.14
$\sigma(^4$He)/σ(Li)[b]		0.23			0.26	
$\sigma(^4$He)/σ(Li)[c]		0.46			0.52	

[a]Present work.
[b](γ,n) reaction, Ref. [5].
[c]$\sigma(\gamma,n)\approx\sigma(\gamma,p)$ is assumed for ^{4}He.

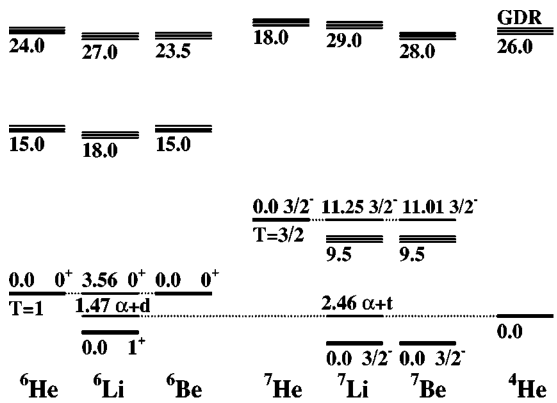

FIG. 4. Energy diagrams for $A=6$ and 7 nuclei observed in the present work. The diagram for ^{4}He is also shown. The solid-thick lines show the ground state of each nucleus. The vertical positions are set such that the positions corresponding to the separation energies of α particle in ^{6}Li and ^{7}Li are equal to that of the ground state of ^{4}He.

reaction at 336 MeV ($E_x=14.6\pm0.2$ MeV and $\Gamma=5.9\pm0.7$ MeV) [30], and in our previous (^{7}Li, ^{7}Be) reaction ($E_x=15.0\pm0.5$ MeV and $\Gamma=3.0\pm0.5$ MeV) [20]. Since the excitation energies and widths for the G2 resonances are similar to each other, these dipole resonances are inferred to be the members of the $A=6$ isobaric triplet.

In both ^{7}Li and ^{7}Be we observed the dipole resonance at $E_x=9.5$ MeV (G3). In the (p,n) reaction, Yang *et al.* also observed a dipole resonance at $E_x=10$ MeV in ^{7}Be [11]. These resonances have not been observed in the (γ,n) reactions [5,6,8], and no positive parity states have been reported in this excitation-energy region [13,14]. These dipole resonances might be an isobaric doublet in $A=7$ nuclei, because the excitation energies and widths are similar to each other.

B. Excited α cluster

1. Cross-section ratios

The ratios of the cross sections of the G1 resonance in $A=6$ to that in $A=7$ for He, Li, and Be are listed in Table II. The absolute value of cross sections may depend strongly on both the reaction employed and nuclear structure. However, the ratio of the cross sections using the same reaction may depend only on the nuclear structure. Therefore, if the G1 resonance is the GDR in an α cluster the observed ratio should become nearly unity, because the same GDR in ^{4}He in the same element is excited via the same reaction. The ratios deduced in the present work are consistent with unity within the errors, and their average is 1.2 ± 0.3. In the (^{7}Li, ^{7}Be) reaction we separately measured the $\Delta S=1$ and $\Delta S=0$ cross sections for the G1 resonance in ^{6,7}He [12]. The ratio of the $\Delta S=1$ cross section to the $\Delta S=0$ cross section has been found to be 1.2 ± 0.4 and 1.4 ± 0.7 for ^{6}He and ^{7}He, respectively. This suggests that the observed peak of the G1 resonance consists of the SDR and the GDR with comparable strength. This feature has been observed in light nuclei [17].

TABLE IV. Q-value differences for the G1 resonances between $A=6$ and 7 isotopes.

	He	Li	Be
ΔQ (MeV)[a]	1.7 ± 0.5	2.0 ± 0.5	1.1 ± 0.5

[a] $\Delta Q=Q(A=6)-Q(A=7)$.

The cross section ratios of the G1 resonance to the GDR measured herein are listed in Table III. The averaged value for these ratios is 0.44 ± 0.08. The cross section ratios of the GDR in ^{4}He to those in ^{6,7}Li reported in the (γ,n) reaction [5] are also listed. For the GDR in ^{4}He the GDR strength in the (γ,n) reaction was reported to be nearly equal to that in the (γ,p) reaction [18,23]. Since this GDR strength was missing in the (γ,n) reaction, we estimated that the GDR cross section is twice as large as that reported in the (γ,n) reaction, as listed in Table III. If the G1 resonance is the GDR in the α cluster, the present ratios should be the same as those obtained in the photonuclear reactions. Indeed, most of the ratios presently obtained are consistent with the ratios estimated from the photonuclear reactions.

