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Study of the Level Structure of ^{48}Ti Using the ^{47}Ti(n, γ) Reaction

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The capture γ-ray spectrum resulting from thermal-neutron capture in ^{47}Ti has been measured using a 30-cm^3 Ge(Li) detector and angular-correlation measurements carried out using NaI(Tl) detectors. Some 28 γ lines corresponding to transitions between levels of ^{48}Ti were observed, and the neutron separation energy of ^{48}Ti was determined to be 11.630 ± 0.008 MeV. The following assignments of spins and parities for some levels were made: 2.422(1^+, 2^+, 3^+), 3.626(2^+, 4^+), 3.794(2^+, 3^+, 4^+), and 4.467(2^+, 3^+). The results of a comparison between the measured strengths of exciting the ^{48}Ti levels in the (n, γ) and (d, p) reactions are discussed.

I. INTRODUCTION

In a previous paper[1] we have reported the results from the (n, γ) reaction on ^{46}Ti. In the present paper, the (n, γ) reaction on ^{47}Ti was used for investigating the energy levels of ^{48}Ti and for further studying the reaction mechanism of the (n, γ) process. The results are discussed in the light of recent studies made by other investigators. These studies employed the ^{47}Ti(d, p),[2] ^{46}Ti(t, p),[3] ^{50}V(d, α),[4] ^{48}Ti(α, α'),[5] ^{48}Ti(p, $p'\gamma$),[6] and the β decay of ^{48}V[7] for investigating structural properties and spins and parities of ^{48}Ti. In particular, using the (d, p) reaction, it was possible to identify all the single-particle states associated with the $2p_{3/2}$, $2p_{1/2}$ shells as well as other shells such as $1f_{7/2}$, $2d_{3/2}$, $3s_{1/2}$, and $1f_{5/2}$.

According to the simple shell model, the ground state of ^{47}Ti consists of two $1f_{7/2}$ protons and five $1f_{7/2}$ neutrons outside the ^{40}Ca doubly magic core. The five $1f_{7/2}$ neutrons may also be viewed as three neutron holes in the full $1f_{7/2}$ shell. Since the two protons are coupled to zero, the spin of the ground state is determined by three $1f_{7/2}$ hole neutrons, which couple to $J=\frac{5}{2}^-$. Thus, the ^{48}Ti state formed by s-wave thermal-neutron capture should be either 2^- or 3^-. It is therefore expected that only levels with $J^\pi=1^+$, 2^+, 3^+, and 4^+ in ^{48}Ti will be populated by primary $E1$ transitions from the capture state. It is interesting to note that levels with the same spins may also be easily populated by the ^{47}Ti(d, p) reaction through transitions, which lead to single-particle states having neutron configurations $1f_{7/2}^{-3}\,2p_{3/2}$ and $1f_{7/2}^{-3}\,2p_{1/2}$. As pointed out by Bockelman,[8] any correlation between the strength of primary γ transitions in the (n, γ) reaction and $l_n=1$ transitions in the (d, p) reaction, leading to the same levels, may be indicative of a direct mechanism process in the (n, γ) reaction.

The (n, γ) reaction on natural titanium was studied by Knowles *et al.*[9] using a magnetic pair spectrometer and a flat crystal diffraction spectrometer, and some results regarding ^{47}Ti(n, γ)^{48}Ti were obtained. In the present work, an enriched ^{47}Ti target was used together with a Ge(Li) detector to study the decay scheme of ^{48}Ti. Angular-correlation measurements were also carried out using NaI detectors, and the spins of some of the low-lying levels were measured.

II. EXPERIMENTAL ARRANGEMENT

The thermal-neutron beam was obtained from a tangential beam tube of the Israel Research Reactor-2 (IRR-2). A detailed account of the experimental arrangement has been given previously[1]; here only the details which are unique for the ^{47}Ti target will be mentioned. The thermal-neutron flux at the target position is $3\times10^6\ n/\text{cm}^2$ sec. The target consisted of 0.3 g of titanium oxide of isotopic composition 66% Ti^{47}, 1.4% Ti^{46}, 31.4% Ti^{48}, 0.7% Ti^{49}, and 0.5% Ti^{50}. This was inserted into a cylindrical perspex container 16 mm in diameter and 20 mm long with a wall thickness of 0.2 mm. For coincidence measurements a graphite container of the same dimensions was employed for reducing the number of background photons produced by the (n, γ) reaction in hydrogen present in the perspex container. Since the (n, γ) cross section of ^{47}Ti is 1.6 b and that of ^{48}Ti is 8.3 b, the ^{48}Ti(n, γ)^{49}Ti reaction represents a serious background to the reaction studied; the effect of the other isotopes is very small.

