Dipole Excitation of α Clusters in ^{6}Li and ^{7}Li

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Dipole excitations in highly excited energy regions of ^{6}He and ^{7}He nuclei were investigated via the (^{7}Li, ^{7}Be) reaction with an incident energy of 65*A* MeV at forward scattering angles. The resonances at $Q \simeq -30$ MeV observed commonly for both ^{6}Li and ^{7}Li targets were found to be excited via both spin-flip and spin-nonflip transitions with $\Delta L = 1$. Based on the observed excitation energy, width, and cross section of each resonance, the relevant resonances are inferred to be analogs of the dipole resonances of α clusters in the ^{6}Li and ^{7}Li nuclei.

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Since the discovery of α decay, α clustering has played an important role in understanding nuclear structure and nuclear reactions as demonstrated by α-cluster models [1]. The existence of α clusters in nuclei has been established from light to heavy nuclei [2]. The α cluster can be regarded as a substructure in a nucleus. A natural yet primitive question might be the following: Is there a new excitation mode in which the α cluster itself can be excited in a nucleus? So far in α-cluster models, however, the discussion has been restricted to the ground state of the α particle. Evidence for the excitation of α clusters in nuclei has not yet been elucidated. Such excitations of α clusters in nuclei may provide a new concept of nuclear excitation. The excited α clusters may, further, have characteristics different from those exhibited by excited free α particles due to nuclear medium effects. Thus, it is of great interest to search for a new type of excitation in nuclei.

In the present work, we searched for possible excited α clusters in ^{6}Li and ^{7}Li. Since it is known that the ground states of ^{6}Li and ^{7}Li nuclei are well described by $d + \alpha$ and $t + \alpha$ cluster structures, respectively [3], these nuclei are suitable for the present purpose. In the (n, p) reactions on ^{6}Li and ^{7}Li, Brady *et al.* reported a new resonance structure at $Q \simeq -30$ MeV riding on a broad bump of analogs of the giant dipole resonances in ^{6}Li and ^{7}Li [4]. In the (^{7}Li, ^{7}Be) reaction on ^{6}Li, Jänecke *et al.* also reported a structure similar to that observed in the (n, p) spectrum [5]. Though they did not discuss the details of this new resonance, the fact that the excitation energy and width are very similar to those for the analogs of the isovector dipole resonances of a free α particle is apparent. We speculate that such a resonance might be the excited α cluster in a nucleus. In the free α particle, the giant dipole resonance (GDR; $\Delta S = 0$) and analog of the spin-dipole resonance (SDR; $\Delta S = 1$) have been established by the (γ, n) [6] and $(d, ^2\mathrm{He})$ [7] reactions, respectively, and have been observed as compact resonant peaks at excitation energies of about 25 MeV with widths of about 5 MeV.

We searched for excitation of the dipole resonance in order to observe possible excitations of α clusters in nuclei, by using the (^{7}Li, ^{7}Be) reaction at 65*A* MeV and forward scattering angles. The (^{7}Li, ^{7}Be) reaction has been demonstrated to be a suitable tool to excite the analog of the dipole resonance in the target nucleus [8]. Furthermore, the $\Delta S = 0$ and $\Delta S = 1$ excitations are separated by measuring ^{7}Be ejectiles in coincidence with the γ ray emitted from the excited ^{7}Be [9], and consequently the GDR and SDR can simultaneously be observed in the (^{7}Li, ^{7}Be) reaction. The transferred ΔL may be determined by measuring angular distributions of differential cross sections at forward scattering angles, the shapes of which depend on the transferred ΔL [10]. Thus, we can study the (^{7}Li, ^{7}Be) reactions on ^{6}Li and ^{7}Li to detect analogs of the α-cluster dipole resonances which can be observed commonly in both $\Delta S = 0$ and $\Delta S = 1$ spectra for both ^{6}Li and ^{7}Li targets, as bumps on high-lying continua resulting from noncluster excitations in the target.

