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Evidence for charged-particle decay of dipole-excited ^{4}H clusters embedded in ^{6}He and ^{7}He

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Charged-particle decay from the dipole resonances at $E_x = 24$ MeV in ^{6}He and at $E_x = 18$ MeV in ^{7}He was studied via the ^{6,7}Li(^{7}Li,^{7}Be x) coincidence experiment at 455 MeV and at 0°. These resonances are those that were interpreted as the analogs of the dipole resonances in the α clusters of ^{6}Li and ^{7}Li in our previous work. The dominant decay channels (branching ratios) of the dipole resonances are found to be $d + t + n$ ($26 \sim 32\%$) and $\alpha + 2n$ ($47 \sim 69\%$) for ^{6}He and $t + t + n$ ($47 \sim 55\%$) and $\alpha + 3n$ ($38 \sim 47\%$) for ^{7}He. The branching ratios measured for the $d + t + n$ and $t + t + n$ channels in ^{6}He and ^{7}He, respectively, are larger than those calculated in a simple statistical model by a factor of $\sim$100. These results are consistent with the picture that the observed dipole resonances are analogs of the corresponding dipole resonances in the α clusters of ^{6}Li and ^{7}Li.

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Clusters in nuclei play an important role in nuclear structure and nuclear reactions. Because clusters in nuclear systems are weakly bound and spatially localized subsystems consisting of strongly correlated nucleons [1], we can expect to observe two types of excitations: relative motion of the cluster such as a rotational excitation [2] and an intrinsic excitation of the cluster itself. The latter type of excitation has not been well known until recently. In a photonuclear reaction Costa *et al.* [3] have suggested a possible excitation of the α cluster. They have observed two resonances at excitation energies of $E_x = 11.5$ and 26 MeV in the ^{6}Li(γ, n) spectra [3] and have concluded that the resonance at 11.5 MeV is the isovector giant dipole resonance (GDR) in ^{6}Li and the resonance at 26 MeV is the excitation of the 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 [4–6]. In the $^{\rm nat}$Li(γ, n) spectrum a peak at $E_x = 30$ MeV has been reported [7] in addition to the GDR peak at $E_x = 17$ MeV. However, this 30-MeV peak has not been observed in other ^{7}Li(γ, n) work [4,5]. Existence of the GDR in the α cluster is not conclusively identified in the photonuclear reactions.

On the other hand, the GDR in the α cluster seems to have been observed by Brady *et al.* [8] at $Q \sim -30$ MeV in the ^{6,7}Li(n, p)^{6,7}He reaction. Jänecke *et al.* [9] have reported a structure similar to that observed in the (n, p) reaction [8] by the ^{6}Li(^{7}Li,^{7}Be) reaction. In the ^{6,7}Li(p, n) reaction, Yang *et al.* [10] have reported high-lying dipole resonances at $E_x = 25$ MeV in ^{6}Be and at $E_x = 30$ MeV in ^{7}Be. The Q values and widths for the resonances observed in these nuclear reactions are very similar to those for the GDR in ^{4}He reported in the ^{4}He(γ, n) reaction [4].

On the basis of the fact that the ground states of ^{6}Li and ^{7}Li have the α clustering structure and that the isovector dipole resonances (DRs) consisting of the GDR and spin dipole resonance (SDR) are the most significant excitation modes in ^{4}He, these intrinsic excitations of α clusters have been searched for and recently observed [11–13]. The first evidence for the excitation of the α clusters in ^{6}Li and ^{7}Li has been presented in the ^{6,7}Li(^{7}Li,^{7}Be) reactions in which the high-lying DRs are observed in ^{6}He and ^{7}He at $E_x \sim 24$ and 18 MeV, respectively [11]. The analogous DRs have also been observed in ^{6,7}Li via the (p, p') reactions and in ^{6,7}Be via the (^{3}He, t) reactions [12]. These DRs locate at excitation energies much higher than those for the GDRs in ^{6}Li ($E_x =$ 12 MeV) and in ^{7}Li ($E_x = 17$ MeV) [4] and are observed with reaction Q values and widths similar to those for the DR in ^{4}He. We have compared the excitation energies, widths, and excitation cross sections for the DRs with those for the DR in ^{4}He observed in the (p, p') reaction [13] and for the GDR observed in the (γ, n) reactions [4,14]. On the basis of these comparisons, we have suggested that the observed excitation energies, widths, and excitation cross sections for the resonances in ^{6,7}Li are consistent with those of the DRs of α clusters in ^{6,7}Li and that the corresponding properties of the DRs in ^{6,7}He and ^{6,7}Be are consistent with their being the analogs of the DRs in the α clusters of ^{6,7}Li [11–13].

