α cluster states in ^{44,46,52}Ti

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α decaying states of ^{44,46,52}Ti were investigated with angular correlation functions between t and α with the ^{40,42,48}Ca(^{7}Li,$t\alpha$)^{40,42,48}Ca reactions at $E = 26.0$ MeV. Many α cluster states were newly observed in the 10–15 MeV excitation energy of ^{44}Ti and their spin-parities were assigned, in which $J^\pi = 7^-$ state was found at 11.95 MeV as a candidate for the member of the $K = 0_1^-$ negative parity band. In ^{46}Ti many α cluster states were also found in the 11–17 MeV excitation energy with the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca reaction, though its strength is weak compared with ^{44}Ti. No α cluster states were detected for the ^{48}Ca(^{7}Li,$t\alpha$)^{48}Ca reaction, in which the number of coincidence events decaying from ^{48}Ca was very small.

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I. INTRODUCTION

The α cluster model plays an important role in the study of nuclear structure as well as the shell model and the collective model. It is especially important for understanding the structure of light nuclei such as ^{8}Be to ^{24}Mg in the decay threshold energy region [1,2]. To study α clusters in heavier nuclei many theoretical and experimental investigations have been performed focusing on ^{40}Ca and ^{44}Ti [3–5]. The negative parity $K = 0_1^-$ band with α cluster structure predicted by theoretical calculations [6–8] has been discovered using α transfer experiments [9,10].

Detailed experimental studies have been devoted to ^{44}Ti, which is a typical $4N$ nucleus in the fp shell, and the existence of 1^-, 3^-, and 5^- states of the $K = 0_1^-$ band has been reconfirmed [11,12]. It is interesting to explore the negative parity states with $J > 5$ of the $K = 0_1^-$ band, but it seems that the ^{40}Ca(^{6}Li,d)^{44}Ti reaction is not good at finding α cluster states at excitation energies above 10 MeV. This is because the continuous spectrum of deuterons produced as a result of the disintegration of ^{6}Li when bombarded against ^{40}Ca is large. On the other hand angle correlation reactions such as (^{6}Li,$d\alpha$) and (^{7}Li,$t\alpha$) are effective for investigating the α cluster structure in that highly excited region, as we showed in the study of the α cluster states in ^{38}Ar in Ref. [13]. Artemov *et al.* [14] also studied the excited energy region above 11 MeV in ^{44}Ti using the angle correlation reaction with the (^{6}Li,$d\alpha$) reaction but negative parity states with $J > 5$ were not found.

On the other hand it has been shown that extra valence neutrons play an important role in the stabilization of the α cluster structure for non-$4N$ nuclei. ^{46}Ti is an analog of ^{10}Be and ^{22}Ne for which it has been shown that the α cluster structure persists [15–20]. In ^{52}Ti a possible α cluster structure was discussed for the ground band from the viewpoint of unified description of structure and scattering of the $\alpha + {}^{48}$Ca system [21]. However, few experimental studies have been done in the highly excited energy region.

In the present paper the α cluster structures in ^{44}Ti, ^{46}Ti, and ^{52}Ti were investigated with the (^{7}Li,$t\alpha$) reaction.

II. EXPERIMENTAL PROCEDURE AND RESULTS

^{7}Li ions at 26-MeV incident energy from the Pelletron Accelerator at Kyoto University were bombarded against ^{40,42,48}Ca targets. The ^{40}Ca (150 μg/cm^2) target was prepared by evaporating natural Ca metal (^{40}Ca component 96.9%) on carbon foil. The ^{42}Ca (310 μg/cm^2) target was prepared by chemical vapor deposition from enriched (93.65%) ^{42}CaCO$_3$ on carbon foil. The ^{48}Ca (2.03 mg/cm^2) target was obtained by rolling enriched (97.80%) ^{48}Ca metal in dried pure Ar gas.

Tritons were detected by a detector telescope, which consisted of a 150-μm-thick silicon ΔE detector and a 2-mm-thick silicon E detector placed at an angle of 7.5° to the horizontal plane of the beam axis. The acceptance angle of the telescope was 1.5° in the scattering plane and its solid angle was 2.0 msr. A 120-μm-thick Al foil was placed in front of the ΔE detector to stop the ^{7}Li ions that were elastically scattered by the target. The α particles were detected in coincidence with the tritons by eight silicon photodiode detectors placed at eight angles between +103.2° and +173.2°. The aperture of each photodiode was 10 mm wide and 20 mm high. Its solid angle was 15.1 msr and the depletion layer was 300 μm. A 100-μm Solid State Detector (SSD) was used to monitor the variation of the beam intensity and the target thickness.

Figures 1 and 2 show the two-dimensional energy spectra of t-α coincidences from the ^{40}Ca target and ^{42}Ca target, respectively. In Fig. 1 the locus (a) is from the ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca(g.s.) reaction and the locus (b) is from the ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca*(3.35 MeV; 2_1^+) reaction. In Fig. 2 the locus (a) is from the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca(g.s.) reaction and the locus (b) is from the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca*(1.52 MeV; 2_1^+) reaction. In the case of the ^{48}Ca(^{7}Li,$t\alpha$)^{48}Ca reaction, the locus of t-α that came out from ^{52}Ti could not be discerned buried in the background data, though the thickness of the target was increased 13.5 times and the beam integration of ^{7}Li was increased to a factor of 1.5 compared with the ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca reaction. Figure 3 shows the energy spectrum of the tritons obtained from the ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca(g.s.) reaction. Figure 4 shows the energy spectra of the tritons from the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca(g.s.)