A 65*A* MeV $^7\mathrm{Li}^{3+}$ beam was provided from the Ring Cyclotron of the Research Center for Nuclear Physics, Osaka University. The targets used were self-supporting foils of enriched ^{6}Li (95.4%) and ^{7}Li (99.9%) isotopes with thicknesses of 2.5 mg/cm^2. Details of the experimental setup have been described in Ref. [9]. The ^{7}Be ejectiles were analyzed using the spectrograph "Grand Raiden"

[11] set at 0.3° with respect to the beam direction. The aperture of the entrance slit of the Grand Raiden was set at ±20 mrad horizontally and ±15 mrad vertically. The scattering angles θ_L for the ^{7}Be ejectiles were determined by tracing back their positions and incident angles at the focal plane of the Grand Raiden. The 0.43-MeV γ rays from ^{7}Be ejectiles were measured with the γ-ray detector system "NYMPHS" [9] surrounding the target chamber. The γ rays from the ^{7}Be ejectiles were observed via their subsequent contribution to a prominent photopeak in the coincident γ-ray spectra. The coincident ^{7}Be spectra were obtained by gating on the photopeak of the 0.43-MeV γ rays from the ^{7}Be ejectiles.

Figure 1 shows the singles ^{7}Be spectra obtained in the (^{7}Li, ^{7}Be) reactions on the ^{6}Li (a) and ^{7}Li (b) targets at 65A MeV and $\theta \leq 1.5°$. Two resonancelike structures are observed at $Q \simeq -10$ and -30 MeV in the ^{6}Li target and $Q \simeq -20$ and -30 MeV in the ^{7}Li target. The excitation energies of these resonances correspond well to those observed in the (n, p) and (^{7}Li, ^{7}Be) reactions [4,5]. The resonances at $Q \simeq -10$ MeV in ^{6}Li and at $Q \simeq -20$ MeV in ^{7}Li are known as an analog of the $GDR + SDR$. A common structure in the ^{6}Li and ^{7}Li targets is observed at $Q \simeq -30$ MeV.

In order to confirm whether or not the resonance at $Q = -30$ MeV was excited via both $\Delta S = 0$ and $\Delta S = 1$ transitions, the singles and coincidence ^{7}Be spectra were used to separate $\Delta S = 0$ and $\Delta S = 1$ spectra. The (^{7}Li, ^{7}Be) spectra were decomposed into the $\Delta S = 0$ and $\Delta S = 1$ spectra by following the procedure described in Ref. [12]. A peak due to hydrogen contamination in the target was used as a calibration for the relative contributions of the $\Delta S = 0$ and $\Delta S = 1$ spectra. Here the $\Delta S = 0$ and $\Delta S = 1$ transition strengths used for the H(^{7}Li, ^{7}Be) reaction, $B_{\mathrm{F}} = 1$ and $B_{\mathrm{GT}} = 3$, were taken from the neutron β-decay data [13].

The $\Delta S = 0$ and $\Delta S = 1$ spectra thus obtained are shown in Fig. 2. The GDR and SDR in ^{6}Li and ^{7}Li are expected to be excited as their analog resonances in the $\Delta S = 0$ and $\Delta S = 1$ spectra, respectively. The strength distribution of the GDR has been established by the (γ, n) reaction. On the other hand, that of the SDR has not yet been confirmed. The strength distributions of the GDR and SDR in some light nuclei were observed to be similar to each other, as observed in our previous work [14]. Therefore, the SDR is assumed to have the same spectral shape as that of the GDR in the present work. Further, quasifree (QF) contributions are also assumed to have the same shape in the $\Delta S = 0$ and $\Delta S = 1$ spectra. Here the shape of QF contributions was estimated in a manner similar to that used in previous works [12,15,16]. The parameters which fit the data, enabling a reasonable estimation of QF contributions, have values similar to those used in Ref. [16]. The results are shown as dot-dashed lines in Fig. 1. Dashed lines in Figs. 1 and 2 denote the sum of the QF contributions and the relative strength distributions of the GDR obtained by the (γ, n) reactions on ^{6}Li and ^{7}Li. In ^{7}Li, the GDR consists of two isospin components with $T = 1/2$ and $3/2$, both of which may be excited by the (γ, n) reaction. Since only the $T = 3/2$ component of the GDR is excited in the (^{7}Li, ^{7}Be) reaction, the (γ, n) spectral shape for the high energy side of the GDR was comparable to the present spectra, as shown by the dashed lines in Fig. 2(b). Closed symbols in Fig. 2 are obtained by subtracting the assumed strength distribution (dashed lines in Fig. 2) from the $\Delta S = 0$ and $\Delta S = 1$ spectra. In the subtracted $\Delta S = 1$ spectrum in the ^{6}Li target, there is an enhancement around $Q = -8.5$ MeV, which has been discussed as evidence for a soft-dipole resonance in our previous work [10]. The subtracted spectra show that a