It has been proposed that the analogs of the DRs observed in ^{6}He and ^{7}He are excited via the charge exchange reactions on the α clusters in ^{6}Li and ^{7}Li, leaving the d cluster in ^{6}Li and the t cluster in ^{7}Li as spectators [15]. The analogous excitations of α clusters in ^{6}He and ^{7}He excited via (^{7}Li,^{7}Be) reactions correspond to those of the residual ^{4}H cluster, and

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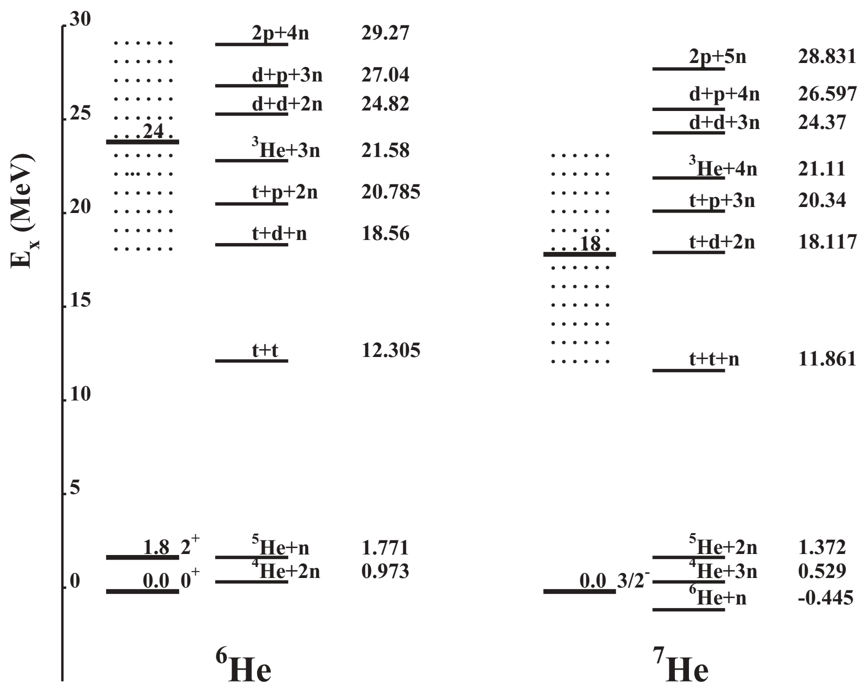

FIG. 1. The threshold energies for the decay channels in ^{6}He and ^{7}He. The locations and widths for the resonances in ^{6,7}He are indicated.

^{4}H is the resonant system of $t+n$. Therefore, ^{6}He and ^{7}He nuclei involving the analog of the DRs of the α cluster may have components of $d+t+n$ and $t+t+n$, respectively, and the observation of which gives evidence for the existence of the intrinsic excitation of the α clusters.

In the present work, we investigated charged-particle decay from the high-lying DRs in ^{6}He and ^{7}He at $E_x \sim 24$ and 18 MeV, respectively. Figure 1 shows the threshold energies for the particle decay channels in ^{6}He and ^{7}He. The DRs are located at excitation energies higher than the thresholds for two or three particle emission. Thus, if the dominant decay channels of the DRs are found to be $d+t+n$ in the ^{6}Li(^{7}Li,^{7}Be) reaction and $t+t+n$ in the ^{7}Li(^{7}Li,^{7}Be) reaction, it is inferred that the DRs are the analogs of the DRs in the α cluster.

Targets were bombarded with the 455-MeV ^{7}Li beams from the ring cyclotron at the Research Center for Nuclear Physics (RCNP), Osaka University. A similar experimental setup has been reported in previous work [16]. Targets used were self-supporting metallic foils of enriched ^{6}Li (95.4%) and ^{7}Li (99.5%) with thicknesses of 0.6 and 0.7 mg/cm^2, respectively. The targets were tilted by 45° with respect to the beam direction to minimize the energy loss of the decay particles in the target.

The ^{7}Be particles emitted from the reactions were analyzed by using the magnetic spectrograph "Grand Raiden" at $\theta_L = 0°$ and were detected with the focal plane detector system, consisting of two multiwire drift chambers backed by a ΔE-E plastic scintillator telescope [17]. The aperture of the entrance slits of the spectrograph was ±20 mr horizontally and ±30 mr vertically. After passing through the target, the beams were stopped with a Faraday cup inside of the spectrograph. Typical energy resolution was 800 keV, which was mainly due to the energy spread of the incident beam and the ^{7}Be particle excitation ($E_x = 0.43$ MeV). The reaction spectra at $E_x = 5 \sim 43$ MeV were measured in the coincidence experiment.