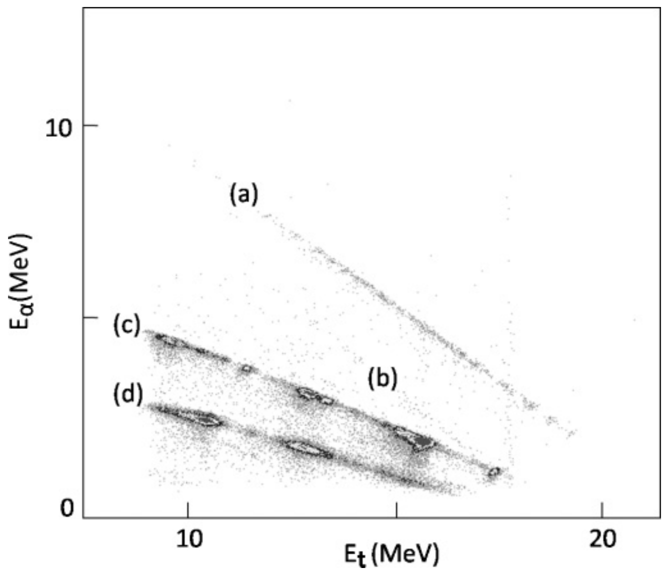

FIG. 1. Two-dimensional energy spectrum for the reaction ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca. Dots represent t-α coincident events with the photodiode at +173.2°. (a) Locus from the ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca(g.s.) reaction. (b) Locus from the ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca*(3.35 MeV; 2_1^+) reaction. (c) Locus from the ^{16}O(^{7}Li,$t\alpha$)^{16}O(g.s.) reaction. (d) Locus from the ^{12}C(^{7}Li,$t\alpha$)^{12}C(g.s.) reaction.

in the lower part and the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca(2_1^+) reactions in the upper part. The horizontal axes show the excitation energy of ^{44}Ti in Fig. 3 and ^{46}Ti in Fig. 4, and the vertical axes show the summed counts of the tritons detected with eight silicon photodiode detectors. The energy resolution of the triton was within 70 keV in both reactions. The number of

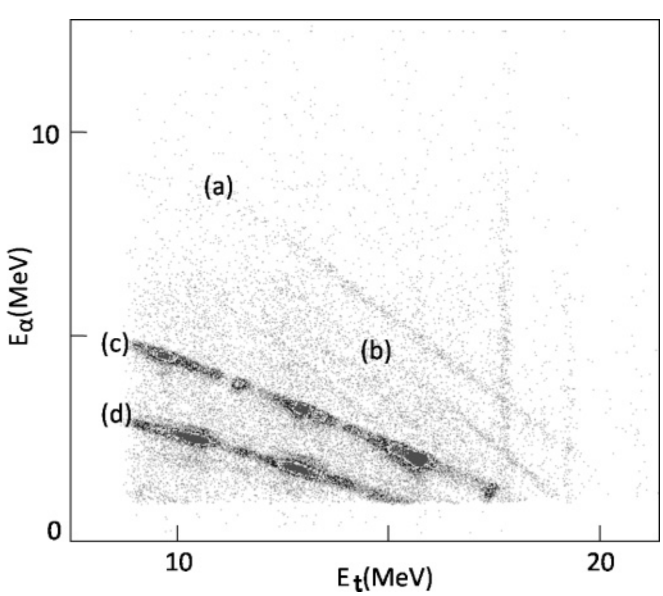

FIG. 2. Two-dimensional energy spectrum for the reaction ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca. Dots represent t-α coincident events with the photodiode at +173.2°. (a) Locus from the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca(g.s.) reaction. (b) Locus from the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca*(1.52; 2_1^+) reaction. (c) Locus from the ^{16}O(^{7}Li,$t\alpha$)^{16}O(g.s.) reaction. (d) Locus from the ^{12}C(^{7}Li,$t\alpha$)^{12}C(g.s.) reaction.

t-α coincidence events decaying from ^{40}Ca(2_1^+) is very small compared with that from ^{40}Ca(g.s.). In contrast the number of $t-\alpha$ coincidence events decaying from ^{42}Ca(2_1^+) is larger than that from ^{42}Ca(g.s.) by a factor of 1.5.

III. ANALYSIS AND DISCUSSION

Figures 5 and 6 show the angular correlation distributions of the levels excited in the ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca(g.s.) reaction. The experimental data have been fitted with the squares of the Legendre polynomial $|P_L(\cos\theta)|^2$. Figures 7 and 8 show the angular correlation distributions of the levels excited in the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca(g.s.) reaction.

In our present correlation experiment the detection angle of the triton was fixed at $\Theta_{\text{lab}} = 7.5°$. When the triton is detected at angles other than 0°, it is known that the angular distribution patterns of the α particle shift from 180° symmetry in the center-of-mass system in the reaction plane, because the wave function of the triton is distorted in the exit channel of the reaction. The amount of this angle shift tended to decrease with the increase of the excitation energy of the α-emitting nucleus [22,23]. In the present experiment, the shift also decreased linearly from +7° as the excitation energy of the ^{44,46}Ti nuclei got higher. In fitting our experimental data the amount of the shift calculated from that linear relationship was used.