2. Excitation-energy systematics

Figure 4 shows a summary of the energy diagrams for $A=6$ and 7 nuclei observed in the present work. The energy diagram for ^{4}He is also shown. In order to clarify the isobaric analog relations in $A=6$ and 7 nuclei, the analog states of 0^+, $T=1$ in $A=6$ and of $3/2^-$, $T=3/2$ in $A=7$ are shown. Furthermore, the energy diagrams for ^{6}Li and ^{7}Li are shifted such that the vertical positions corresponding to the excitation energies for the separation energy of an α particle in these nuclei coincide with that of the ground state in ^{4}He. As seen in Fig. 4, the excitation energies for the G1 resonance in every nucleus agree well with that of the GDR in ^{4}He, i.e., $E_x\sim26$ MeV, irrespective of mass, although their individual excitation energies have very different values from each other.

In Table IV, the differences of the reaction Q values between $A=6$ and 7 nuclei, $\Delta Q=Q(A=6)-Q(A=7)$, for the excitation of the G1's in He, Li, and Be deduced for each reaction are listed. Since evaluation of the ΔQ's do not strongly depend on the absolute values of the energy scale for the excitation energy, the errors for the ΔQ's are much smaller than those for the excitation energies. The ΔQ is also expressed as $\Delta Q=\Delta M(A=7)-\Delta M(A=6)$, where ΔM's are the mass increases for the G1 excitation in $A=6$ and 7 nuclei relative to the ground states in ^{6}Li and ^{7}Li, respectively. All the ΔQ's are positive. The difference in the mass increase between $A=7$ and 6 is 1.6 ± 0.3 MeV on the average. When measured from the α-particle separation energies in ^{6}Li and ^{7}Li, the difference is reduced to 0.6 ± 0.3 MeV.

V. CONCLUSION

We searched for the excitations of the α cluster in nuclei via the ^{6,7}Li(p,p'), ^{6,7}Li(^{3}He$,t)$, and ^{6,7}Li(^{7}Li, ^{7}Be) reactions at the incident energies of 300, 450, and 455 MeV, respectively. Resonances were observed in ^{6}Li, ^{6}He, and ^{6}Be at $E_x=27.0, 24.0$, and 23.5 MeV, respectively, and in ^{7}Li, ^{7}He, and ^{7}Be at $E_x=29.0$, 18.0, and 28 MeV, respectively. All the resonances were assigned to the dipole resonances and the resonance shapes were reproduced well with the GDR shape reported in the ^{4}He(γ,n) reactions. The ratios of the cross sections for the resonance in the $A=6$ nuclei to that in the $A=7$ nuclei for each element were found to be nearly unity, and the averaged value was 1.2 ± 0.3. The averaged value of the cross-section ratios of the resonance to the GDR in respective target nuclei was 0.44 ± 0.08, which was found to be consistent with the ratios of the cross sections for the GDR in ^{4}He to those for the GDR in ^{6,7}Li estimated from the photonuclear reactions [5,18]. The excitation energies for the dipole resonances in $A=6$ and 7 nuclei measured from the separation energies of α particle in ^{6}Li and ^{7}Li, respectively, agree well with the excitation energy for the GDR in ^{4}He, which, taking into account the Coulomb displacement energies, is about 26 MeV. We conclude that the resonances observed in ^{6,7}Li are consistent with the GDR in the α clusters, and the resonances in ^{6,7}He and ^{6,7}Be are consistent with the analogs of the GDR in the α cluster. The Q-value difference $(0.6\pm0.3$ MeV) for the excitation of the GDR in the α cluster measured from the separation energy in ^{6}Li and ^{7}Li may be due to a *medium effect*; that is, after ^{6}Li and ^{7}Li disintegrate into $\alpha+d$ and $\alpha+t$, respectively, the α cluster undergoes its intrinsic GDR excitation with different effective masses in ^{6}Li and ^{7}Li media.

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