Analogs of the giant dipole and spin-dipole resonances in ^{4}He and in α clusters of ^{6,7}Li studied by the ^{4}He,^{6,7}Li(^{7}Li,^{7}Beγ) reactions

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We studied analogs of the giant dipole resonance (GDR) and spin-dipole resonance (SDR) in ^{4}He and in the α clusters of ^{6,7}Li via the (^{7}Li,^{7}Beγ) reactions on ^{4}He, ^{6}Li, and ^{7}Li at an incident energy of 455 MeV and at a scattering angle of 0° by measuring spin-nonflip and spin-flip spectra. The reaction Q-values for the analogs of the GDR and SDR in the α clusters of ^{6,7}Li were found to be more negative than those in ^{4}He by 2.0 ± 0.5 MeV. The ratios of the cross section for the analog of the GDR to that for the analog of the SDR in ^{4}He and in the α clusters of ^{6}Li and ^{7}Li were found to be the same within errors, 0.5 ± 0.1. The cross sections for the analogs of the GDR as well as those for the analogs of the SDR in the α clusters of ^{6,7}Li were 0.6$\sim$0.8 times smaller than those in ^{4}He. These results suggest that excitations of α clusters embedded in nuclei are suppressed as compared with excitations of free α particles.

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An α cluster is a spatially localized subsystem consisting of strongly correlated nucleons in a nuclear system [1]. In the previous work we proposed an idea of "cluster excitation" in which a cluster itself is excited while the remaining nucleons stay as spectators [2]. Existence of α-cluster excitation was suggested from the similarity of observed spectral shapes between isovector dipole resonances (DRs) in ^{4}He and high-lying DRs in ^{6,7}Li. The ground states in ^{6}Li and ^{7}Li are well recognized to have cluster structures such as $d+\alpha$ and $t+\alpha$, respectively [3]. The DRs observed at a reaction Q-value of $Q \approx -30$ MeV in the (^{7}Li,^{7}Be) reactions on ^{6}Li and ^{7}Li were interpreted to be due to isovector dipole excitations of a common constituent, an α cluster, in ^{6}Li and ^{7}Li. This interpretation is based upon the fact that the most significant excitation modes in ^{4}He are the DRs, consisting of the giant dipole resonance (GDR) and the spin-dipole resonance (SDR) at $E_x \approx 24$ MeV [4].

To obtain supporting evidence for the α-cluster excitation in ^{6,7}Li, Yamagata *et al.* [5,6] carried out the following measurements. Excitations of the DRs in the α clusters of ^{6,7}Li and their analogs were investigated by using the reactions of ^{6,7}Li(p, p')^{6,7}Li at 300 MeV, ^{6,7}Li(^{7}Li,^{7}Be)^{6,7}He at 455 MeV, and ^{6,7}Li(^{3}He,t)^{6,7}Be at 450 MeV [5]. In addition to the intrinsic GDRs in ^{6,7}Li and their analogs [7], the DRs in ^{6,7}Li, ^{6,7}He, and ^{6,7}Be were observed at similar Q values ($Q \approx -30$ MeV); $E_x \approx 27.0$ MeV in ^{6}Li, 29.0 MeV in ^{7}Li, 24.0 MeV in ^{6}He, 18.0 MeV in ^{7}He, 23.5 MeV in ^{6}Be, and 28.0 MeV in ^{7}Be. The resonance shapes of the DRs were reproduced well with the shape of the GDR observed in the ^{4}He(γ, n) reactions [7]. It was concluded that the DRs in ^{6,7}Li are the GDRs in the α cluster and that the DRs in ^{6,7}He and ^{6,7}Be are the analogs of the GDRs in the α cluster. Furthermore charged particles decaying from the DRs at $E_x = 24.0$ MeV in ^{6}He and at 18.0 MeV in ^{7}He excited via the ^{6,7}Li(^{7}Li,^{7}Be) reaction at 455 MeV were observed [6]. Dominant decay channels from the DRs were found to be $d+t+n$ for ^{6}He and $t+t+n$ for ^{7}He. This fact suggested that the α cluster excited via the (^{7}Li,^{7}Be) reaction is transformed to a ^{4}H cluster that is a resonant system of $t+n$. Thus the measurements described above provided evidence for the existence of α-cluster excitation in ^{6,7}Li.