A. ^{44}Ti

Figure 9 shows the energy levels of ^{44}Ti above α decay threshold that have been observed up to now in α transfer reactions. Yamaya *et al.* [9,11] used the (^{6}Li,d) reaction with incident energies of 50 [9] and 37 MeV [11]. Similarly, Guazzoni *et al.* [12] used the (^{6}Li,d) reaction with an incident energy of 60.1 MeV. In those experiments no levels could be obtained above 11 MeV. Meanwhile Artemov *et al.* [14] performed the (^{6}Li,$d\alpha$) correlation experiment with an incident beam of 22 MeV and reported some α cluster states and bands in the excitation energy range of 11–16 MeV, though they did not mention the structures below 11 MeV. We have found more than 20 α cluster states with the (^{7}Li,$t\alpha$) reaction and our results are compared with those of others as follows.

(i) 7.01 and 7.56 MeV. Because the threshold level of discriminators of the particle-detecting system reduced the α yields, we could not obtain angular correlation distributions of these states. However these states show clear peaks as seen in Fig. 3, although there may be some levels scattered around 7.56 MeV. We concluded these states are α cluster states that correspond to the ones found by Yamaya *et al.* [9,11] and Guazzoni *et al.* [12].

(ii) 8.20 MeV. This is the lowest excited state that could be fitted with the angular correlation function and we assigned its spin-parity as $J^\pi = 1^-$ or 2^+. Yamaya *et al.* [9,11] and Guazzoni *et al.* [12] found $J^\pi = 1^-$ state at 8.17 and 8.18 MeV, respectively. We may conclude the present state corresponds to those levels.

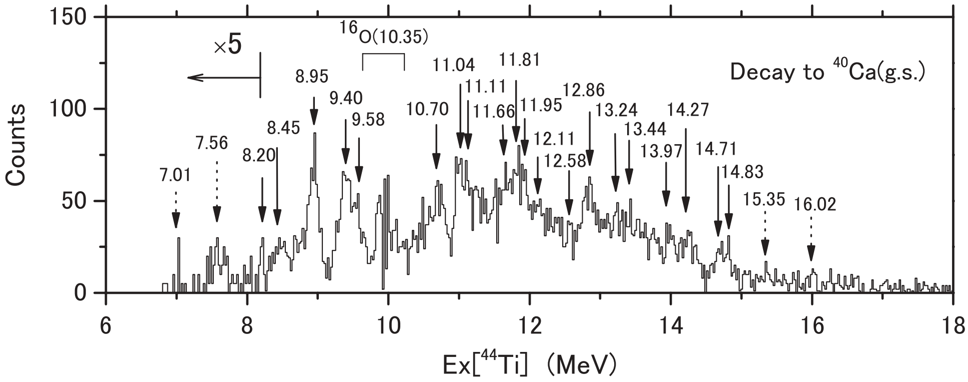

FIG. 3. Spectrum of t-α coincidences from the ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca reaction. The counts are the sum of the events from the eight photodiode detectors. Peaks fitted with $|P_L(\cos\theta)|^2$ are indicated by solid arrows. Data below 8.25 MeV in the excitation energy are multiplied by a factor of five.

(iii) 8.45 MeV. We could assign its spin-parity to $J^\pi = 3^-$, though we detected a weak peak on the shoulder of this state. Meanwhile Yamaya *et al.* [9,11] assigned $J^\pi = 3^-$ to this state and they also found the state with $J^\pi = 2^+$ or 3^- at 8.54 MeV. In addition Guazzoni *et al.* [12] found $J^\pi = 3^-$ state at 8.38 and 8.54 MeV.

(iv) 8.95 MeV. This is a strongly activated state as seen in Fig. 3 and we assigned the spin-parity to $J^\pi = 4^+$. Yamaya *et al.* [9,11] found the 8.96-MeV state whose spin-parity was assigned to $J^\pi = 2^+$, whereas Guazzoni *et al.* [12] found the 8.95 MeV state with $J^\pi = 4^+$.

(v) 9.40 MeV. It is also a strongly excited state whose peak width is a little broadened and we assigned its spin-parity as $J^\pi = 5^-$. We could fit it with the $L = 5$ angular correlation function very well, though it may consist of two levels, indicating that it is the same 5^- level at 9.43 MeV found by Yamaya *et al.* [9,11] and Guazzoni *et al.* [12].

(vi) 9.58 MeV. This state was well fitted with $L = 5$ and assigned to be a $J^\pi = 5^-$ level. This level is in good agreement with Yamaya *et al.* [9,11].

(vii) 10.70 MeV. We assigned its spin-parity to be $J^\pi = 4^+$.

(viii) 11.04 MeV. It is a newly found level and we assigned its spin-parity to $J^\pi = 4^+$.

(ix) 11.11 and 11.66 MeV. We assigned the spin-parities of these states to $J^\pi = 5^-$ or 6^+, and $J^\pi = 3^-$, respectively.

(x) 11.81 MeV. We assigned the spin of this state to $J^\pi = 4^+$ or 5^- whereas Artemov *et al.* [14] assigned it to $J^\pi = 1^-$.