The γ-ray singles spectrum was measured with a 30-cm^3 coaxial Ge(Li) detector (Princeton Gamma-

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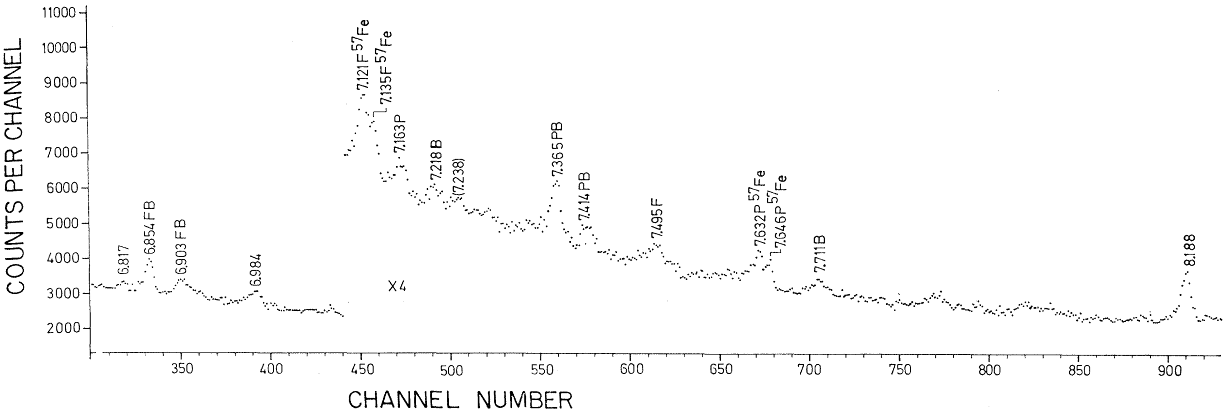

FIG. 1. Part of the γ spectrum from the ^{47}Ti$(n, \gamma)^{48}$Ti reaction using an enriched ^{47}Ti target measured with a 30-cm^3 coaxial Ge(Li) detector. Lines denoted by P and F correspond to photopeaks and first escape peaks; other lines correspond to double-escape peaks of the ^{47}Ti target. Background lines are marked with B. The origin of some lines was traced to ^{57}Fe.

Tech) placed 8 cm from the center of the target. The over-all resolution of this detector in conjunction with a biased amplifier and 1024-channel TMC analyzer in a typical run of several days was 12-keV full width at half-maximum (FWHM) at an energy of 7 MeV. The absolute energy calibration of the detector was carried out using the well-known capture γ lines of chlorine[10] and nitrogen,[11] and the capture line of hydrogen. For angular-correlation measurements, the same system described previously[1] was used. In particular, two NaI crystals were employed, a fixed crystal of 5×5 in. and a rotating crystal of 3×3 in. Moreover, the techniques of extracting useful information from the experimental results, including fitting and calculating the A_2/A_0 and A_4/A_0 ratios, were the same as those of Ref. 1.

III. RESULTS

A. Singles Spectrum

Part of the singles spectrum of the ^{47}Ti(n, γ) reaction measured with a 30-cm^3 Ge(Li) diode is shown in Fig. 1. Table I summarizes the energies and line intensities as measured here together with those reported earlier.[12] The lines marked with an asterisk are weak transitions not seen in the direct spectrum, but observed in the coincidence spectrum. A comparison of the present results with those reported in the literature shows the presence of new transitions and indicates a general agreement with the previously reported γ lines. There is, however, disagreement with the transitions reported[12] at 7.319, 7.550, and 8.252 MeV. Our singles γ spectrum gives no evidence of lines at 7.319 and 7.550 MeV. However, a line with an appreciable intensity at 7.582 MeV and another line of very weak intensity at 8.260 MeV were obtained.

B. Decay Scheme

The decay scheme of ^{48}Ti as constructed mainly from the results obtained in the present work is shown in

TABLE I. Measured γ-ray transitions and intensities for the ^{47}Ti$(n, \gamma)^{48}$Ti reaction; γ energies in parentheses are uncertain. The lines marked with an asterisk are weak transitions not seen in the singles spectrum but observed in the coincidence spectrum.

