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Di-triton molecular structure in ^{6}He

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Resonances above the t+t threshold in ^{6}He have been studied via the ^{6}Li(^{7}Li, ^{7}Be t)^{3}H reaction at 0° taken with a ^{7}Li beam of 65 MeV/nucleon. By observing the binary triton decay, a new prominent resonance is found at $E_x = 18.0 \pm 0.5$ MeV with a width of 7.7 ± 1.0 MeV. The branching ratio for the binary triton decay from this resonance is deduced to be $90 \pm 10\%$, suggesting that the resonance at 18 MeV has a di-triton molecular structure.

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Over many years, an enormous amount of effort has been devoted to understand excitation energy spectra of light nuclei. Low-lying discrete states in light nuclei are often discussed in terms of the independent-particle shell model, as well as of the α cluster model [1–3]. For high-lying resonance states, the most successful model is the α cluster model [3]. Some of the excited states in light nuclei are well explained as an oscillation of a few-nucleon cluster. For example, in ^{6}He, one of the neutron-rich light nuclei, the giant dipole resonance, and the giant spin-dipole resonance are understood as a vibration of a two-proton cluster against a four-neutron cluster. In addition, the existence of the soft-dipole resonance becomes evident [4]. This resonance is understood as an oscillation of an α cluster in the neutron halo.

One naive question naturally arises; are there any resonances including ^{3}He, or ^{3}H particles acting as a cluster? Such resonant states are known to exist at low excitation energies [5,6]. Trinucleon cluster states at high excitation energies were predicted by Thompson and Tang [7], who claimed that the ''molecular'' resonance with two trinucleon clusters should exist in the $A=6$ triad, ^{6}He, ^{6}Li, and ^{6}Be. In their model, the triton and ^{3}He clusters behave like a neutron and a proton, respectively, in the two-nucleon system, respectively. These two-trinucleon systems are expected to have resonant states similar to those generated in the two-nucleon systems; the lowest state is classified as $^{13}S_1$ and other multiplets as $^{31}S_0$, ^{33}P, which are expected to be located at higher excitation energies. Here, the symbols denote $^{(2T+1)(2S+1)}L_J$.

In the past, trinucleon resonances were experimentally reported in ^{6}Li and ^{6}Be on the basis of radiative capture reactions [8–10], and of the phase shift analysis on the ^{3}He $+{}^3$H and ^{3}He$+{}^3$He elastic scattering data [11,12]. In the case of ^{6}Li, Ventura *et al.* [9] found evidence for the $^{33}P_2$ resonance at $E_x = 18.3$ MeV. On the other hand, Vlastou *et al.* [11] reported that the $^{33}P_2$ and $^{33}P_0$ resonances exist at 21.0 and 21.5 MeV, respectively. Concerning the $^{33}P_2$ resonance in ^{6}Li, there was a serious discrepancy by about 3 MeV in the excitation energy. In order to understand the reason for this discrepancy, Mondragón and Hernández [13] reanalyzed simultaneously both the data from the ^{3}He$+{}^3$H elastic scattering [11] and from the radiative capture reaction [9]. They concluded that the $^{33}P_2$ resonance in ^{6}Li should exist at $E_x = 17.984$ MeV and that the resonance energy for other multiplets in ^{6}Li should be lower by $\sim$3 MeV than those reported in Ref. [11]. Recently, a similar conclusion was theoretically reported by Ohkura *et al.* [14]. However, the precision of the extracted level parameters stated in Ref. [13] is still a subject of some objection [15].

In the case of ^{6}Be, contradictory results were also reported about the trinucleon cluster resonance. Ventura *et al.* assigned a broad resonance at $E_x = 23$ MeV in ^{6}Be to be the $^{33}F_3$ resonance from the radiative capture reaction of ^{3}He on ^{3}He [10]. However, Vlastou *et al.* did not observe this state in the phase shift analysis of elastic scattering of polarized ^{3}He on ^{3}He, but they observed the $^{33}F_4$, $^{33}F_2$, and $^{33}F_3$ resonances located at $E_x = 23.4$, 26.2, and 26.7 MeV, respectively [12]. Thus, the issue of trinucleon clustering in $A=6$ nuclei appears highly contentious and seems to be presently unproven.

In order to solve the long standing controversy over the trinucleon clustering in $A=6$ nuclei, we employed a different experimental approach: we searched for the di-triton molecular state in ^{6}He by means of a coincidence measurement of decay tritons in the ^{6}Li(^{7}Li, ^{7}Be) reaction at $\theta \simeq 0°$ and at an incident energy of 65 MeV/nucleon. If the two-triton-cluster molecular state in ^{6}He exists above the $t+t$ threshold and is excited, it is natural to expect that a branching ratio of triton emission from the resonance would be much larger than that expected by the statistical model calculations.