(xi) 11.95 MeV. This newly found state was assigned to be a $J^\pi = 7^-$ level, because the phase pattern is reproduced better by $L = 7$, though $L = 4$ improves the fit in the angles larger than 150°. It seems to correspond to the 7^- state of the $K = 0_1^-$ band predicted around 12.4 MeV in Ref. [6].

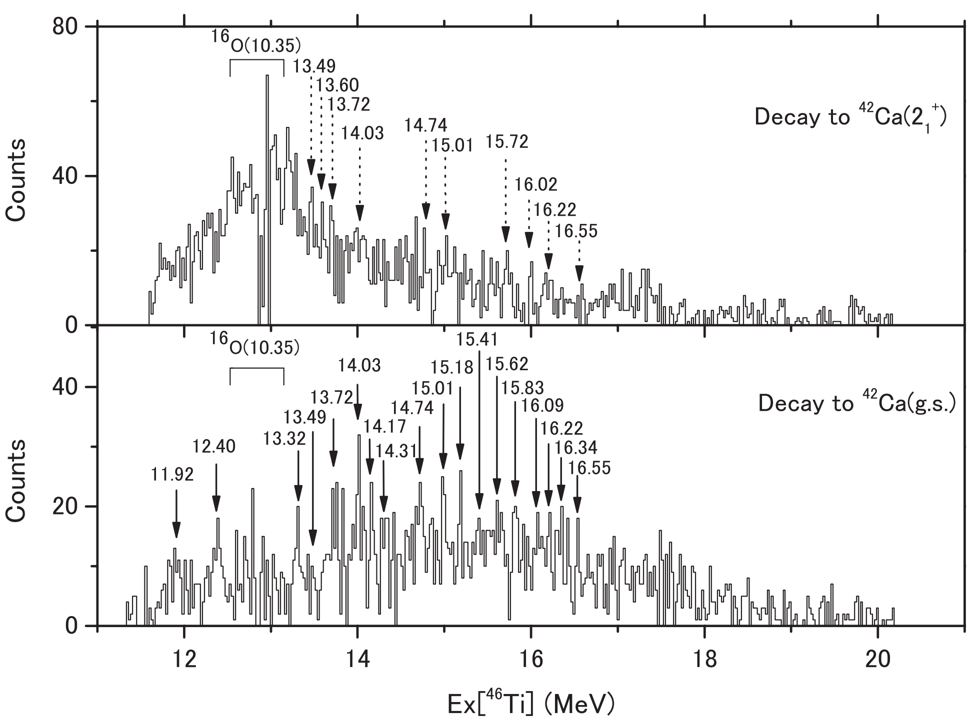

FIG. 4. Spectra of t-α coincidences from the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca reaction. The upper part is from that decaying to the first excited state (1.524 MeV, 2_1^+) of ^{42}Ca. The lower part is from that decaying to the ground state of ^{42}Ca. Both counts are the sum of the events from the eight photodiode detectors. Peaks fitted with $|P_L(\cos\theta)|^2$ are indicated by solid arrows.

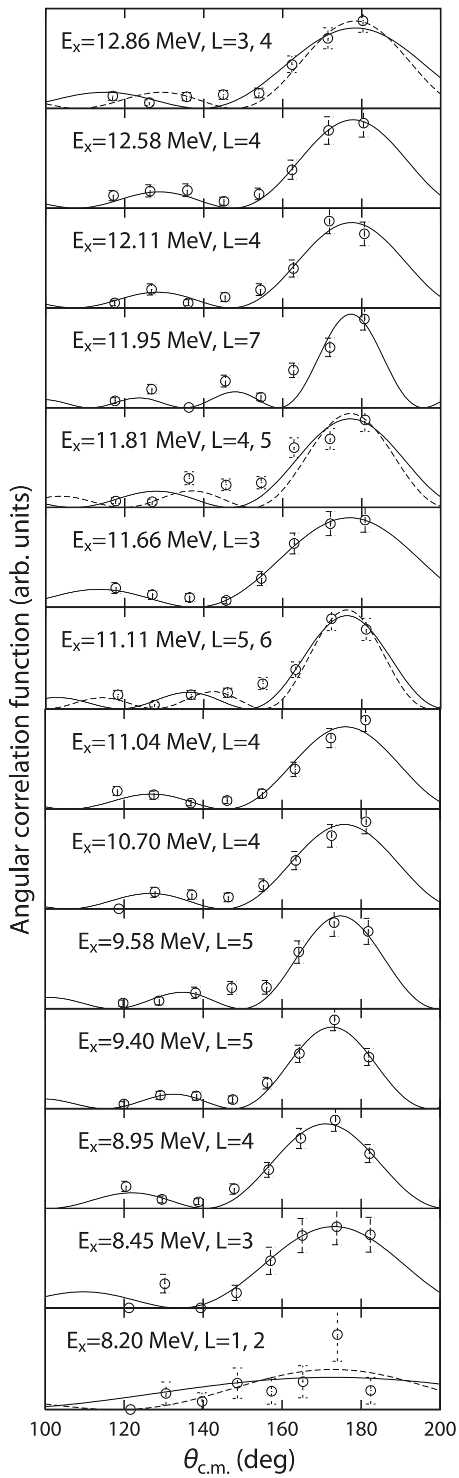

FIG. 5. Angular correlation functions at $E_x(^{44}\mathrm{Ti}) = 8.20$, 8.45, 8.95, 9.40, 9.58, 10.70, 11.04, 11.11, 11.66, 11.81, 11.95, 12.11, 12.58, and 12.86 MeV. The solid lines are the best $|P_L(\cos\theta)|^2$ fits to the data. The dashed lines show the second best fits in case it is difficult to obtain unique L values.

