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Trinucleon cluster structures in ^{6}Li

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The $t+{}^3$He cluster structures in ^{6}Li were investigated by using the ^{7}Li(^{3}He$,\alpha$) reaction at 450 MeV and at $\theta_L=0°$. A binary decay into $t+{}^3$He with a branching ratio of 0.8 ± 0.2 from a broad state at $E_x=21$ MeV in ^{6}Li was observed by measuring t and ^{3}He decay particles. From the measured angular correlations and with the analysis of the spectral shape by using the Breit-Wigner formula, the 21-MeV resonance was decomposed into the ^1P $(T=0)$ state at $E_x=18.0\pm0.5$ MeV with Γ(FWHM)$=5.0\pm0.5$ MeV (where FWHM means full width at half maximum), and the ^3P $(T=1)$ state at $E_x=22\pm1$ MeV with $\Gamma=8\pm1$ MeV.

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Clustering is an interesting phenomenon in nuclear excitation processes as well as in nuclear structure [1]. α-clusters have been proven to exist in light to heavy nuclei. Exotic cluster structures have been also revealed in unstable nuclei [1,2]. Existence of a trinucleon cluster state in the $A=6$ isobars was theoretically suggested a few decades ago [3]. Trinucleon clusters, t and ^{3}He, are fermions and are analogous to neutrons and protons in nuclear systems, respectively, and are essentially different than α clusters which are bosons. Therefore, nuclei with trinucleon clusters have very different structure than those with α clusters. In the $A=6$ isobars, excitations in a trinucleon cluster system are expected to generate spectra analogous to a two-nucleon system. In the two-nucleon system, the only bound state is a triplet $^3S_1$ $(T=0)$ and no singlet resonance exist. In a trinucleon cluster system of $A=6$ nuclei, on the other hand, not only are there many bound states, $^3S_1$ $(T=0)$, $^1S_0$ $(T=1)$, $^3D_{1,2,3}$ $(T=0)$, etc., but also the resonant states, $^1P_1$ $(T=0)$, $^3P_{0,1,2}$ $(T=1)$, $^1F_3$ $(T=0)$, $^3F_{2,3,4}$ $(T=1)$, etc., are expected. Here, the symbols denote $^{2S+1}L_J$. Therefore, a detailed study of trinucleon clusters in $A=6$ nuclei may provide insights into the two-fermion system which cannot be studied via the two-nucleon system.

In the *LS*-coupling cluster model of the $t+{}^3$He system in ^{6}Li, Thompson and Tang predicted a P doublet ($^1P_1$ and $^3P_{0,1,2}$) around $E_x=22$ MeV and an F doublet ($^1F_3$ and $^3F_{2,3,4}$) around $E_x=29$ MeV with the resonating group method (RGM) calculation [3]. Recently Ohkura *et al.* performed a more elaborate calculation by using the complex-scaled RGM (CSRGM) [4]. They reported that these states exist at lower excitation energies by about 3 MeV than the RGM prediction, namely, the P and F doublets exist around $E_x=17$ and 26 MeV, respectively.

Experimentally, the nature of deuteronlike $t+{}^3$He cluster configurations for the ground state of ^{6}Li was studied via the ^{6}Li(γ,t) reaction [5], and there are also some data for unbound isovector states, $^3P_{0,1,2}$ and $^3F_{2,3,4}$ states [6,7]. Ventura *et al.* found evidence for the ^3F state around $E_x=26$ MeV from the ^{3}He(t,γ) reaction [6]. On the other hand, Vlastou *et al.*, reported that the $^3P_2$, $^3P_0$, $^3F_4$, and $^3F_3$ states exist at $E_x=21.0$, 21.5, 25.7, and 26.7 MeV, respectively, from the $^3\overrightarrow{\mathrm{He}}+t$ elastic scattering [7]. They carefully investigated the excitation energy region of 20 MeV and confirmed evidence for the $^3P_2$ state which had not been obtained by Ventura *et al.* [6]. In order to reliably investigate a resonance structure in ^{6}Li, Mondragón and Hernández reanalyzed both data from the $^3\overrightarrow{\mathrm{He}}+t$ elastic scattering and from the radiative capture reaction [8]. Their results showed that the $^3P_2$ isovector state in ^{6}Li exists at $E_x=17.985\pm0.025$ MeV, and that its excitation energy should be lower by about 3 MeV than that reported by Vlastou *et al.* [7]. Such a conclusion was reproduced with the CSRGM calculation by Ohkura *et al.* [4]. However, it is noted that the precision with which Mondragón and Hernández were able to extract the parameters therein remains controversial [9].