Although the excitation of the α clusters embedded in nuclei may differ from that of the free α particle, there is no theoretical prediction to show how the excitation energy, width, and cross section for the DR in the α cluster might differ from those of the free α particle. To compare the DRs in the α clusters of ^{6,7}Li with those in ^{4}He, Yamagata *et al.* [8] investigated the spectral shapes of the DRs by using the (p, p') scatterings from ^{4}He, ^{6}Li, and ^{7}Li at 300 MeV. The cross sections and excitation energies for the DRs in the α clusters of ^{6,7}Li were found to be different from those in ^{4}He. The differences were suggested to be caused by the fact that the 2^- SDR at $E_x = 22.1$ MeV in ^{4}He [9] is suppressed in the α-cluster excitations of ^{6,7}Li [8]. It was speculated that suppression of the 2^- excitation strength for the ^{6,7}Li(p, p') reaction may be due to a difference in the degrees of coherence between the GDR and the SDR [8]. However in the previous work [8], spin-nonflip ($\Delta S = 0$) and spin-flip ($\Delta S = 1$) transitions could not be separately measured. Because the (p, p') scattering at 300 MeV dominantly excites isovector states via $\Delta S = 0$ or $\Delta S = 1$ transitions [10], it is not yet clear whether or not the differences observed in

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the (p, p') reaction arise from isovector $\Delta S = 0$ or $\Delta S = 1$ excitations.

On the basis of the above conclusion, a difference between $\Delta S = 1$ spectra for ^{4}He and for the α clusters of ^{6,7}Li is expected to be more remarkable than the corresponding difference in $\Delta S = 0$ spectra because the GDR and the SDR are observed in $\Delta S = 0$ and $\Delta S = 1$ spectra, respectively. In this work, to detect a possible medium effect on excitation of the DRs in the α clusters of ^{6,7}Li, we investigated differences between the spectral shapes for the analogs of the DRs in the free α particle and in the α clusters embedded in ^{6,7}Li by separately measuring $\Delta S = 0$ and $\Delta S = 1$ spectra. The $\Delta S = 0$ and $\Delta S = 1$ spectra were measured by using the (^{7}Li,^{7}Beγ) reactions on ^{4}He, ^{6}Li, and ^{7}Li at an incident energy of 455 MeV and at a scattering angle of 0° in our previous work [2,11,12]. The Q values and cross sections for the analogs of the GDR and the SDR in the α clusters of ^{6,7}Li were compared with those in ^{4}He. We discuss the differences between the analogs of the DRs in ^{4}He and the corresponding resonances in the α clusters of ^{6,7}Li observed in the $\Delta S = 0$ and $\Delta S = 1$ spectra.

The experimental procedures for these measurements on ^{4}He and ^{6,7}Li targets are briefly summarized here, with detailed descriptions given in Refs. [12] and [2], respectively. A 455-MeV ^{7}Li^{3+} beam was provided from the ring cyclotron at the Research Center for Nuclear Physics (RCNP), Osaka University. Targets used were a ^{4}He gas target with a thickness of 7 mg/cm^2 and self-supporting foils of enriched ^{6}Li (95.4%) and ^{7}Li (99.9%) isotopes with thicknesses of 2.5 mg/cm^2. Scattered ^{7}Be particles were analyzed by using the magnetic spectrometer "Grand RAIDEN" [13] set at 0°. The ^{7}Be particles were detected with the focal plane detector system consisting of two multiwire drift chambers backed by a ΔE-E plastic scintillator telescope. Excitation energies for the residual nuclei were calibrated by observing the discrete transitions in the (^{7}Li,^{7}Beγ) reactions on ^{6}Li, ^{7}Li, and ^{12}C. The excitation energies in the target nuclei were calculated by using the isospin multiplet relation: The $(I^\pi, T) = (2^-, 1)$ states at $E_x = 23.33$ MeV in ^{4}He, the $(0^+, 1)$ state at $E_x = 3.563$ MeV in ^{6}Li, and the $(3/2^-, 3/2)$ state at $E_x = 11.24$ MeV in ^{7}Li correspond to the ground states of $(2^-, 1)$ in ^{4}H [4], $(0^+, 1)$ in ^{6}He [3], and $(3/2^-, 3/2)$ in ^{7}He [3], respectively. We estimated uncertainty in the excitation energy and the Q value of the (^{7}Li,^{7}Beγ) reaction to be about 500 keV, which was due to the energy spread of the incident beam, the target thickness, and the reaction kinematics.