(xii) 12.11 and 12.58 MeV. These states were well fitted with $L = 4$ and assigned to $J^\pi = 4^+$.

(xiii) 12.86 MeV. This is estimated to be either $J^\pi = 3^-$ or 4^+. Artemov *et al.* [14] found a $J^\pi = 3^-$ state at 12.86 MeV, and the present state may correspond to that state.

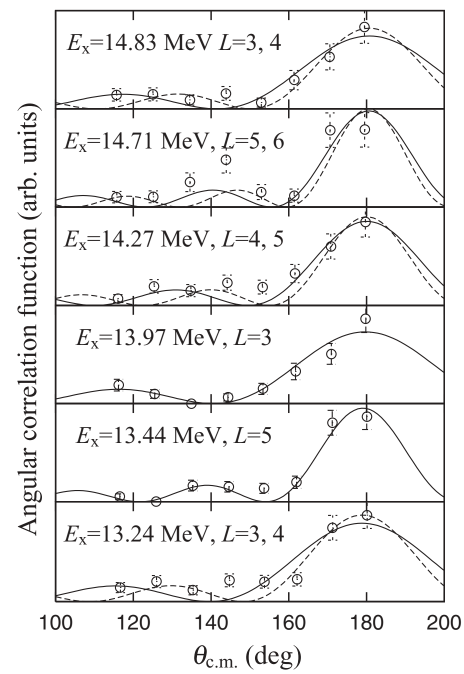

FIG. 6. Angular correlation functions at $E_x(^{44}\mathrm{Ti}) = 13.24$, 13.44, 13.97, 14.27, 14.71, and 14.83 MeV. The solid lines are the best $|P_L(\cos\theta)|^2$ fits to the data. The dashed lines show the second best fits in the case it is difficult to obtain unique L values.

(xiv) 13.24 MeV. This is also estimated to be either $J^\pi = 3^-$ or 4^+.

(xv) 13.44 MeV. This state was well fitted with $L = 5$ and we assigned its spin-parity to $J^\pi = 5^-$. However, Artemov *et al.* [14] reported the state of $J^\pi = 4^+$ around 13.42 MeV.

(xvi) 13.97 MeV. We assigned the spin-parity of this state to $J^\pi = 3^-$. This state corresponds well to the $J^\pi = 3^-$ state of the higher nodal $K = 0_2^-$ band with the well-developed $\alpha + {}^{40}\mathrm{Ca}$ cluster structure discussed by Ohkubo *et al.* [8].

(xvii) 14.27 MeV. We assigned the spin-parity of this state to $J^\pi = 4^+$ or $J^\pi = 5^-$. Because the state has a clear peak and it is apart from the $J^\pi = 5^-$ state found by Artemov *et al.* [14], it cannot correspond to the state with a wide energy width of 14.5–14.9 MeV.

(xviii) 14.71 and 14.83 MeV. These states are estimated to be $J^\pi = 5^-$ or 6^+, and $J^\pi = 3^-$ or 4^+, respectively. The present levels lie in a broad band centering on the excitation energy of 14.7 ± 0.2 MeV for which Artemov *et al.* [14] assumed $J^\pi = 5^-$.

(xix) 15.35 and 16.02 MeV. The yields at these states were too small to obtain L values from the angular correlation distributions. The $J^\pi = 6^+$ band at 15.9–16.3 MeV denoted by Artemov *et al.* [14] is the only excited state that has been reported above 15 MeV. The present states with narrow peaks may show that the band $J^\pi = 6^+$