Present results		Earlier results[a]	
γ energy (MeV)	Relative intensity[b]	γ energy (MeV)	Relative intensity
(0.42*±0.003)			
0.943±0.003	1.5		
0.982±0.003	27.0	0.984	75
1.315±0.003	8.0		
1.440±0.003	4.7	1.438	65
1.497±0.003			
(2.04*±0.007)			
2.165±0.007			
2.385±0.007			
2.644±0.007	1.5		
2.80*±0.007			
3.485±0.007	1.6		
(3.745±0.007)			
(5.393±0.007)			
(5.477±0.007)			
5.584±0.007			
(5.637±0.007)			
6.480±0.007	0.6		
6.825±0.007	0.4		
7.163±0.007	2.3	7.149	15
(7.236±0.007)			
		7.319	20
7.582±0.007	0.2	7.550	2.0
7.839±0.007	0.2	7.844	1.5
8.006±0.007	0.7	7.996	4.0
(8.260±0.007)		8.252	9.5
(8.387±0.007)			
9.210±0.007	0.9	9.189	4.0
10.647±0.007	0.2	10.621	1.5

[a] Reference 12.

[b] Errors are about ±30%.

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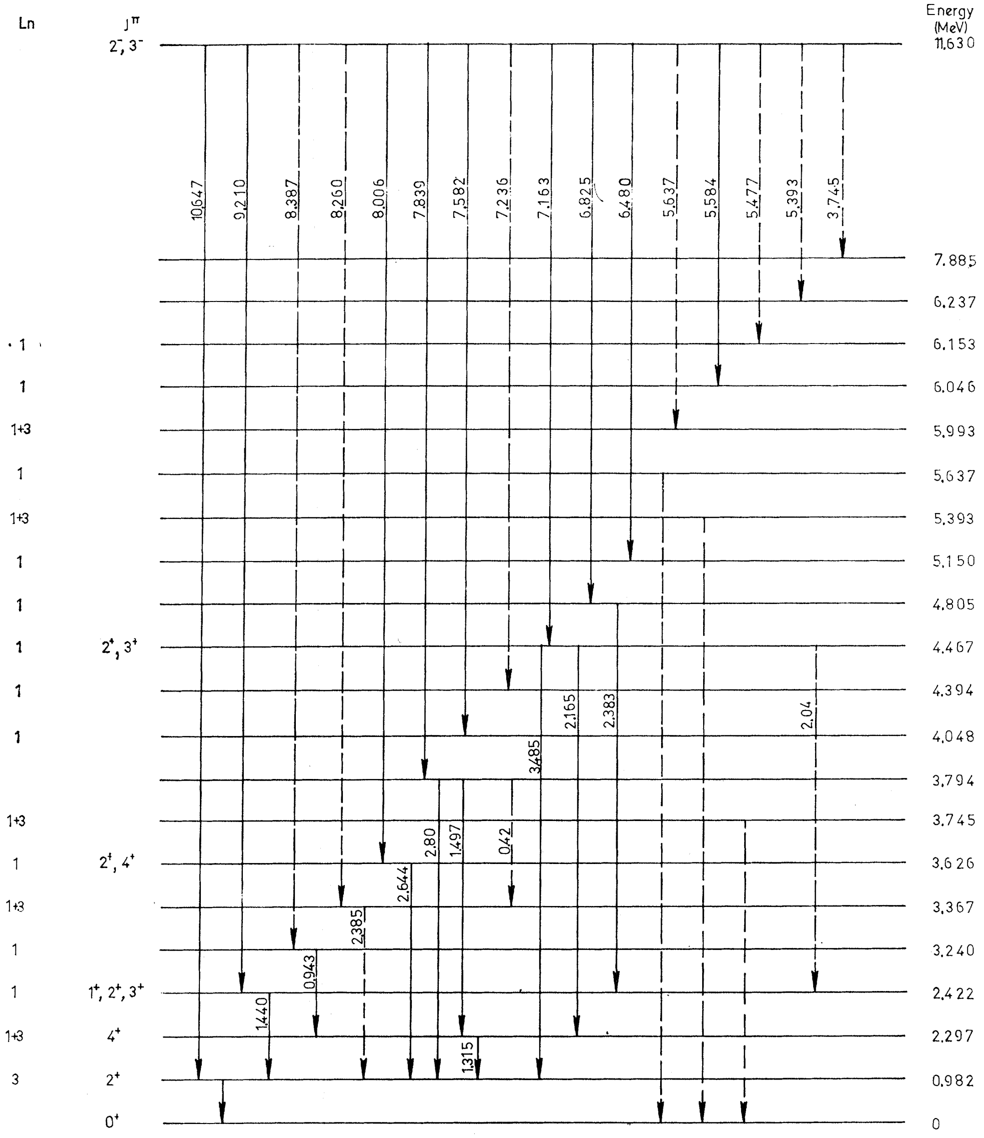