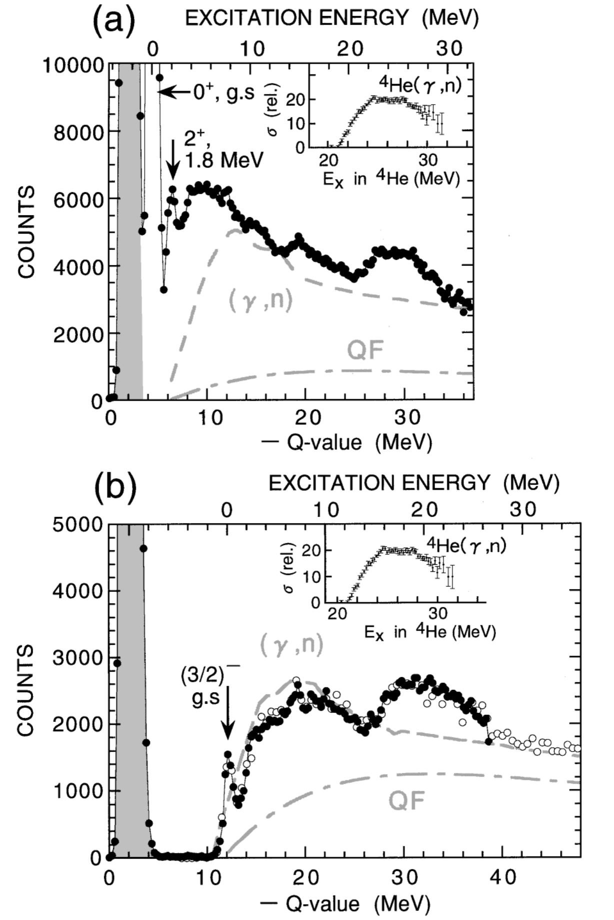

FIG. 1. Singles ^{7}Be spectra in the (^{7}Li, ^{7}Be) reactions at 65A MeV and at $\theta_L < 1.5°$ on (a) ^{6}Li and (b) ^{7}Li (closed circles). Open circles in (b) are the singles spectrum measured up to an excitation energy of 36 MeV in ^{7}Li. Dot-dashed lines are the contribution from quasifree scattering (QF) which is estimated in order to reproduce the slope of the spectrum around $Q \simeq -45$ MeV in the ^{7}Li target (see text). Dashed lines show relative strength distributions obtained with the (γ, n) reaction [6] riding on the QF contributions. Hatched peaks are due to hydrogen contamination in the target. Insets show the spectrum observed in the (γ, n) reaction on ^{4}He [6]. The excitation energy of ^{4}He is scaled by accounting for the separation energies of an α particle in ^{6}Li and ^{7}Li as 1.475 and 2.468 MeV, respectively [3].