In order to confirm the results of the CSRGM calculation, Akimune *et al.*, recently searched for the trinucleon cluster state with a different approach [10]. The analog of the isovector resonance at $E_x=18$ MeV in ^{6}Li is expected to exist around $E_x=15$ MeV in ^{6}He by taking into account the Coulomb displacement energy of 3.56 MeV [9]. They found evidence for the $t+t$ binary decay not from the resonance at $E_x=15$ MeV but from that at $E_x=18.0$ MeV in ^{6}He. Though a spin assignment for the resonance was not obtained in this experiment, the resonance at $E_x=18.0$ MeV in ^{6}He was suggested to be the ^3P state from the comparison with the *LS*-coupling cluster model [3]. Since the excitation energy of 18.0 MeV in ^{6}He is estimated to be a Coulomb corrected

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21.6 MeV in ^{6}Li, their experimental result was in apparent contradiction to the Mondragón's work [8] and the CSRGM calculation [4].

It is very important to confirm the existence of the resonance at E_x=21.6 MeV in ^{6}Li, and to determine experimentally the multipolarity of the resonance to resolve the experimental and theoretical contradictions on spectra of the trinucleon cluster system in ^{6}Li. In this paper, we report on the $t+{}^3$He cluster resonances in ^{6}Li investigated via the ^{7}Li(^{3}He,α) reaction by measuring t and ^{3}He decay particles in coincidence with α particles. Since the ground state of ^{7}Li is described as the $t+\alpha$ cluster state, the states with $t+{}^3$He cluster configuration may be populated via the neutron pickup reaction on the α cluster in ^{7}Li [1]. Since the participating particles in this reaction have low spins, spin populations of excited states are expected to be aligned by measuring α particles at $\theta_L \sim 0°$. Measurements of the angular correlations of decay particles may be used to uniquely determine angular momenta of populated states. Since the ^{7}Li(^{3}He,α) reaction can excite both isoscalar and isovector states in ^{6}Li not only ^3P (T=1) but also ^1P (T=0) states may be observed in ^{6}Li. So far, the ^1P state with a $t+{}^3$He cluster configuration in ^{6}Li has not been experimentally observed [9].

A 450-MeV ^{3}He^{2+} beam was provided from the Ring Cyclotron of the Research Center for Nuclear Physics, Osaka University. The target used was a self-supporting foil of a separated ^{7}Li isotope (99.9%) with a thickness of 0.5 mg/cm^2. After passing through the target, the ^{3}He beam was stopped inside the D1 magnet of the spectrometer. The α particles were analyzed using the magnetic spectrometer "Grand RAIDEN" [11] set at θ_L=−0.5°. The angular acceptance of ±15 mr horizontally and ±15 mr vertically with respect to θ_L=0° was selected by a software gate in a ray-trace method. The α particles were detected using a focal-plane detection system, which consisted of two multiwire drift chambers backed by a ΔE-E plastic-scintillator telescope. The ΔE and E signals were utilized for particle identification. The typical energy resolution was about 300 keV.

Charged decay particles were detected by eight Si detectors with 500 μm thicknesses. These detectors were positioned from θ_L=90° to θ_L=160° at 10° intervals and about 30 cm from the target. An identification of decay particles was performed by a time of flight method. Here triton and ^{3}He particles are not separable. Only the t and ^{3}He decaying particles having energies less than 10 MeV were selected in order to guarantee the multiplicity 2 for t and ^{3}He emissions. Each detector was backed by a Si detector with a 300-μm thickness. The backed 300-μm detector was used as a veto detector for rejection of p and d. The ratios of true to random coincidence events were found to be about 8:1 to 10:1 depending on the detection angle. The decaying t and ^{3}He were selected by gating on $t/{}^3$He particle loci with the true coincidence. The threshold energy due to the noise discrimination level of the detectors was about 0.1 MeV. The target was tilted by 45° with respect to the beam direction in order to reduce the energy loss of the decay particle throughout the target.