FIG. 2. Decay scheme of ^{48}Ti as obtained by measuring the singles and coincidence spectra in the ^{47}Ti(n,γ) reaction. The spin and parity assignments are the most probable values obtained in the present work; the l_n values were taken from Ref. 2. Dotted arrows denote uncertain γ transitions.

Fig. 2. The level energies may be seen to be in agreement with those obtained from the ^{47}Ti$(d,p)^{48}$Ti reaction.[2] It is interesting to note that all levels populated by strong γ lines were found to have $l_n=1$ angular distributions in the (d,p) reaction.

It was not possible to decide whether the four lines at 3.745, 5.393, 5.637, and 7.582 MeV are primary or secondary transitions. This is because levels of the same energies are known to exist in ^{48}Ti. In addition, levels at 7.885, 6.237, 5.993, and 4.048 MeV which correspond to energy differences between the capture state and the energies of the γ lines are also known to exist[2] in ^{48}Ti. It appears, however, that the 7.582-MeV line is a primary transition, because if one assumes that the $E1$ transition probability follows the E^3 law, then the 7.582-MeV γ line should be an order of magnitude more probable than an assumed 4.048-MeV primary transition.

The sum of the energies of the different cascades from the capture state to the ground state (not corrected for recoil energies) permitted an evaluation of the neutron separation energy of ^{48}Ti. The analysis gave a value of 11.630 ± 0.008 MeV in excellent agreement with the value of 11.628 ± 0.027 MeV reported earlier.[12]

C. Coincidence and Angular-Correlation Measurements

The γ coincidence spectra were measured using gates set for the following energy ranges (in MeV): (a) 10.35–

TABLE II. Angular-correlation results for ${}^{47}\text{Ti}(n,\gamma){}^{48}\text{Ti}$ reaction.

Cascade (MeV)	A_2/A_0	A_4/A_0	Intermediate level Energy (MeV)	J^π	Mixing parameter[a]	Capturing state spin contribution (%) 2^-	3^-
10.647–0.982	0.133 ± 0.043	···	0.982	2^+	$\delta=\infty$	37	63
9.210–1.440	-0.022 ± 0.025	···	2.422	1^+	$-0.23\leq\delta\leq-0.19$	100	0
				2^+	$0.30\leq\delta\leq0.38$	7–20	80–93
				3^+	$0.06\leq\delta\leq0.12$	34–55	45–66
9.210–0.982	0.011 ± 0.043[b]	···	0.982	2^+	···	···	···
8.006–2.644	-0.114 ± 0.050	···	3.626	2^+	$0.22\leq\delta\leq0.25$	2–10	90–98
				4^+	$\delta=\infty$	0	100
7.163–3.485	-0.033 ± 0.021	···	4.467	2^+	$0.28\leq\delta\leq0.31$	7–20	80–93
				3^+	$0.10\leq\delta\leq0.13$	3–50	50–97
1.440–0.982	-0.006 ± 0.027[c]	-0.004 ± 0.040[c]	0.982	2^+	$0.19\leq\delta\leq0.23$		
				2^+	$-0.38\leq\delta\leq-0.30$	···	···
				2^+	$-0.12\leq\delta\leq-0.06$		
2.644–0.982	0.056 ± 0.028	-0.002 ± 0.041	0.982	2^+	$-0.25\leq\delta\leq-0.22$	···	···
					$-0.31\leq\delta\leq-0.28$		
3.485–0.982	0.018 ± 0.007	0.010 ± 0.016	0.982	2^+		···	···
				2^+	$-0.13\leq\delta\leq-0.10$		

[a] A change of sign of δ appears in the last three cascades due to a change in the γ-ray order: S. Ofer, Phys. Rev. **114,** 870 (1959).

[b] This value was obtained after subtracting the contribution of the 10.639–0.982 cascade.