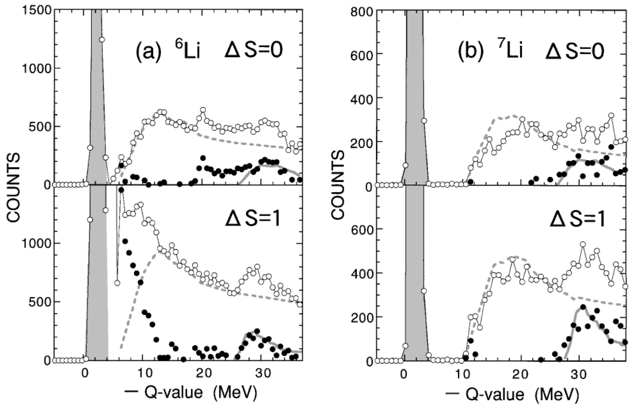

FIG. 2. Spin-nonflip ($\Delta S = 0$) and spin-flip ($\Delta S = 1$) spectra (open circles) in the (^{7}Li, ^{7}Be) reactions at 65A MeV and at $\theta_L < 1.5°$ on (a) ^{6}Li and (b) ^{7}Li. Hatched peaks are due to hydrogen contamination in the target. Dashed lines are a sum of the assumed contributions from quasifree scattering and strength distributions for the GDR and SDR of ^{6}Li and ^{7}Li. Here the latter contributions are assumed to have the same strength distributions for the GDR and SDR. Closed circles denote the spectra obtained from subtraction of contributions represented by the dashed lines in the $\Delta S = 0$ and $\Delta S = 1$ spectra. Solid lines are the renormalized, relative strength distributions for the GDR [6] and SDR [7] of the free α particle with their excitation energies adjusted to fit the data (see text).

resonancelike structure (RS) is excited around $Q \simeq -30$ MeV in both the $\Delta S = 0$ and $\Delta S = 1$ spectra. The excitation energy of the RS corresponds well to that observed in the singles spectra obtained from the reactions on ^{6}Li and ^{7}Li targets.

Angular distributions of differential cross sections for the RS were obtained by gating the scattering angles of ^{7}Be particles in a bin width of 10 mrad horizontally. The differential cross sections were estimated for the resonance in the Q-value region from -28 to -32 MeV. Their angular distributions thus obtained are shown in Fig. 3 as the closed circles for the $\Delta S = 0$ and $\Delta S = 1$ transitions, respectively. Errors indicated are mainly from uncertainties in the decomposition into $\Delta S = 0$ and $\Delta S = 1$ spectra. The angular distributions for the ground state ($\Delta S = 1$, $\Delta L = 0$) of ^{6}He and analog of the GDR ($\Delta S = 0$, $\Delta L = 1$) observed at $Q = -12.5$ MeV in the ^{6}Li target are shown as references (closed triangles in Fig. 3). These angular distributions have characteristic patterns at forward scattering angles for their respective ΔL transfers, which were compared with those calculated via microscopic distorted-wave Born approximation (DWBA) calculations [10]. The DWBA calculations for ($\Delta S = 0$, $\Delta L = 1$) and ($\Delta S = 1$, $\Delta L = 0$) transitions were normalized to the cross section observed around $\theta_L = 0°$, and are shown in Fig. 3 by solid and dashed lines, respectively. The observed GDR is consistent with the dipole ($\Delta L = 1$) resonance. Though uncertainties in differential cross sections of the angular distributions observed for the RS's at $Q \simeq -30$ MeV are large, the $\Delta L = 1$ angular distributions are consistent with those calculated for both $\Delta S = 0$