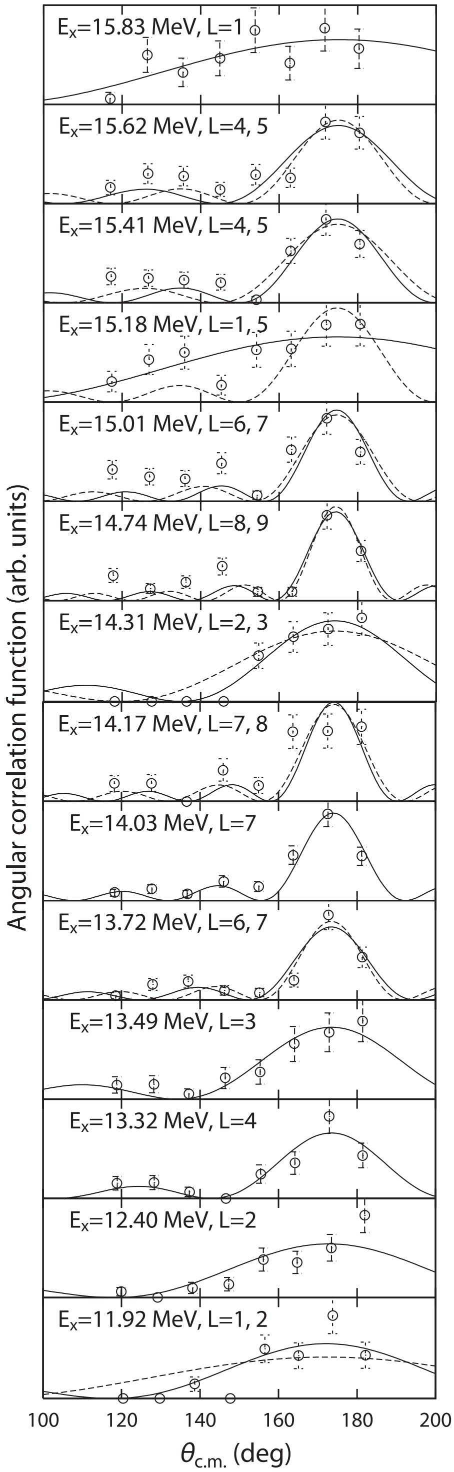

FIG. 7. Angular correlation functions at $E_x(^{46}\mathrm{Ti}) = 11.92$, 12.40, 13.32, 13.49, 13.72, 14.03, 14.17, 14.31, 14.74, 15.01, 15.18, 15.41, 15.62, and 15.83 MeV. Data are from the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ti(g.s.) reaction. The solid lines are the best $|P_L(\cos\theta)|^2$ fits to the data. The dashed lines show the second best fits in the case it is difficult to obtain unique L values.

state is fragmented in this area if the report by Artemov *et al.* [14] is correct.

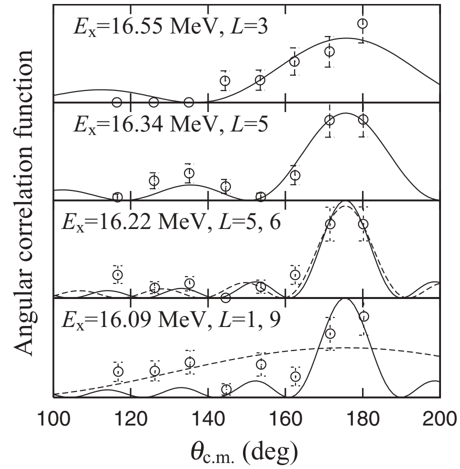

FIG. 8. Angular correlation functions at $E_x(^{46}\mathrm{Ti}) = 16.09, 16.22,$ 16.34, and 16.55 MeV. Data are from the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ti(g.s.) reaction. The solid lines are the best $|P_L(\cos\theta)|^2$ fits to the data. The dashed lines show the second best fits in case it is difficult to obtain unique L values.

B. ^{46}Ti

It has been shown that α clustering persists in neutron-rich nuclei, for example, in ^{10}Be [15,16] with the two valence neutrons added to the $\alpha + \alpha$ cluster structure in the $0p$-shell region and in ^{22}Ne in which two valence neutrons are added to the $\alpha + {}^{16}$O cluster structure in the sd-shell region [16,18–20]. It is very interesting to study to what extent the α clustering persists in the fp-shell region when the extra valence neutrons are added to the typical nucleus ^{44}Ti with the $\alpha + {}^{40}$Ca cluster structure. ^{46}Ti, for which few experimental and theoretical α cluster studies have been devoted, is an analog of ^{22}Ne. Although many excited states of ^{46}Ti have been reported below 10 MeV, the purposes of those experiments were not to investigate whether ^{46}Ti shows the ^{42}Ca $+ \alpha$ structure. An α transfer experiment with the (^{6}Li,d) reaction was reported in Ref. [24]. However, only the ground state and the first excited state of ^{46}Ti were examined.

The present angular correlation experiment is the first to investigate the α cluster structure of ^{46}Ti. Table I shows the observed α cluster states in ^{46}Ti with the spin assignments obtained from the analysis given in Figs. 7 and 8.

We may conclude that the present excited states with natural parities have the $\alpha + {}^{42}$Ca(g.s.) or $\alpha + {}^{42}$Ca(2_1^+) structure in ^{46}Ti, although α strengths are not as strong as in ^{44}Ti. On the other hand the main feature of the present ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca reaction is that the decay to the 2_1^+ state of ^{42}Ca was stronger than to the ground state unlike the ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca reaction. Because almost the same number of states are excited in ^{44}Ti and ^{46}Ti in the relevant energy region, α cluster structure in ^{46}Ti may be analogous to ^{44}Ti. Since the core ^{42}Ca is soft compared with the core ^{40}Ca, the two α cluster structures with the $\alpha + {}^{42}$Ca(g.s.) and $\alpha + {}^{42}$Ca(2_1^+) configurations may coexist in ^{46}Ti in the relevant energy region.