[c] This ratio was obtained after subtracting contributions from competing cascades entering this gate.

10.75, (b) 8.95–9.45, (c) 7.82–8.20, (d) 6.90–7.30, (e) 3.25–3.65, (f) 2.37–2.77, and (g) 1.25–1.57. These gates were chosen to correspond to the most intense lines in the singles spectrum. The ratio of the number of true to random coincidences was in general better than 8:1. In most cases where the contribution of the ^{48}Ti isotope was relatively high, it was necessary to carry out separate coincidence measurements using a natural TiO$_2$ target in order to permit a precise subtraction of the effect of the ${}^{48}\text{Ti}(n,\gamma)$ reaction. In almost all cases, angular-correlation measurements were taken at four angles: 90°, 120°, 150°, and 180°. As mentioned earlier, the ^{47}Ti ground state is $\frac{5}{2}^-$; therefore the ^{48}Ti state formed by thermal-neutron capture should be $J=2^-$ or 3^-. It is expected that mainly levels with $J=1^+$, 2^+, 3^+, and 4^+ should be populated via primary unmixed $E1$ transitions. The secondary transitions between low-lying levels are generally mixed; the $E2/M1$ mixing ratio δ was evaluated in the present measurements. In the following we deal with the coincidence spectra and angular-correlation measure-

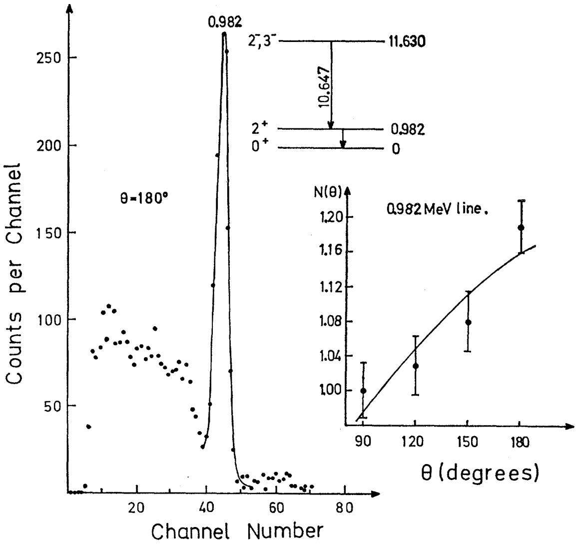

FIG. 3. γ spectra at 180° as measured with a 3×3-in. NaI crystal in coincidence with a 5×5-in. NaI crystal for the gate $10.35<E<10.75$ MeV. The angular distribution of the 0.982-MeV line relative to the 10.647-MeV line is also shown.

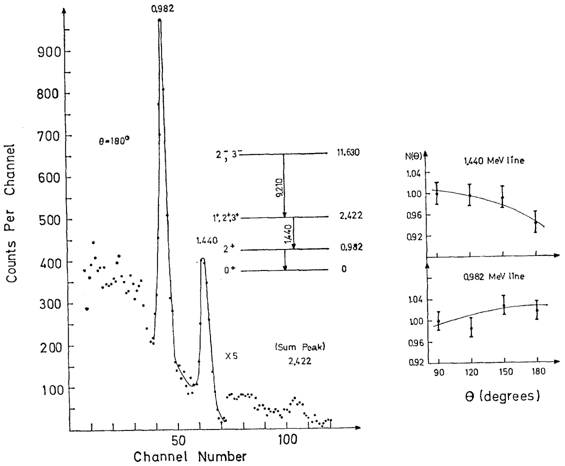

FIG. 4. γ spectra at 180° as measured with a 3×3-in NaI crystal in coincidence with a 5×5-in. NaI crystal for the gate $8.95<E<9.45$ MeV. The angular distribution of the 1.440- and 0.982-MeV lines relative to the 9.210-MeV line is also shown.