The thin solid curve in Fig. 1(a) shows the singles spectrum for the ^{7}Li(^{3}He,α)^{6}Li reaction at 450 MeV and at θ_L =0°. There are also some peaks due to carbon and oxygen contaminations in the target. By measuring the singles spectrum, ^{12}C was found to contribute to negligible contamination in the continuum spectra above $E_x \sim 15$ MeV. Most of the low-lying states are known as cluster states of $d+\alpha$ [9]. In the high excitation energy region, on the other hand, a resonance previously unknown was observed at E_x =21 MeV. The existence of trinucleon cluster states in this excitation region has been discussed [3–7]. An s-hole state has been observed around E_x=18 MeV by using the ^{7}Li(p,pn) reaction at E=1 GeV [12].

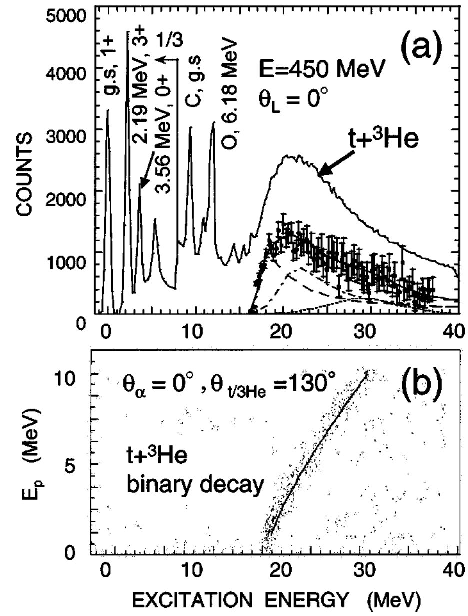

FIG. 1. (a) Singles spectrum for the ^{7}Li(^{3}He,α)^{6}Li reaction at 450 MeV and at θ_α=0° (thin solid curve). A spectrum obtained in coincidence with triton and ^{3}He decay particles is shown by closed circles. See text for details. Error bars indicated are due to only statistical. The symbols of C and O denote peaks due to carbon and oxygen contaminations in the target, respectively. The long-dashed curve denotes the peak shape calculated with the Breit-Wigner formula for two resonances at E_x=18 MeV (dashed curve) and 22 MeV (dot-dashed curve), respectively. The dotted curve is a Gaussian peak at E_x=29 MeV and with Γ=10 MeV. The solid curve is the sum of all the resonances. (b) Two-dimensional scatter plot between α particles and $t/{}^3$He decay particles. The triton and ^{3}He decay particles were measured at θ_L=130°. The abscissa and ordinate are the excitation energy in ^{6}Li and the energy of decay particle, respectively. The solid curve shows the kinematical locus calculated for $t+{}^3$He binary decay.

Figure 1(b) shows a two-dimensional scatter-plot measured at θ_L=130° for decaying t and ^{3}He in coincident with α particles. The solid curve in Fig. 1(b) shows a locus of the threshold energy for the $t+{}^3$He decay-channel calculated by taking into account the recoil effect of the residual nucleus ^{6}Li. The coincidence events corresponding to t and ^{3}He emissions are clearly observed; one can easily recognize a locus along the threshold line of $t+{}^3$He decay, indicating that these events are definitely due to the two-body decay. Similar loci in all the Si detectors were recognized in the two-dimensional scatter plots presently observed.

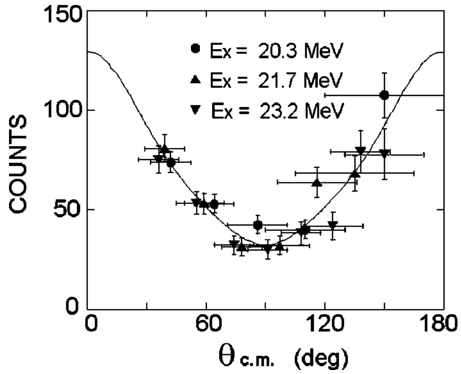

FIG. 2. Angular correlations obtained at the excitation energies of E_x=20.3, 21.7, and 23.2 MeV by making use of the singles data to obtain relative normalizations. The abscissa is the angle of particle emission in the center of mass frame of the residual nucleus ^{6}Li. The solid angles and emission angles of decaying particles were represented in the center of mass system of ^{6}Li. The fitting result is shown by a solid curve. See the text.