The experiment was performed at the RCNP cyclotron facility of Osaka University with a ^{7}Li^{3+} beam of 65 MeV/

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nucleon. The target used was a self-supporting foil of an enriched ^{6}Li isotope (95.2%) with a thickness of 1.0 mg/cm^2. Spectra for the ^{6}Li(^{7}Li, ^{7}Be) reaction were measured with the magnetic spectrometer ''Grand Raiden'' [16] at $\theta \simeq 0°$. The angular acceptance of the spectrometer was ± 20 mr horizontally and ± 40 mr vertically. The ^{7}Be particles were detected using a focal-plane detector system, which consisted of two multiwire drift chambers backed by a ΔE-E plastic-scintillator telescope. A typical energy resolution was 850 keV, which was mainly due to the beam energy spread and the excitation of the ^{7}Be ejectile ($E_x = 0.43$ MeV). The ΔE and E signals were utilized for particle identification. Charged particles from the excited states in ^{6}He formed in the ^{6}Li(^{7}Li, ^{7}Be) reaction were detected using an array of 14 Si solid-state detector (SSD) telescopes. The thicknesses of the ΔE detectors were 20 μm (five sets), 50 μm (four sets), and 100 μm (5 sets). Each ΔE detector was backed by a 5-mm-thick E detector. These telescopes were located at $\theta = 113°$ ($\phi = 30°$, 90°, 150°, 210°, 270°, and 330°), 135° ($\phi = 30°$, 90°, 210°, 270°, and 330°), and 158° ($\phi = 30°$, 270°, and 330°). The solid angle covered by the SSD array was 4.0% of 4π.

Figure 1(a) shows the singles spectrum for the ^{6}Li(^{7}Li, ^{7}Be)$\,^{6}$He reaction at 65 MeV/nucleon. Peaks due to carbon contamination in the ^{6}Li target were subtracted by using the measured $^{\mathrm{nat}}$C(^{7}Li,^{7}Be) spectrum. We observed two prominent discrete states in ^{6}He, i.e., the ground state (0^+), and the first excited state (2^+) at 1.8 MeV. Three broad resonances were observed at $E_x = 5$, 15, and 25 MeV. These resonances have been observed in the ^{6}Li(n,p) reaction [17], and the ^{6}Li(^{7}Li,^{7}Be) reaction [4,18,19]. The resonances at $E_x \simeq 5$ and 25 MeV were assigned by Nakayama *et al.* to be the soft dipole resonance [4] and the analog of the dipole resonance caused by an excitation of the α cluster in the ^{6}Li nucleus [18], respectively.

Figure 1(b) shows a two-dimensional scatter plot of ^{7}Be-decay-particle coincidence events at $\theta = 158°$ and $\phi = 30°$. Here, accidental coincidence events have been subtracted, and no particle identification has been done. Negative counts resulting from the subtraction are not shown. The solid lines in Fig. 1(b) show the threshold energies for several decay channels calculated by taking into account the recoil effect of ^{6}He. The coincidence events corresponding to triton emission are clear; one can easily recognize a locus along the threshold line of triton decay. Similar loci were recognizable in the two-dimensional scatter plots obtained in coincidence with decay particles measured at various angles, indicating that these events are definitely due to the two-body decays. In the region from $E_x = 14$ MeV to 20 MeV, the observed locus is located slightly below the threshold for the $t+t$ decay channel, since decay tritons suffer an energy loss in the target. On the contrary, other loci along the kinematical lines corresponding to the $\alpha + 2n$, ^{5}H$+p$, and ^{4}H$+d$ thresholds are less evident. Most of the events spread over the region below the $\alpha + 2n$ thresholds show no particular concentration, suggesting that these events are mainly due to three-body decays.