The (^{7}Li,^{7}Beγ) reaction can provide separately $\Delta S = 0$ and $\Delta S = 1$ isovector excitations by measuring scattered ^{7}Be particles in coincidence with the 0.43-MeV γ ray of ^{7}Be. The 0.43-MeV γ ray from ^{7}Be was measured by using the Gd_2SiO_5(Ce) γ-detector system "NYMPHS" [14]. The detection efficiencies for the photopeak of the ^{7}Be γ ray were determined to be 12.5% for the ^{4}He measurement [12] and 20% for the ^{6,7}Li one [2,11] by measuring the $\Delta S = 1$ transition of $0^+ \to 1^+$ in the ^{12}C(^{7}Li,^{7}Beγ)^{12}B reaction.

The singles spectra were decomposed into $\Delta S = 0$ and $\Delta S = 1$ spectra. The procedure to obtain the $\Delta S = 0$ and $\Delta S = 1$ spectra from the singles and coincidence events in the (^{7}Li,^{7}Beγ) reaction were described in detail in our previous work [2,11,12]. We note here that the $\Delta S = 1$ spectrum was obtained from the coincidence events whose reaction proceeds dominantly via $\Delta S = 1$ transitions, while the $\Delta S = 0$ spectrum was derived by subtracting the $\Delta S = 1$ spectrum from the ^{7}Be singles spectrum. Figure 1 shows the singles, $\Delta S = 0$, and $\Delta S = 1$ spectra for the (^{7}Li,^{7}Be) reactions on ^{4}He, ^{6}Li, and ^{7}Li. As shown in Fig. 1(a), a resonance structure in ^{4}H with $\Delta L = 1$ is clearly observed at $Q \approx -25$ MeV and corresponds to the analogs of the DRs in ^{4}He [8,12]. Figures 1(b) and 1(c) show that the resonance structures in ^{6,7}He with $\Delta L = 1$, which have been discussed as the analogs of the DRs in the α clusters of ^{6,7}Li [2,5,8], are observed in the region of $Q \approx -30$ MeV on top of continua in the $\Delta S = 0$ and $\Delta S = 1$ spectra. The $\Delta S = 0$ and $\Delta S = 1$ spectra show strength distributions for the analogs of the GDR and SDR, respectively, in ^{4}He and in the α clusters of ^{6,7}Li.