Charged particles emitted from ^{6,7}He excited via the (^{7}Li,^{7}Be) reactions were detected in coincidence with ^{7}Be by using eight Si detectors telescopes (SSDs), each of them consisting of a 500-μm ΔE and a 300-μm E detector with an aperture of 3.8 cm^2. The SSDs were positioned at a distance of 30 cm from the target and at 10° intervals between $\theta_L = 90°$ and $\theta_L = 160°$. A time of flight (TOF) technique was utilized for identification of low energy particles that stopped in the ΔE detectors. Figures 2(a) and 2(c) show the typical two-dimensional scatter plots of TOF vs ΔE. Here, ^{3}He cannot be distinguished from t with a TOF technique. However, the events for coincident ^{3}He are assumed to be small, because the threshold energies for the ^{3}He channels are high in both ^{6}He and ^{7}He. Particles penetrating the ΔE detectors were identified using the ΔE-E method. Figures 2(b) and 2(d) show two-dimensional scatter plots of ΔE vs $\Delta E + E$. It is clearly seen that the events corresponding to each particle were well separated in both methods.

The threshold energy was set at about 0.1 MeV, which was just high enough to eliminate most of the noise, yet eliminated less than 3% of the real events. Because there was some evidence of ^{12}C contamination in the singles spectra on the Li targets, coincidence spectra with a ^{12}C target were measured and were used to confirm that the background from ^{12}C in the coincidence spectra on the Li targets was negligible.

Figures 3(a) and 3(f) show singles spectra for the (^{7}Li,^{7}Be) reactions on ^{6}Li and ^{7}Li, respectively. The spectra are very similar to those observed in previous work [11,12,16,18]. The resonances at $E_x \sim 24$ MeV in ^{6}He and at 18 MeV in ^{7}He have been assigned to the analogs of the α-cluster excitation in ^{6}Li and ^{7}Li, respectively [11,12]. Figures 3(b)–3(e) and 3(g)–3(j) show the coincidence spectra. Here, the coincidence yields in each of the SSDs have been summed assuming that

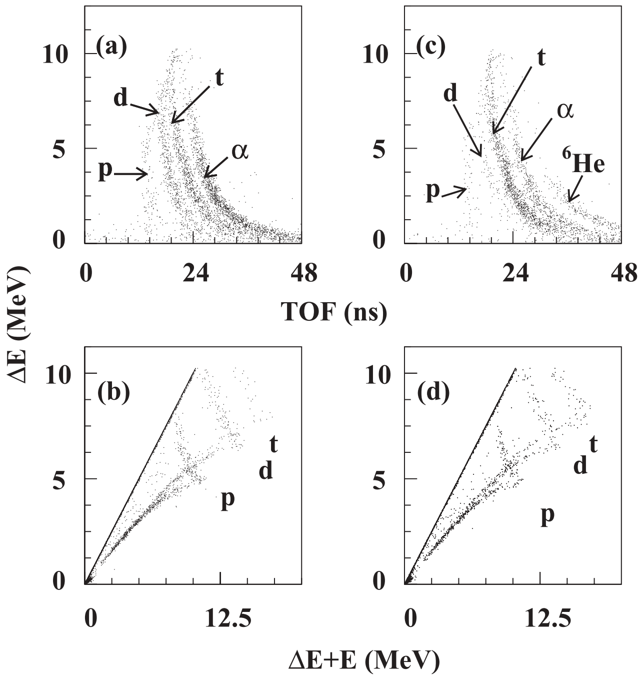

FIG. 2. Two-dimensional scatter plots of the coincidence events for identification of decay particles. The upper and lower figures show scatter plots for ΔE vs TOF and ΔE vs $\Delta E + E$, respectively. Panels (a) and (b) represent the ^{6}Li(^{7}Li,^{7}Be x) reaction at $\theta_L = 100^{\circ}$, and panels (c) and (d) represent the ^{7}Li(^{7}Li,^{7}Be x) reaction at $\theta_L = 100^{\circ}$. The time scales in panels (a) and (c) show only a relative time difference for each particle because the null time in a TOF is not experimentally determined. The straight lines in panels (b) and (d) correspond to the events stopping in the ΔE detectors.