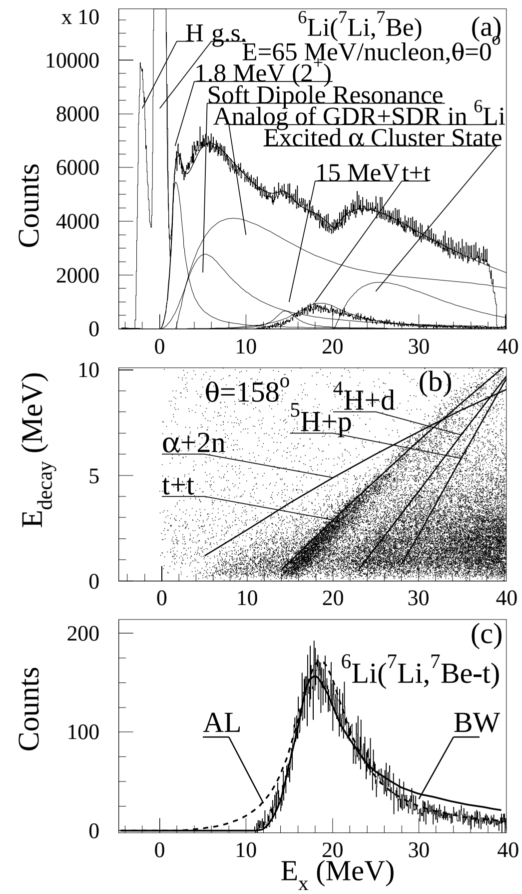

FIG. 1. (a) Singles spectrum for the ^{6}Li(^{7}Li, ^{7}Be) reaction at 65 MeV/nucleon. A spectrum obtained in coincidence with tritons is shown. The solid lines are the results of a χ^2 fit (see text). (b) Two-dimensional scatter plot of ^{7}Be-decay-particle coincidence events at $\theta = 158°$ and $\phi = 30°$. The horizontal and vertical axes are the excitation energy in ^{6}He and the energy of decay particles, respectively. The kinematical loci calculated for several decay channels are shown by the solid lines. (c) Coincidence spectrum for the ^{6}Li(^{7}Li, ^{7}Be t)$\,^{3}$H reaction. The solid line shows the peak shape calculated with the Breit-Wigner one level formula (BW). The dashed line is the result of the χ^2 fit with an asymmetric Lorentzian function (AL).

The coincidence spectrum in the ^{6}Li(^{7}Li, ^{7}Be t)$\,^{3}$H reaction obtained by gating on the binary triton-decay events is shown in Fig. 1(c). Only a broad peak was observed at $E_x = 18.0 \pm 0.5$ MeV. The width (full width at half maximum, FWHM) of this broad peak in Fig. 1(c) was found to be 7.7 ± 1.0 MeV. Surprisingly, no peak was visible at 18 MeV in the singles spectrum. The threshold energy due to the noise discrimination level of the detectors was 0.5 MeV. The number of low energy tritons eliminated due to the detector threshold was estimated to be small, and this did not significantly influence the peak shape. The angular correlation pattern of tritons from the 18-MeV peak was isotropic within the statistical error. The 18-MeV peak obtained in the coincidence measurement is also shown in Fig. 1(a), where the peak height is normalized to the singles yield by taking into account the solid angles of the SSD's and the multiplicity for

TABLE I. Experimental excitation energy E_x, width Γ, and spin parity J^π.

Expt. [a]			Expt. [b]		Expt. [c]		Expt. [d]		Expt. [e]	
E_x (MeV)	Γ (MeV)	J^π	E_x (MeV)	Γ (MeV)	E_x (MeV)	Γ (MeV)	E_x (MeV)	Γ (MeV)	E_x (MeV)	Γ (MeV)
g.s.		0^+	g.s.		g.s.		g.s.		g.s.[f]	
1.8		2^+	1.8		1.8		1.8		1.8[f]	
					4.4±0.1	4.0±0.1	4.0±1.0	4.0±1.0	3.9±1.0	6.4±1.0
5.6±0.3	12.1±1.1	2^+			7.7±0.2	2.3±0.4				
					9.9±0.4	3.3±0.7	8.5	15.0	8.5[f]	15.0[f]
14.6±0.7	7.4±1.0	$(1,2)^+$	15.5±0.5	4±1.5	14.6±0.2	5.9±0.7	14.6		15.0±0.5	3.0±0.5
									18.0±0.5	7.7±1.0
23.3±1.0	14.8±2.3		25.1±0.5	8±2			25.0		25.5±1.0	12[f]

[a]Reference [19], (^{7}Li,^{7}Be) at 50 MeV/nucleon.
[b]Reference [17], (n,p) at 60 MeV/nucleon.
[c]Reference [23], (t, ^{3}He) at 112 MeV/nucleon.
[d]Reference [4,18], (^{7}Li, ^{7}Be) at 65 MeV/nucleon.
[e]This work.
[f]Fixed in the fits.

triton emission. The solid angles were corrected for the center of mass system in ^{6}He.

In order to deduce the resonant parameters, the spectral shape of the 18-MeV resonance shown in Fig. 1(c) was fitted by using the Breit-Wigner one level formula [20]. We assumed the triple differential cross section $d^3\sigma(E_x)/d\Omega_{^7\mathrm{Be}}\, d\Omega_t dE_x$ to be

$$\frac{d^3\sigma(E_x)}{d\Omega_{^7\mathrm{Be}}\, d\Omega_t dE_x} \propto \frac{\Gamma_t}{(E_x - E_R)^2 + (\Gamma/2)^2},$$

where E_R, Γ, and Γ_t are the resonance energy, the total width, and the partial width for triton decay, respectively. The width Γ_t is expressed as [21]