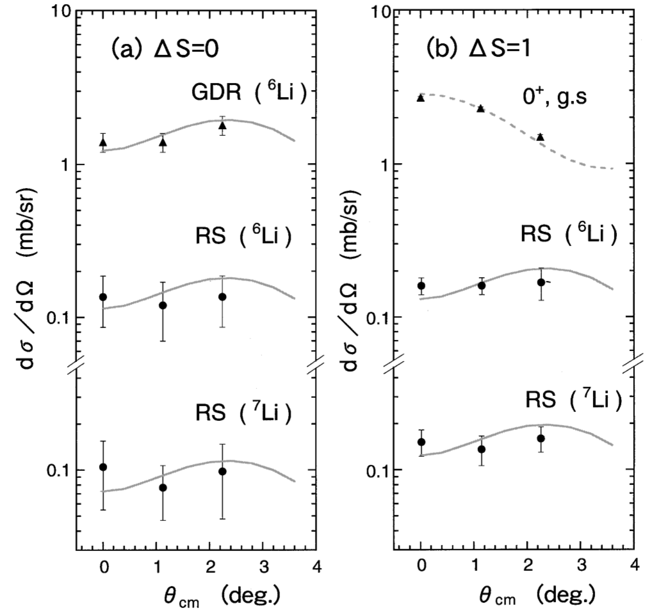

FIG. 3. Angular distributions of the differential cross sections for the $\Delta S = 0$ (a) and $\Delta S = 1$ (b) transitions to the RS at $Q \simeq -30$ MeV in ^{6}Li and ^{7}Li (closed circles). Closed triangles denote the angular distributions for transitions to the ground state ($\Delta S = 1$, $\Delta L = 0$) of ^{6}He and analog of the GDR ($\Delta S = 0$, $\Delta L = 1$) at $Q \simeq -12.5$ MeV in ^{6}Li. Solid and dashed lines denote the DWBA calculations for pure particle-hole excitations with ($\Delta S = 0$, $\Delta L = 1$) and ($\Delta S = 1$, $\Delta L = 0$), respectively [10].

and $\Delta S = 1$ resonances. The present result is also consistent with that obtained by Brady *et al.* who reported the presence of the $\Delta L = 1$ component for the resonance at $Q \simeq -30$ MeV by using the (n, p) reaction at 60 MeV, though they could not separate the $\Delta S = 1$ from $\Delta S = 0$ excitations [4].

The RS's at $Q \simeq -30$ MeV are found to be excited via the $\Delta S = 0$ and $\Delta S = 1$ transitions. The RS's in the $\Delta S = 0$ and $\Delta S = 1$ subtracted spectra were compared with the spectral shapes of the dipole resonances in ^{4}He obtained by the (γ, n) [6] and $(d, {}^2\mathrm{He})$ [7] reactions on ^{4}He, respectively. The results are shown in Fig. 2 as the solid curves. The RS's in both the $\Delta S = 0$ and $\Delta S = 1$ spectra are fitted without changing the widths of the spectral shapes. However, the $\Delta S = 0, 1$ resonances in ^{6}Li and the $\Delta S = 0$ resonance in ^{7}Li were best fit when the excitations of the centroids of the dipole resonances were increased by 2.5 MeV, and by 3.5 MeV for the $\Delta S = 1$ resonance in ^{7}Li. The approximate 1-MeV spread in the positioning of the centroids of the renormalized dipole resonance contributions is most likely due to uncertainties in the subtraction of underlying continua. The cross sections and the Q values are summarized in Table I together with those for the GDR in ^{6}Li. The ratios of the $\Delta S = 1$ to the $\Delta S = 0$ cross sections for the ^{6}Li and ^{7}Li targets are 1.2 ± 0.4 and 1.4 ± 0.7, respectively, which agree with those for the SDR to GDR in light nuclei [14]. Furthermore, the

TABLE I. Isovector dipole resonances observed via the (^{7}Li, ^{7}Be) reactions on ^{6}Li and ^{7}Li at 65A MeV.

Target	^{6}Li			^{7}Li	
	Analog of the GDR	RS		RS	
		$\Delta S = 0$	$\Delta S = 1$	$\Delta S = 0$	$\Delta S = 1$
Q value (MeV)	-12.5	-31	-29	-32	-30
$\sigma(0°)$ (mb/sr)	1.4 ± 0.2	0.14 ± 0.04	0.16 ± 0.02	0.11 ± 0.05	0.15 ± 0.03

$\Delta S = 0$ cross sections in ^{6}Li and ^{7}Li are similar in magnitude: 0.14 ± 0.04 and 0.11 ± 0.05 mb/sr, respectively. Based on these facts, it seems likely that the RS's reflect an excitation of a common constituent in the ^{6}Li and ^{7}Li nuclei, and that the resonance observed at $Q \simeq -30$ MeV is most likely the analog of the dipole resonance of the α cluster in ^{6}Li and ^{7}Li nuclei. The excitation energy for the α cluster in ^{6}Li and ^{7}Li nuclei is 3.0 ± 0.5 MeV greater than that for the free α particle, which may be due to nuclear medium effects. The presence of excited α clusters in nuclei suggests that a weakly coupled cluster model is valid even in a highly excited nucleus.

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