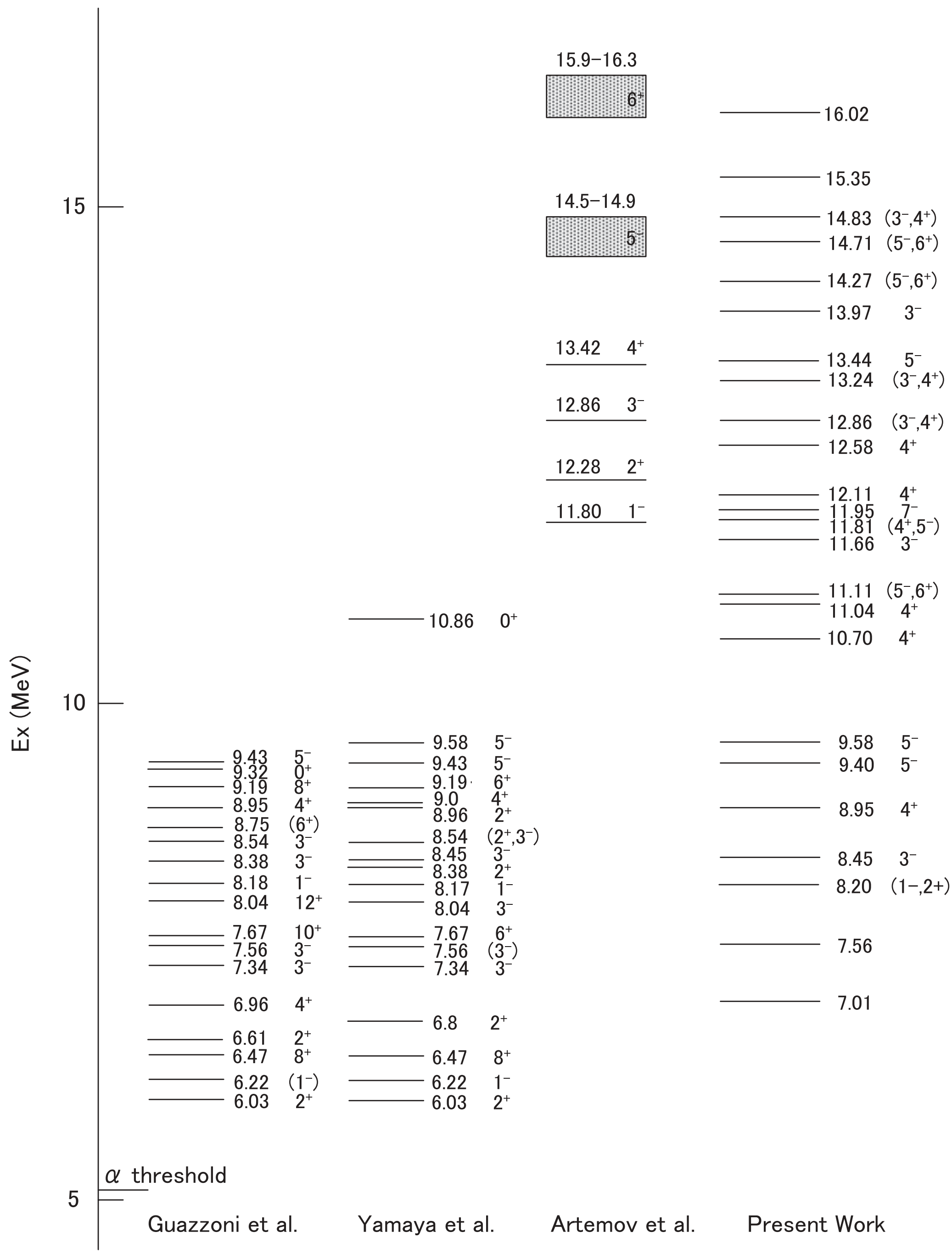

FIG. 9. Energy levels of ^{44}Ti observed in the ^{40}Ca(^{6}Li,d)^{44}Ti reaction by Guazzoni *et al.* [12] as well as Yamaya *et al.* [9,11], the ^{40}Ca(^{6}Li,$d\alpha$)^{40}Ca reaction by Artemov *et al.* [14], and the present ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca reaction are shown.

C. ^{52}Ti

The ^{40}Ca–^{48}Ca nuclei are isotopes with $Z = 20$, in which neutrons fill the $0f_{7/2}$ shell as the mass number increases from $A = 40$ to 48, until ^{48}Ca becomes a doubly closed nucleus. The persistency of α clustering in such nuclei is an interesting theme. Although there are some experiments that have measured the ground band for ^{52}Ti [24–26], it is important to explore the cluster state in the higher excited energy region using the correlation method.

To examine the α cluster structure of ^{52}Ti, we performed the ^{48}Ca(^{7}Li,t)^{52}Ti(α)^{48}Ca reaction experiment using thin ^{48}Ca metal targets deposited onto thin carbon foils. However, no yield was obtained in spite of a long machine time. In the following experiment a thick ^{48}Ca target made by pressing ^{48}Ca metal was used. Nevertheless, the cross section of the α cluster transfer reaction that produced ^{52}Ti was extremely small and no excited states were obtained. In Table II the variation of the relative cross sections in the (^{7}Li,$t\alpha$)

TABLE I. Excited states in ^{46}Ti with adopted J^π.

Decay mode	Excited energy (MeV)	J^π
g.s.	11.92	$(1^-, 2^+)$
	12.40	2^+
	13.32	4^+
	13.49	3^-
	13.72	$(6^+, 7^-)$
	14.03	7^-
	14.17	$(7^-, 8^+)$
	14.31	$(2^+, 3^-)$
	14.74	$(8^+, 9^-)$
	15.01	$(6^+, 7^-)$
	15.18	$(1^-, 5^-)$
	15.41	$(4^+, 5^-)$
	15.62	$(4^+, 5^-)$
	15.83	1^-
	16.09	$(1^-, 9^-)$
	16.22	$(5^-, 6^+)$
	16.34	5^-
	16.55	3^-
2_1^+	13.49	
	13.60	
	13.72	
	14.03	
	14.74	
	15.01	
	15.72	
	16.02	
	16.22	
	16.55	

reaction targeting on ^{40}Ca, ^{42}Ca, and ^{48}Ca is shown. The cross sections there correspond to the coincidence events between the triton detectors in $\Theta_L = 7.5^\circ$ and the eight α detectors, and not the total cross section. The strengths of 5.6% in the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca(g.s.) reaction and 8.4% in the ^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca(2_1^+) reaction were obtained when the strength in the ^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca(g.s.) reaction was assumed to be 1.0. In contrast the strength in the ^{48}Ca(^{7}Li,$t\alpha$)^{48}Ca reaction was only 0.14% or less. This suggests that the α clustering is more suppressed in ^{52}Ti nuclei the more extra neutrons are added filling the $0f_{7/2}$ shell.