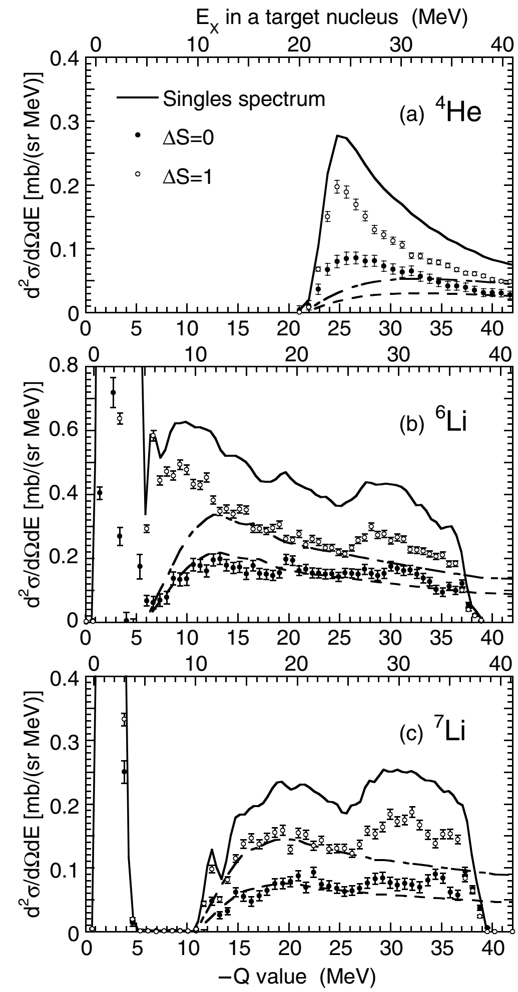

FIG. 1. Singles, $\Delta S = 0$, and $\Delta S = 1$ spectra deduced from the singles and coincidence measurements for the (^{7}Li,^{7}Beγ) reactions on (a) ^{4}He, (b) ^{6}Li, and (c) ^{7}Li at 455 MeV and at 0°. The lower scales of abscissas denote the Q value of the (^{7}Li,^{7}Be) reaction, and the upper ones denote the excitation energy in each target nucleus. The dashed and dotted-dashed curves are the assumed continuum contributions for the $\Delta S = 0$ and $\Delta S = 1$ spectra, respectively.

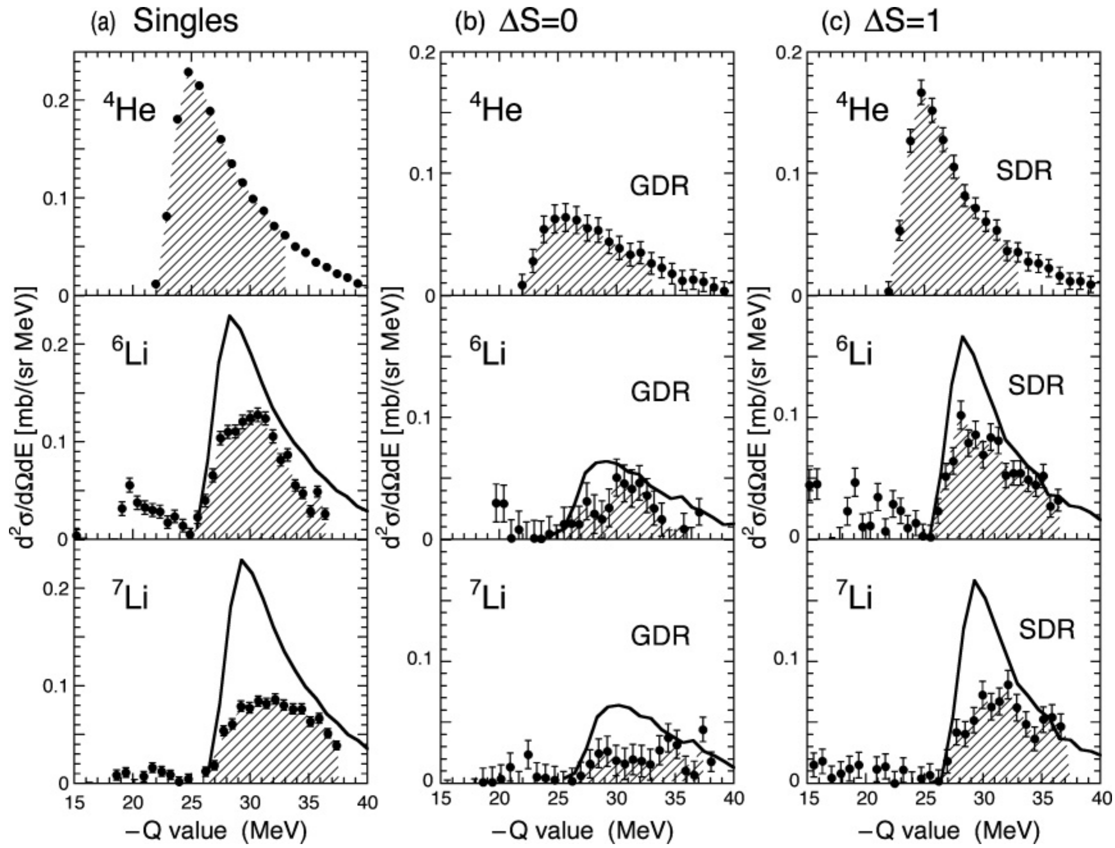

FIG. 2. Comparison of the Q values and cross sections for ^{4}He with those for the α clusters of ^{6,7}Li in (a) singles, (b) $\Delta S = 0$, and (c) $\Delta S = 1$ spectra with the continuum contributions subtracted. The solid curves in the spectra for ^{6}Li and ^{7}Li are the corresponding spectra for ^{4}He, $Q(^4\mathrm{He})$, shifted downward by 3.5 MeV for ^{6}Li and 4.5 MeV for ^{7}Li. The hatched areas are selected to compare the resonances for the α clusters of ^{6,7}Li with the corresponding resonances for ^{4}He.