In order to determine the angular momentum of the resonance around E_x=21 MeV, angular correlations of decaying t and ^{3}He were investigated. We obtained angular correlations for t and ^{3}He decaying from excitation energy regions of E_x=20.3, 21.7, and 23.2 MeV as shown in Fig. 2. The angular correlations obtained were fitted by using the Legendre polynomial functions $[P_L(\theta_{c.m.})]^2$, where L is an angular momentum of the resonance and c.m. means center of mass. A satisfactory fitting was obtained with $N\{1.0+a_1[P_1(\theta_{c.m.})]^2+a_2[P_2(\theta_{c.m.})]^2+a_3[P_3(\theta_{c.m.})]^2\}$, where N is a normalization factor and $(a_1,a_2,a_3)=(2.5\pm0.2, 0.4\pm0.4, 0.4\pm0.4)$. A large value of a_1 suggests that the orbital angular momentum is $L=1$ for $t+{}^3$He ejectiles from the 21-MeV resonance, though there may be an incomplete spin alignment of ^{6}Li due to the reaction mechanism or overlapping contributions from $L=2$ and 3 in the relevant excitation energy region. This fact indicates that the $t+{}^3$He cluster-state at E_x=21 MeV is predominantly the ^1P and/or ^3P states.

The coincidence spectrum in the ^{7}Li(^{3}He,α)^{6}Li reaction was obtained by gating on the $t+{}^3$He binary decay events, from which a random coincidence yield was subtracted. The coincidence yield has been corrected by taking into account the solid angles of the Si detectors, the multiplicity 2 for t and ^{3}He emissions, and the observed angular correlations. Here, the intensity of decay particles was assumed to depend only on the polar angle $\theta_{c.m.}$ in the spherical polar coordinates. The coincidence spectrum thus obtained is shown by closed circles in Fig. 1(a). A broad peak was observed around E_x=21 MeV. The full width at half maximum (FWHM), Γ, of this peak was found to be 12±2 MeV. The location and width of the 21-MeV peak in the coincidence spectrum correspond well to those observed in the singles spectrum. Therefore, we estimated the 21-MeV peak yield in the singles spectrum by assuming for simplicity a constant underlying continuum of the minimum yield around E_x=15 MeV. By comparing the coincidence yield with the singles yield for the 21-MeV peak, a branching ratio to the $t+{}^3$He binary decay was estimated to be about 0.8±0.2. A large branching ratio is strong evidence for the trinucleon cluster structure of the 21-MeV state in ^{6}Li.

Akimune *et al.* observed a $t+t$ cluster resonance at E_x=18.0±0.2 MeV with Γ=7.7±1.0 MeV in ^{6}He [10]. They suggested that the observed resonance is a ^3P (T=1) state by comparing their data with the RGM calculation for ^{6}He [3]. Based on the isospin symmetry, the ^3P state can commonly exist in all A=6 isobars, ^{6}He, ^{6}Li, and ^{6}Be. The analog of the ^3P resonance is expected to be excited at E_x=21.6 MeV in ^{6}Li. The width, 12 MeV, of the 21-MeV peak presently observed is found to be much broader than the width of the resonance observed in ^{6}He. Since the trinucleon cluster LS-coupling model [3,4] predicted not only ^3P (T=1) but also P (T=0) states for ^{6}Li, the broad peak observed at E_x=21 MeV seems to be composed of two resonances with $t+{}^3$He cluster configurations.

We investigated the spectral shape of the 21-MeV peak by assuming that this peak was composed of two resonances. The coincidence spectral shape of the 21-MeV peak in the coincidence spectrum was fitted by using the Breit-Wigner formula [13] with L=1, similar to the analysis described in Ref. [10]. The main decay of the 21-MeV resonance is expected to proceed via n, p, d, $t/{}^3$He, and α emissions. The total width $\Gamma_t=\Gamma_3+\Gamma'$ was assumed, where Γ_3 and Γ' are the partial width for $t/{}^3$He emission and the sum of partial widths for all the other particle emissions, respectively. Since the threshold energies for n, p, d, and α emissions are very low with respect to the threshold energy (E_{th}=15.8 MeV) for $t+{}^3$He decay in ^{6}Li and is much lower than the peak position of E_x=21 MeV, the width Γ' was assumed for simplicity to be constant in the fitting procedure, and a dimensionless reduced width θ^2 to be 1.0 for the resonances, as discussed in Ref. [10].