TABLE II. Relative ratio of the reaction cross sections.

Reaction	$\frac{d\sigma}{d\Omega}$ (arb. unit)	Relative ratio
^{40}Ca(^{7}Li,$t\alpha$)^{40}Ca(g.s.)	$3.6 \pm 0.04 \times 10^{-3}$	1.0
^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca(g.s.)	$2.02 \pm 0.69 \times 10^{-4}$	0.056
^{42}Ca(^{7}Li,$t\alpha$)^{42}Ca(2_1^+)	$3.02 \pm 0.84 \times 10^{-4}$	0.084
^{48}Ca(^{7}Li,$t\alpha$)^{48}Ca(g.s.)	$\ll 5.2 \times 10^{-6}$	$\ll$0.0014

IV. CONCLUSION

Angular correlation experiments with the (^{7}Li,$t\alpha$) reaction were performed using ^{40}Ca, ^{42}Ca, and ^{48}Ca targets to investigate the α cluster states of ^{44}Ti, ^{46}Ti, and ^{52}Ti nuclei.

For ^{44}Ti 24 α cluster states were observed in the excitation energy range of 7–16 MeV. We could uniquely assign spin-parities to the eight states at 10.70 MeV (4^+), 11.04 MeV (4^+), 11.66 MeV (3^-), 11.95 MeV (7^-), 12.11 MeV (4^+), 12.58 MeV (4^+) 13.44 MeV (5^-), and 13.97 MeV (3^-) as newly found α cluster levels, in which the state at 11.95 MeV (7^-) seems to correspond to the $J^\pi = 7^-$ state of the $K = 0_1^-$ band predicted in Ref. [6] but not observed in the (^{6}Li,d)α transfer reactions [9,11,12]. The seven states at 11.11 MeV ($5^-, 6^+$), 11.81 MeV ($4^+, 5^-$), 12.86 MeV ($3^-, 4^+$), 13.24 MeV ($3^-, 4^+$), 14.27 MeV ($4^+, 5^-$), 14.71 MeV ($5^-, 6^+$), and 14.83 MeV ($3^-, 4^+$) are also α cluster levels that had not been discovered in other studies, though some uncertainties remain for the spin assignments in the present study. The state at 8.20 MeV (1^-, 2^+) may correspond to the (1^-) states at 8.17 and 8.18 MeV reported for other experiments [9,11,12]. The states at 8.45 MeV ($J^\pi = 3^-$), 8.95 MeV (4^+), 9.40 MeV (5^-), and 9.58 MeV (5^-) are in good agreement with the states at 8.45, 8.96, 9.43, and 9.58 MeV reported by Yamaya *et al.* [9,11]. Spins could not be assigned to the two states at 7.01 and 7.56 MeV in lower excitation energy and the two states at 15.35 and 16.02 MeV in higher excitation energy, because the number of coincidence events was too small to obtain L values with the angular correlation functions.

For ^{46}Ti many candidates of the α cluster state are found in the excitation energy range of 11–17 MeV by the reactions that decay to the ground state and the first excited state of ^{42}Ca. Spin-parities of the seven states were uniquely assigned at 12.40 MeV (2^+), 13.32 MeV (4^+), 13.49 MeV (3^-), 14.03 MeV (7^-), 15.83 MeV (1^-), 16.34 MeV (5^-), and 16.55 MeV (3^-). We also made assignments with some ambiguities to the eleven states at 11.92 MeV ($1^-, 2^+$), 13.72 MeV ($6^+, 7^-$), 14.17 MeV ($7^-, 8^+$), 14.31 MeV ($2^+, 3^-$), 14.74 MeV ($8^+, 9^-$), 15.01 MeV ($6^+, 7^-$), 15.18 MeV ($1^-, 5^-$), 15.41 MeV ($4^+, 5^-$), 15.62 MeV ($4^+, 5^-$), 16.09 MeV ($1^-, 9^-$), and 16.22 MeV ($5^-, 6^+$).

For ^{52}Ti no peaks could be detected in the energy spectrum of t-α coincidences from the ^{48}Ca(^{7}Li,$t\alpha$)^{48}Ca reaction owing to very scarce coincidence events.

The variation of the (^{7}Li,$t\alpha$) reaction cross section with the increase of neutrons in the Ca target was investigated with three Ca isotopes. The relative α strength for the ^{42}Ca target was about one-tenth that for the ^{40}Ca target and in the case of ^{48}Ca its upper limit was 0.14%. This shows that the increase of neutrons weakens the structure of the α cluster in ^{52}Ti nuclei.

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