For comparison of cross sections for the analogs of the DRs in ^{4}He with ones for the corresponding resonances in the α clusters of ^{6,7}Li, it is necessary to subtract possible underlying continua from the $\Delta S = 0$ and $\Delta S = 1$ spectra. We estimated the underlying continuum in the DR region by assuming that there are contributions from quasifree (QF) scatterings [15] in the ^{4}He(^{7}Li,^{7}Be) reaction and from QF scatterings and intrinsic DRs (GDR and SDR) in the ^{6,7}Li(^{7}Li,^{7}Be) reactions, e.g., $E_x = 12$ MeV and 17 MeV in ^{6}Li and ^{7}Li, respectively. A spectral shape for the QF scattering was simulated by using a method similar to one employed in our previous work [2]. Spectral shapes for the intrinsic DRs in ^{6}Li and ^{7}Li were assumed to be obtained from the photonuclear reactions on ^{6}Li and ^{7}Li [7], respectively. Because the excitation energies and widths for the GDR and SDR in light nuclei were observed to be similar, as shown in our previous work [11,12], we assumed that shapes for the continua in the $\Delta S = 0$ and $\Delta S = 1$ spectra were similar to each other except for the low excitation energy region where the soft dipole resonance was observed in the $\Delta S = 1$ spectrum for ^{6}Li [16]. The magnitudes for the $\Delta S = 0$ and $\Delta S = 1$ continua were determined by fitting the spectra around at $Q \approx -40$ MeV in ^{4}He and at $Q \approx -25$ MeV in ^{6}Li and ^{7}Li with smooth continuum shapes for both $\Delta S = 0$ and $\Delta S = 1$ spectra. The results are shown in Fig. 1 by the dashed and dotted-dashed curves, respectively. The ratios of the magnitude for the $\Delta S = 1$ continuum to that for the $\Delta S = 0$ one were 1.7 for ^{4}He, 1.6 for ^{6}Li, and 1.8 for ^{7}Li. The continuum contributions thus assumed were subtracted from the singles, $\Delta S = 0$, and $\Delta S = 1$ spectra for ^{4}He, ^{6}Li, and ^{7}Li. The continuum subtracted spectra for ^{4}He, ^{6}Li, and ^{7}Li are shown in Fig. 2.

First, we discuss excitation energies for the analogs of the DRs in the α clusters of ^{6,7}Li as compared with ones in ^{4}He, i.e., a free α particle. We compared the Q values for the analogs of the DRs in ^{4}He, $Q(^4\mathrm{He})$, with those for the corresponding resonances observed in ^{6,7}Li, $Q(^6\mathrm{Li})$, and $Q(^7\mathrm{Li})$. The differences between the Q values for the resonances in ^{6}Li and in ^{4}He, $\Delta Q(^6\mathrm{Li}) = \mathrm{Q}(^6\mathrm{Li}) - \mathrm{Q}(^4\mathrm{He})$, were -3.5 ± 0.5, -3.0 ± 1.0, and -3.5 ± 0.5 MeV for the singles, $\Delta S = 0$, and $\Delta S = 1$ spectra, respectively, and those in ^{7}Li and ^{4}He, $\Delta Q(^7\mathrm{Li}) = \mathrm{Q}(^7\mathrm{Li}) - \mathrm{Q}(^4\mathrm{He})$, were -4.4 ± 0.5, -4.5 ± 1.0, and -4.5 ± 0.5 MeV, respectively. The differences in the Q values were found to be independent of spin transfer. As a result the mean differences in Q values for the resonances in Li isotopes were $\Delta Q(^6\mathrm{Li}) = -3.5 \pm 0.5$ MeV and $\Delta Q(^7\mathrm{Li}) = -4.5 \pm 0.5$ MeV. The solid curves in Fig. 2 are drawn by taking the ΔQs into account, in order to compare the resonances in ^{6,7}Li with those in ^{4}He.