$$\Gamma_t = \frac{2\hbar}{R}\left(\frac{2E}{\mu}\right)^{1/2} \theta^2 P_l,$$

where R, E, μ, θ^2, and P_l are the interaction radius of ^{6}He, the triton energy in the center of mass system, a reduced mass, a dimensionless reduced width, and the penetrability with an angular momentum l, respectively. The interaction radius is given by $R = r_0(A_t^{1/3} + A_t^{1/3})$ with $r_0 = 1.4$ fm. Since the 18-MeV resonance is expected to mainly decay by triton and neutron emissions, $\Gamma = \Gamma_t + \Gamma_n$ was also assumed, where Γ_n is the partial width for neutron decay. Since the threshold energy for neutron decay is 0.93 MeV in ^{6}He and is much lower than the peak position of $E_x = 18$ MeV, the width Γ_n was assumed to be constant in the fitting procedure, for simplicity.

As shown in Fig. 1(c), the shape of the coincidence spectrum is well reproduced with the Breit-Wigner one level formula assuming $l = 0$. We note that the calculated shape for $l = 1$ is very similar to that for $l = 0$. The location, the peak shape, and the FWHM were well reproduced with $E_R = 18.0 \pm 0.5$ MeV, $\Gamma_n = 3.0 \pm 1.0$ MeV, and $\theta^2 = 1.0 \pm 0.4$. It is remarkable that the branching ratio for triton decay, Γ_t/Γ, averaged over the excitation energy region up to 40 MeV amounts to 90%.

In order to check whether or not such a large branching ratio is consistently yielded from the observed singles spectrum, we fitted it using a χ^2 method. In this fit, we took into account the 18-MeV resonance and the known excited states, i.e., the first excited state at $E_x = 1.8$ MeV, the soft-dipole resonance at $E_x = 4$ MeV [4], the analog of the giant dipole resonance and spin dipole resonance at $E_x = 8.5$ MeV [18], a resonance at $E_x = 15$ MeV [19], and the analog of dipole resonance of α cluster at $E_x = 23$ MeV [18]. Asymmetric Lorentz formulas [22] were assumed for the shapes of the first excited state, the soft-dipole resonance, and the 18-MeV resonance. A Gaussian function was assumed for the shape of the 15-MeV resonance [23]. The peak shapes for the resonances at 8.5 MeV and 25 MeV were taken from the ^{6}Li(γ,n) and ^{4}He(γ,n) reaction studies [24], respectively. A contribution from the quasifree charge-exchange process from a proton in the target nucleus was included using a procedure reported in Ref. [19].

The result of the best fit is shown in Fig. 1(a). The singles spectrum for the ^{6}Li(^{7}Li, ^{7}Be) reaction is well reproduced, when we set the $t+t$ branching ratio to be $90 \pm 10\%$. The contribution from the quasifree process seemed to be very small at $\theta = 0°$. In Fig. 1(c), the coincidence spectrum is also compared with the asymmetric Lorentzian peak shape fitted for the 18-MeV resonance. In Table I, the excitation energies and widths of the resonance deduced in the present work are summarized.

In order to understand such a large $t+t$ branching ratio, we compared the observed branching ratio with that evaluated from a simple statistical-model calculation [25]. In this calculation, neutron and binary-triton decays were assumed to take place in the evaporation and fission processes, respectively, from the 18-MeV resonance in ^{6}He. The level density parameter was chosen to be $a = A/8$, where A is the mass number. The branching ratio calculated for the binary triton decay was typically 0.2%. We estimated the errors in the statistical-model calculation by modifying the parameters for the the Coulomb, surface, and excitation energies, in the permissible range. The branching ratio changed from 0.1% to 1%. Importantly, the value of 1% is still two orders of magnitude smaller than the branching ratio obtained in the present work. It is, therefore, reasonable to infer that the observed $t+t$ branching ratio is attributable not to the statistical decay process but to a $t+t$ molecular structure for the 18-MeV resonance.

We have observed also other three resonances in the singles and coincidence spectra above the $t+t$ threshold at $E_x=15.0$, 18.0, and 25.5 MeV. Among these resonances, only the 18.0-MeV resonance was found to decay into $t+t$. Theoretically, the ^{33}P di-triton state in ^{6}He was predicted at $E_x=18.1$ MeV in the calculation by Thompson and Tang [7]. The agreement of the excitation energies between the present result and their calculated value is very good.

In summary, the existence of a di-triton molecular resonance at $E_x=18$ MeV in ^{6}He has been demonstrated by measuring decay tritons in coincidence with the ^{6}Li(^{7}Li, ^{7}Be) reaction at 0°. Since two-trinucleon cluster resonances of various multiplets are also predicted in the $A=6$ triad, further experimental as well as theoretical efforts to establish the existence of these resonances are urgently required.

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