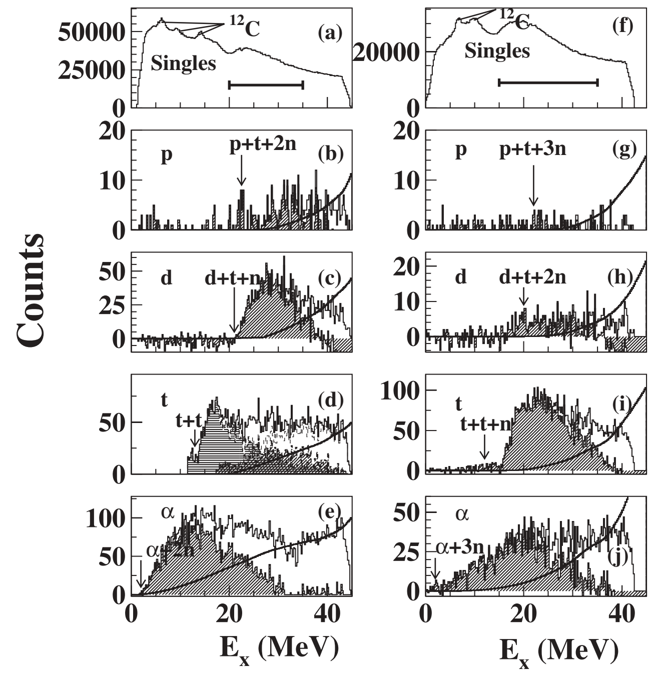

FIG. 3. ^{6}Li(^{7}Li,^{7}Be) spectra for (a) singles and coincidence with (b) proton, p; (c) deuteron, d; (d) triton, t; and (e) α particle, α. ^{7}Li(^{7}Li,^{7}Be) spectra for (f) singles and coincidence with (g) p, (h) d, (i) t, and (j) α are shown in the right panel. The arrows indicate the lowest threshold energies for each particle emission. The coincidence events in every SSDs have been summed and accidental coincidence events have been subtracted. Contaminant peaks due to ^{12}C are indicated. The solid lines show the continuum shapes based on the phase space calculations. The inclined-hatched spectra show the continua subtracted spectra. In the spectrum (d) the horizontal-hatched histogram showing the binary t decay from the $t + t$ resonance of ^{6}He, previously reported in Refs. [16] and [18], was also subtracted from t coincidence spectrum. The energy regions where coincidence yields are integrated are indicated by the horizontal thick lines in spectra (a) and (f).

each particle has an isotropic angular distribution. A significant number of events corresponding to d, t, and α (insignificant for protons) were observed in the ^{6}Li(^{7}Li,^{7}Be) coincidence spectra. A peak observed at $E_x = 18$ MeV in the coincidence spectrum for the ^{6}Li(^{7}Li,^{7}Be t) reaction [Fig. 3(d)] is from the binary t decay of the previously reported $t + t$ resonance of ^{6}He [16,18]. On the other hand, in the ^{7}Li(^{7}Li,^{7}Be) coincidence spectra, there were numerous events in coincidence with t or α particle and few events with a coincident p or d.

To deduce the branching ratios for each decay channel from the DRs, the contributions due to the underlying continua should be considered. Because not one of the cause, magnitude, or shape of the underlying continua was well known, the data in Fig. 3 were analyzed with and without the inclusion of an assumed underlying continua.

Because the thresholds for two or more particle decay channels are at low excitation energies, we simply assumed that the magnitudes of the continua were proportional to the phase space of the decay particles. The calculated phase space was assumed to be a function of the excitation energy, yet for simplicity was assumed to be independent of both the spins of the decay particles and the Coulomb effects. Because the spectroscopic amplitudes for each decay channel were not well known, the calculations were phenomenologically normalized to the experimental data at the excitation energy of $E_x \sim$ 45 MeV. Thus calculated continua are shown as the solid curves in Fig. 3.