The separation energies for α particles in ^{6}Li and ^{7}Li are 1.47 and 2.46 MeV, respectively [3]. If we measure the

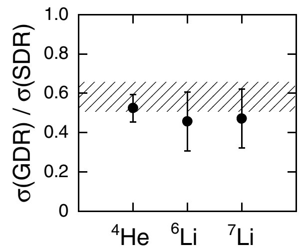

FIG. 3. Cross-section ratios of σ(GDR)/σ(SDR) for ^{4}He and for the α clusters of ^{6}Li and ^{7}Li. The hatched region shows the mean ratios for the analogs of the intrinsic GDR and SDR observed in the (^{7}Li,^{7}Beγ) reactions on ^{6}Li, ^{7}Li, and ^{12}C [2].

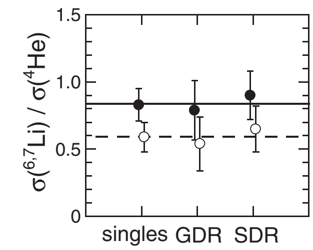

FIG. 4. Cross-section ratios of $\sigma(^6\text{Li})/\sigma(^4\text{He})$ (•) and $\sigma(^7\text{Li})/\sigma(^4\text{He})$ (○) per unit α-particle spectroscopic factor in the singles, $\Delta S = 0$, and $\Delta S = 1$ spectra. The solid and dashed lines are the mean ratios for ^{6}Li and ^{7}Li, respectively.

Q values for the α-cluster excitations from the Q values corresponding to the separation energies for $d + \alpha$ in ^{6}Li and $t + \alpha$ in ^{7}Li, the differences in the Q values, $\Delta Q(^6\text{Li})$ and $\Delta Q(^7\text{Li})$, are independent of spin transfer and are both -2.0 ± 0.5 MeV. This means that the analogs of the GDR as well as of the SDR in the α clusters of ^{6,7}Li are observed at excitation energies higher than those in ^{4}He by about 2.0 MeV. In the present work, a mass dependence in the Q values for the analogs of the DRs in the α clusters of the Li isotopes could not be detected due to a large uncertainty in the Q value, though Yamagata *et al.* [5] reported that the excitation energy for the DR in ^{7}Li becomes higher than that in ^{6}Li by 0.6 MeV.

Second, to establish whether or not cross sections for the analogs of the DRs in the α cluster embedded in nuclei are comparable to the ones in the free α particle, we investigate cross sections for the analogs of the DRs in ^{4}He and in the α clusters of ^{6,7}Li. Their cross sections were evaluated by integrating double differential cross sections in the regions of $Q = -22.0 \sim -33.0$ MeV in ^{4}He, $Q = -25.5 \sim -36.5$ MeV in ^{6}Li, and $Q = -26.5 \sim -37.5$ MeV in ^{7}Li, as shown in Fig. 2 by the hatched regions. The cross sections for the analogs of the GDRs, σ(GDR), were compared with those for the analogs of the SDRs, σ(SDR), in ^{4}He and in the α clusters of ^{6,7}Li. The cross-section ratios of σ(GDR)/σ(SDR) for ^{4}He, ^{6}Li, and ^{7}Li are shown in Fig. 3. All the cross-section ratios were found to be the same within errors, 0.5 ± 0.1, and consistent with those for the analogs of the intrinsic GDR and SDR previously reported in the (^{7}Li,^{7}Beγ) reactions on ^{6}Li, ^{7}Li, and ^{12}C [2]. This shows that a difference in the $\Delta S = 0$ spectra for the free α particle and for the α clusters embedded in nuclei is similar to the corresponding difference in the $\Delta S = 1$ spectra.