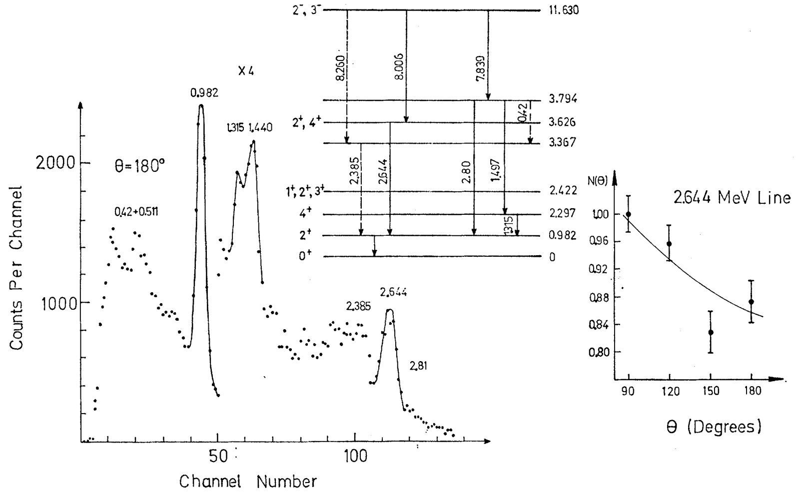

FIG. 5. γ spectra at 180° as measured with a 3×3-in NaI crystal in coincidence with a 5×5-in NaI crystal for the gate $7.82<E<8.20$-MeV. The angular distribution of the 2.644-MeV line relative to the 8.006-MeV line is also shown.

ments corresponding to each of the strong populated levels in the ^{47}Ti(n,γ) reaction.

1. 0.982-MeV Level

This level is populated by the 10.647-MeV line. Figure 3 shows the coincidence spectrum with the gate set on position (a); it also shows the angular-correlation measurement of the cascade 11.630→0.982→0. Since the 0.982-MeV level is known[2] to be 2^+, the results of the angular-correlation measurement may supply direct information regarding the relative contribution of the two spin components 4^- and 3^- of the capture state. In fact, by assuming pure $E1$ transition from the capture state to the 0.982-MeV, 2^+ level, the experimental angular correlation was found to be a mixture of the two possible sequences $2^-(1)2^+(2)0^+$ and $3^-(1)2^+(2)0^+$, with amplitudes of 0.4 and 0.6, respectively.

2. 2.422-MeV Level

This level is populated by the 9.210-MeV line. Figure 4 shows the coincidence spectrum with the gate set on position (b); it also shows the angular-correlation measurement of the two cascades: (i) 11.630→2.422→0.982 and (ii) 11.630→2.422→0.982→0, of which the transition 2.422→0.982 was treated as unobserved.[13]

It may be noted that the weak line at 2.422 MeV in the coincidence spectrum was found to correspond to the sum peak of 0.982 and 1.490 MeV and not to an independent branch. The fact that the 2.422-MeV level is populated directly from the capture state indicates that this level may be either 1^+, 2^+, 3^+, or 4^+. The 4^+ assignment may be excluded because the experimental angular correlation for cascade (i) is $1-(0.022\pm 0.025)p_2(\cos\theta)$ (Table II) which is not compatible with a $3^-(1)4^+(2)2^+$ correlation of the form $1-0.14p_2(\cos\theta)$.

An attempt was made to distinguish among the three spin possibilities 1^+, 2^+, and 3^+ by measuring the angular correlation of a third cascade: (iii) 4.422→0.982→0 [gate set on position (g)]. However, the various δ values (Table II) calculated from the experimental distribution (iii) corresponding to each one of these possible spins were found to be consistent with the experimental angular distributions of cascades (i) and (ii) when the contribution of the spin mixture in the capture state is taken into account. Thus, the present experiment was not able to distinguish among the three assignments 1^+, 2^+, and 3^+ for the 2.422-MeV level.

3. 3.367-, 3.626-, and 3.794-MeV Levels

These levels are populated by the 8.260-, 8.006-, and 7.839-MeV lines, respectively. Figure 5 shows the coincidence spectrum with the gate set on position (c), it also shows the angular-correlation measurement of the cascade (i) 11.630→3.626→0.982. By considering the coincidence spectrum, the decay scheme related to the three levels 3.367, 3.626, and 3.794 MeV was constructed (Fig. 5). From the decay scheme it may be concluded that the 3.794-MeV level may have one of the spin values 2^+, 3^+, or 4^+, the spin value 1^+ being excluded because this level decays to a 2^+ and a 4^+ level. The 1^+ assignment to the 3.626-MeV level can be excluded because there exist no δ values which give the experimental distribution of the 11.630→3.626→0.982 cascade (Table II). A 3^+ assignment to the 3.626-MeV level should also be excluded as may be seen by considering the results of the angular correlation of another cascade 3.626→0.982→0 [gate set at position (f)]. Assuming the 3.626-MeV level to be 3^+, the δ values calculated from this second angular correlation (Table II) were not compatible with the δ values obtained from the 11.630→3.626→0.982 correlation for any assumed