Excess yields from the assumed continua in the coincidence spectra were integrated over the energy region of the DRs of

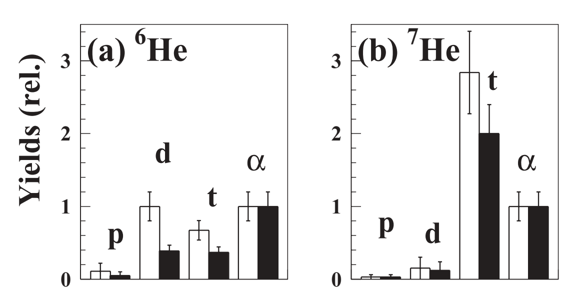

FIG. 4. The coincidence yields from the DRs in ^{6}He (a) and ^{7}He (b) by normalizing the α decay yields to be unity. The open and closed histograms show the results assuming the presence and absence of the underlying continua, respectively.

the α clusters, i.e., $20 \leqslant E_x \leqslant 35$ MeV for ^{6}He and $15 \leqslant E_x \leqslant 35$ MeV for ^{7}He, as indicated in Figs. 3(a) and 3(f). The excess yields, relative to those for α decay, are shown by open histogram in Fig. 4. It is noted that the relative yields in Figs. 3 and 4 are not exclusive and are not corrected for the decay multiplicities.

To establish the upper limit on the error introduced by the uncertainty in the determination and subtraction of the continua, we next assumed that the entire coincidence yields were due to the decay of the DRs. We integrated coincidence yields over the energy region of the DRs. In this case, the relative coincidence yields are shown by closed histogram in Fig. 4. We derived the branching ratios for each decay channel in the manner described in the following paragraph, assuming that the branching ratio for γ decay was negligibly small.

Because the proton coincidence yields are very small in ^{6}He, the yields in coincidence with t [see Fig. 3(d)] are mainly due to the $d + t + n$ channel. The deuteron yields from this channel are also presented in Fig 3(c). The yields for deuteron are slightly larger than those for triton, because the yields from reactions other than the $d + t + n$ channel present in the deuteron yields. In ^{7}He, because the proton and deuteron yields are also small, the triton yields in Fig. 3(i) are mainly due to the $t + t + n$ channel. Because the triton multiplicity in this channel is two, the net yields should be half of the measured yields. The branching ratios in ^{6}He obtained by subtracting the underlying continua (non-subtracting) for the $d + t + n$ and $\alpha + 2n$ channels are found to be $32 \pm 15\%$ ($26 \pm 10\%$) and $47 \pm 15\%$ ($69 \pm 15\%$), respectively. Those in ^{7}He for the $t + t + n$ and $\alpha + 3n$ channels are found to be $55 \pm 15\%$ ($47 \pm 15\%$) and $38 \pm 15\%$ ($47 \pm 15\%$), respectively.

To understand the physical significance of the measured branching ratios, we estimated the ratios for the branching ratios $\Gamma(d + t + n)/\Gamma(\alpha + 2n)$ for ^{6}He and $\Gamma(t + t + n)/\Gamma(\alpha + 3n)$ for ^{7}He by using a simple statistical model [19] assuming that each decay undergoes an evaporation process of nucleons, as carried out in a manner similar to the procedure done in our previous work [16]. An order-of-magnitude estimate with this simple calculation may be enough for the purpose of interpreting the experimental results. The ratio is expressed as $\Gamma(i)/\Gamma(j) \sim (Q_i/Q_j) \times \exp[2(a_n Q_i)^{1/2} - 2(a_n Q_j)^{1/2}]$, where Q_i and Q_j are the decay Q values for the i and j channels, respectively, and a_n is a level density parameter. Here we employed $a_n = A/8$ [16]. The calculated ratios $\Gamma(d + t + n)/\Gamma(\alpha + 2n)$ for ^{6}He and $\Gamma(t + t + n)/\Gamma(\alpha + 3n)$ for ^{7}He are $\sim 3 \times 10^{-3}$ and $\sim 1 \times 10^{-2}$, respectively. The measured ratios are 0.7 ± 0.4 for ^{6}He and 1.4 ± 0.7 for ^{7}He in the case of underlying continua subtraction and 0.4 ± 0.2 for ^{6}He and 1.0 ± 0.5 for ^{7}He in the case of non-subtraction. In every case, the measured ratios are found to be about two orders of magnitude larger than the calculations.

In summary, we investigated the charged-particle decay from the DRs in ^{6}He and ^{7}He at $E_x = 24$ and 18 MeV, respectively. The dominant decay channels of the DRs were found to be $d + t + n$ and $\alpha + 2n$ for ^{6}He and $t + t + n$ and $\alpha + 3n$ for ^{7}He. The branching ratios measured for the $d + t + n$ and $t + t + n$ channels in ^{6}He and ^{7}He, respectively, are larger than those calculated in a simple statistical model by a factor of ~ 100. These results show that the DRs in ^{6}He and ^{7}He involve the clustering structures of ^{4}H. The present experimental results are consistent with the picture that the observed DRs in ^{6}He and ^{7}He are analogs of the DR in the α clusters of ^{6}Li and ^{7}Li.

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