Finally, we discuss cross sections for the DRs in the α clusters embedded in nuclei as compared with ones in the free α particle. We compared the cross sections for the analogs of the DRs in the α clusters of ^{6}Li and ^{7}Li, $\sigma(^6\text{Li})$ and $\sigma(^7\text{Li})$, with those for the corresponding resonances in ^{4}He, $\sigma(^4\text{He})$. The cross-section ratios of $\sigma(^6\text{Li})/\sigma(^4\text{He})$ obtained from the singles, $\Delta S = 0$, and $\Delta S = 1$ spectra were 0.6 ± 0.1, 0.6 ± 0.2, and 0.7 ± 0.2, respectively, and the ratios of $\sigma(^7\text{Li})/\sigma(^4\text{He})$ were 0.5 ± 0.1, 0.5 ± 0.2, and 0.6 ± 0.2, respectively. It is known that the α-particle spectroscopic factors that represent the probabilities of finding α particles in nuclei are 0.7 ± 0.1 for ^{6}Li and 0.9 ± 0.1 for ^{7}Li [3,8]. The ratios of $\sigma(^6\text{Li})/\sigma(^4\text{He})$ and $\sigma(^7\text{Li})/\sigma(^4\text{He})$ per unit α particle spectroscopic factor are shown in Fig. 4. The cross-section ratios were found to be the same within errors in all the singles, $\Delta S = 0$, and $\Delta S = 1$ spectra. The mean value of $\sigma(^6\text{Li})/\sigma(^4\text{He})$ was 0.8 ± 0.2 and that of $\sigma(^7\text{Li})/\sigma(^4\text{He})$ was 0.6 ± 0.2. This shows that the cross sections for the analogs of the GDR as well as those of the SDR in the α clusters of ^{6,7}Li are 0.6$\sim$0.8 times smaller than those for the corresponding resonances in ^{4}He. This fact means that the GDR and SDR strengths of an embedded α cluster in nuclei are less than those of the free α particle by a common factor. Though Yamagata *et al.* [8] suggested that the SDR strength would be suppressed more than the GDR one due to a possible difference between the coherences of the GDR and SDR, the present result shows that the coherence effects on excitations of the GDR and SDR in the α cluster are not large enough to be detectable.

There may be other possible origins for suppressing excitations of the GDR as well as of the SDR in the α clusters of ^{6,7}Li, for example, a Pauli blocking effect of occupied states for both $\Delta S = 0$ and $\Delta S = 1$ excitations. A simple cluster model suggests that isovector excitations of the GDR and SDR in the α cluster would be suppressed by the presence of an existing cluster, d or t [17]. Dipole excitations in the α clusters of ^{6,7}Li would be prohibited in the degrees of freedom associated with the direction of a neighboring cluster. This may explain in part both an increase in excitation energies and a reduction of cross sections for α clusters of ^{6,7}Li as compared with those for ^{4}He: The apparent increase in the excitation energies observed for the GDR and SDR in the α clusters of ^{6,7}Li, both of which were higher by about 2 MeV than those in ^{4}He, may be due to suppression of the GDR as well as the SDR strengths for the α-cluster excitations in ^{6,7}Li. The suppressed strengths in the α clusters of ^{6,7}Li are speculated to be fragmented toward higher excitation energies.

In summary, we investigated α-cluster excitation by comparing analogs of the GDR and the SDR in ^{4}He with the corresponding resonances in the α clusters of ^{6,7}Li. The analogs of the GDR and the SDR in ^{4}He and in the α clusters of ^{6,7}Li were separately measured by using the (^{7}Li,^{7}Beγ) reactions on ^{4}He, ^{6}Li, and ^{7}Li. The Q values for the analogs of the GDR and SDR in the α clusters of ^{6,7}Li were more negative than those in ^{4}He by 2.0 ± 0.5 MeV. The ratios of the cross section for the analog of the GDR to that for the analog of the SDR in ^{4}He and in the α clusters of ^{6,7}Li were found to be the same within errors, 0.5 ± 0.1, and similar to those observed in light nuclei. The cross sections for the analogs of the GDR as well as those of the SDR in the α clusters of ^{6,7}Li were 0.6∼0.8 times those for the corresponding resonances in ^{4}He. These results suggest that the cross sections for the analogs of the GDR and the SDR in the α clusters embedded in nuclei are suppressed as compared with those for the corresponding resonances in the free α particle.

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