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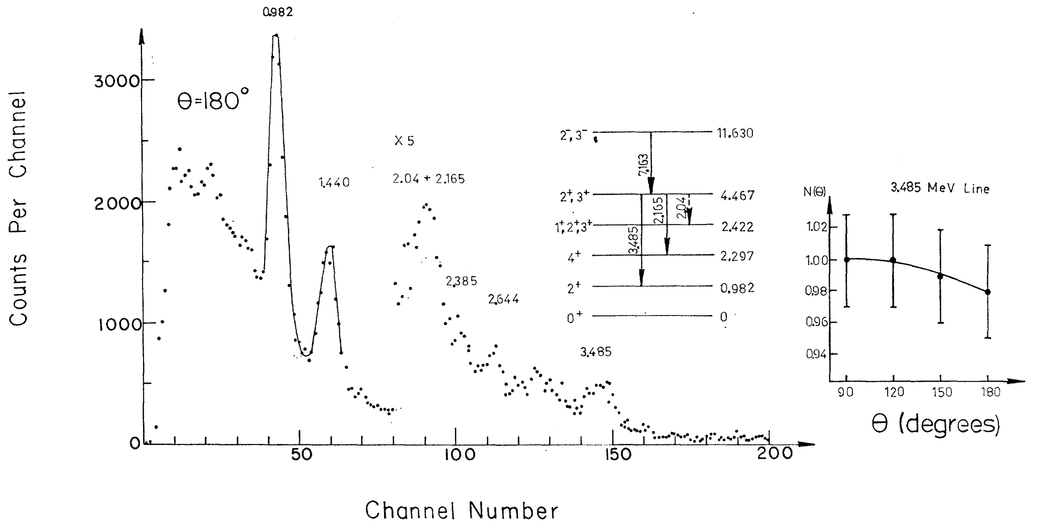

FIG. 6. γ spectra at 180° as measured with a 3×3-in. NaI crystal in coincidence with a 5×5-in. NaI crystal for the gate $6.90<E<7.30$ MeV. The angular distribution of the 3.485-MeV line relative to the 7.163-MeV line is also shown.

value of the ratios of 2^- and 3^- amplitudes in the capture state. It was therefore concluded that the 3.626-MeV state may be either 2^+ or 4^+.

4. 4.467-MeV Level

The 4.467-MeV level is populated by the 7.163-MeV line from the capture state. Figure 6 shows the coincidence spectrum with the gate set on position (d) using an enriched ^{47}Ti target. By comparison with the corresponding spectrum from natural Ti, it was found that the lines at 3.485, 2.165, and the weak line at 2.04 MeV are associated with levels in ^{48}Ti. These lines correspond to transitions from the 4.467-MeV level to the 0.982-, 2.297-, and 2.422-MeV levels, respectively. The figure also shows the angular distribution of the 3.485-MeV line relative to the 7.163-MeV line.

In order to determine the 4.467-MeV-level spin, the angular correlations of the following two cascades were measured: (1) 4.467→0.982→0 [gate set at position (e)] and (2) 11.630→4.467→0.982. The results of the second cascade immediately rule out a 4^+ assignment because the angular correlation of the cascade $3^-(1)4^+(2)2^+$ should be $W(\theta)=1-0.14p_2(\cos\theta)$, compared with the experimental result $W(\theta)=1-(0.033\pm 0.021)p_2(\cos\theta)$. The δ values obtained from the A_2/A_0 and A_4/A_0 ratios of the first cascade are consistent with

TABLE III. Most probable spins and parities of levels in ^{48}Ti.

Level energy (MeV)	Present work	(d,p) reaction[a]	(t,p) reaction[b]	^{48}V decay[c]	(d,α) reaction[d]
0.982	2^+	2^+	2^+	2^+	2^+
2.422	$1^+, 2^+, 3^+$	$(2)^+$	(2^+)	$(2)^+$	$(2)^+$
3.626	$2^+, 4^+$	···	2^+	$(3,4)^+$	$(1,2,3,4)^+$
3.790	$2^+, 3^+, 4^+$	···	···	···	···
4.467	$2^+, 3^+$	···	···	···	$(1,2,3,4)^+$

[a] Reference 2.
[b] Reference 3.
[c] Reference 7.
[d] Reference 4.