The result of the peak fitting is shown by the long-dashed curve in Fig. 1(a). The locations and widths presently obtained are summarized in Table I. Through the fitting procedure, we deduced the partial width Γ' to be 3±1 MeV. This result is consistent with a previous analysis wherein the Γ' deduced for the $t+t$ resonance in ^{6}He was estimated to be 3 MeV [10]. The branching ratio for $t+{}^3$He binary decay, Γ_3/Γ_t, averaged over the excitation energy region of the 21-MeV resonance up to 40 MeV is about 0.7. A large branching ratio shows that the 21-MeV resonance decays dominantly into $t+{}^3$He. This branching ratio is consistent with the branching ratio obtained from the spectral analysis of singles and coincidence spectra. Two $t+{}^3$He resonances at E_x=18.0±0.5 MeV with a width of 5.0±0.5 MeV and at 22±1 MeV with a width of 8±1 MeV as shown by the dashed and dot-dashed curves in Fig. 1(a), respectively, well reproduced the experimental spectral shape in the E_x=15–25 MeV range. In the higher excitation region of E_x=25–35 MeV, on the other hand, the fit to the data is relatively poor. This might be due to the excitation of other resonances with $L>1$ [3–7]. We fitted the spectral excess by assuming a resonance with a Gaussian shape around E_x=30 MeV. An additional resonance was deduced at E_x=29±2 MeV and with Γ=10±2 MeV as shown by a dotted curve in Fig. 1(a). The 29-MeV resonance is speculated to be the F resonance with the comparison from the LS-coupling cluster model [3].

We deduced two $t+{}^3$He cluster resonances at E_x=18.0±0.5 and 22±1 MeV in ^{6}Li by measuring t and ^{3}He

TABLE I. Excitation energies E_x and widths Γ for ($t+{}^3$He) resonant states ${}^{2S+1}L_J$ in ^{6}Li.

${}^{2S+1}L_J$	$t+{}^3$He cluster model RGM[b]		$t+{}^3$He cluster model CSRGM[c]		Mondragón's work[a]		Present work	
	E_x (MeV)	Γ (MeV)	E_x (MeV)	Γ (MeV)	E_x (MeV)	Γ[d] (MeV)	E_x (MeV)	Γ[d] (MeV)
${}^1P_1$	21.3	6.9	17.1	4.4			18.0±0.5	5.0±0.5
${}^3P_{0,1,2}$	22.3	9.3	16.9	5.5	17.985±0.025[e]	3.0	22±1	8±1
${}^1F_3$	28.8	5.9	25.9	9.5				
							29±2[h]	10±2
${}^3F_{2,3,4}$	29.8	7.5	26.3	11.2	24.8～26.6[f]	5.3～8.7		

[a]Reference [8].
[b]Reference [3]. Theoretical prediction based on the resonating group method (RGM).
[c]Reference [4]. Theoretical prediction based on the complex-scaled resonating group method (CSRGM).
[d]The width is a full width at half maximum.
[e]For the 2^-state of ${}^3P$ [8].
[f]For the 2^-, 3^-, and 4^- states of ${}^3F$ [8].
[h]L value was not deduced.

decay-particles in the (^{3}He, α) reaction on ^{7}Li. Both resonances are assigned to be P states from their angular correlations. The location and width of the 22-MeV resonance correspond well to those of the analog of the resonance observed at $E_x=18$ MeV in ^{6}He [10]. Therefore, the 22-MeV resonance is assigned to be a ${}^3P$ state. The 18-MeV resonance observed in ^{6}Li, on the other hand, has not been observed as an analog around $E_x=15$ MeV in ^{6}He [10]. Therefore, we assign the 18-MeV resonance to be a ${}^1P$ ($T=0$) state. The excitation energies of $t+{}^3$He cluster resonances are compared with the theoretical results [3,4,8] in Table I. The excitation energy of the ${}^3P$ state presently deduced is in contradiction to Mondragón's work [8] and the CSRGM calculation [4], and is rather consistent with the RGM calculation [3]. The excitation energy of the ${}^1P$ state, on the other hand, is in contradiction to the RGM calculation [3], and is rather consistent with the CSRGM calculation [4].

The separation energy of a doublet of ${}^1P$ and ${}^3P$ states presently deduced is about 4 MeV. In the trinucleon cluster model [3,4] for ^{6}Li, two states with $L=1$ were predicted as a doublet of ${}^1P$ and ${}^3P$ states which are separated at most by about 1 MeV. The existing theoretical models do not predict the observed separation energy.

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