TABLE IV. Comparison of ^{47}Ti(n,γ) and ^{47}Ti(d,p) transition strengths; only levels for which $l_n=1$ are included.[a]

Level energy (MeV)	(n,γ) reaction E_γ (MeV)	I_γ/E_γ^3	(d,p) reaction[a] $\frac{(2j_f+1)S_{lj}}{2j_i+1}$
2.422	9.210	1.4	0.17
3.229			0.24
3.626	8.006	1.6	0.13
4.048	7.582	0.7	0.10
4.394	(7.236)		0.61
4.467	7.163	7.2	0.34
4.734			0.18
4.805	6.825	1.3	0.08
4.876			0.14
4.929			0.12
4.956			0.08
5.150	6.480	2.8	0.28
5.637			0.14
5.652			0.55
5.906			0.21
6.046	5.584		0.26
6.332			0.24
6.381			0.10
6.701			0.15
6.767			0.13
7.377			0.18
7.45			0.15
7.73			0.08
7.78			0.09
7.86			0.13
8.02			0.10

[a] Reference 2.

the δ values found for the second cascade only for the two possible spin values 2^+ and 3^+. Table II summarizes the angular-correlation results for the $^{47}\text{Ti}(n,\gamma)^{48}\text{Ti}$ reaction and Table III compares the most probable spins and parities of levels in ^{48}Ti with those obtained by other investigators.

IV. DISCUSSION: MECHANISM OF CAPTURE PROCESS

The comparison of the (n,γ) and (d,p) reactions is now regarded as a good monitor for the occurrence of a direct-reaction mechanism in thermal-neutron capture reactions. The present results apparently indicate that there is some correspondence between the γ-line intensities and the proton intensities of the groups characterized by $l_n=1$ angular distributions. In fact, the levels at 2.422, 3.626, 4.048, 4.467, 4.805, and 5.150 MeV in ^{48}Ti which were strongly populated by γ transitions were also found to be strongly excited by $l_n=1$ transitions via the (d,p) reaction. However, there are other highly excited levels such as 4.734, 4.876, 5.636, 5.652, and 5.906 MeV which were also strongly excited by $l_n=1$ transitions but were very weakly, if at all, populated by γ transitions. The fact that there is a correspondence between the (n,γ) and (d,p) intensities only to some of the $l_n=1$ levels indicates that the contribution of a direct-reaction mechanism is probably small. This was also found to be the case when a quantitative analysis was applied for testing the correlation[14] between the γ line and proton group intensities for all levels characterized by $l_n=1$ transitions.

The correlation coefficient is defined by

$$\rho=\sum_f (x_f-\bar{x})(y_f-\bar{y})/\left[\sum_f (x_f-\bar{x})^2 \sum_f (y_f-\bar{y})^2\right]^{1/2},$$

where $x_f=I_{\gamma f}/E_{\gamma f}^3$, $y_f=[(2j_f+1)/(2j_i+1)]S_{ljf}$, $I_{\gamma f}$ is the relative intensity of the γ line of energy $E_{\gamma f}$ leading to a level f of spin j_f, and S_{ljf} is the spectroscopic factor of the (d,p) reaction leading to the same level f. Table IV gives a list of all $l_n=1$ levels in ^{48}Ti as reported by Wilhjelm *et al.*,[2] together with the intensities of the proton groups and the corresponding γ-line intensities as found in the present work. The calculated value of the correlation coefficient was $\rho=0.2$, which indicates that there is no correlation between the (n,γ) and (d,p) intensities. This result is interesting in view of the fact that ^{48}Ti lies in a region where the $p_{3/2}$ and $p_{1/2}$ shells are being filled and therefore the contribution of the direct-capture mechanism is expected to be relatively strong.[8] It is also remarkable that the correlation coefficient for only those levels that were populated by γ transitions has a large value $\rho=0.9$ and that a steep decrease in the calculated coefficient is obtained when all $l_n=1$ levels (including those for which no γ transitions were observed) are incorporated in the calculation. Apart from the 0.982-MeV level, none of the $l_n=3$ levels is populated by γ decay in the present work in spite of the fact that $E1$ transitions to these levels are permissible from an expected 2^- or 3^- capture state. These two features are probably indicative of an appreciable contribution to the reaction mechanism of a channel resonance capture process, postulated by Lane and Lynn.[15,16]

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