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Level Structure of ^{48}Ti for $E_x < 3.5$ MeV*

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The reactions ^{48}Ti(p,p'), ^{48}Ti(α,α'), ^{48}Ti(^{35}Cl, ^{35}Cl$'$), and $^{48}V(\beta^+)$ have been employed to measure excitation energies, lifetimes, and γ-decay branching ratios for ^{48}Ti levels with $E_x < 3.5$ MeV. The results for excitation energies (in keV) and corresponding lifetimes (in psec) are: 983.35 ± 0.10, 6.0 ± 1.3; 2295.5 ± 0.15, 2.4 ± 0.6; 2420.3 ± 0.15, 0.035 ± 0.007; 2997.4 ± 0.25, 0.160 ± 0.032; 3223.5 ± 0.20, $0.042^{+0.018}_{-0.014}$; 3239.7 ± 0.35, $0.044^{+0.019}_{-0.016}$; 3358.7 ± 0.65, 0.350 ± 0.087; 3370.7 ± 0.30, 0.018 ± 0.007. Reduced electromagnetic-transition matrix elements have also been derived from the data. No evidence is found for a doublet at an energy of 3.224 MeV. The previous data on the 3.224-MeV level are reexamined in the light of the present results, and the tentative assignment $J^\pi = 3^+$ is consistent with all data. A tentative assignment of $J^\pi = 4^+$ is given to the level at 3.240 MeV. The present results are in reasonable agreement with the predictions of a model in which the valence nucleons are confined to the $f_{7/2}$ orbital.

I. INTRODUCTION

The first comprehensive attempt to explain the properties of nuclei in the $f_{7/2}$ shell was the calculation of McCullen, Bayman, and Zamick (MBZ).[1] These authors considered a model in which the extracore nucleons were confined entirely to the $f_{7/2}$ shell, and level spectra were computed using matrix elements for the residual two-body interaction derived from the experimental spectrum of ^{42}Sc. Many of the general features of the nuclei considered were well reproduced by the model, although the number of experimental levels was generally greater than the predicted number. MBZ also pointed out an interesting feature of the wave functions for a nucleus such as ^{48}Ti, which is its own cross-conjugate: the wave functions are either even or odd under the interchange of protons and neutron holes. This property sometimes produces two levels of the same spin which lie close together in energy, and explains the close juxtaposition of two 6^+ levels near 3.5-MeV excitation energy in ^{48}Ti.

A further consequence of this odd-even property, sometimes called the signature of the wave function, has been discussed by Lawson.[2] The $E2$ transition matrix element connecting two such levels is proportional to $e_p \pm e_n$, where e_p and e_n are the proton and neutron effective charges; the plus sign applies if the levels have opposite signature, and the minus sign applies if the signatures are the same. To a good approximation, $e_p - e_n$ should be equal to e, the free proton charge, even in the presence of core polarization effects.[2] Thus, measurement of $E2$ transition matrix elements between levels of the same signature provides a sensitive test for the purity of the configurations involved.

Previous studies of ^{48}Ti have employed the reactions $^{48}V(\beta^+)^{48}Ti$,[3,4] $^{48}Sc(\beta^-)^{48}Ti$,[4,5] $^{47}Ti(d,p)^{48}Ti$,[6-8] $^{50}V(d,\alpha)^{48}Ti$,[9] $^{46}Ti(t,p)^{48}Ti$,[10] $^{48}Ti(\alpha,\alpha')^{48}Ti$,[11] and $^{48}Ti(p,p')^{48}Ti$.[12-17] The profusion of levels above 3 MeV has led to some confusion which is still unresolved. In particular, the 3.224-MeV level has been assigned $J^\pi = 4^+$ from γ-γ angular-correlation measurements following the β^+ decay of ^{48}V,[18] whereas γ-ray angular-distribution measurements in coincidence with backscattered protons[17] from the $^{48}Ti(p,p')$ reaction indicate $J = 2$ or 3 and definitely rule out a $J = 4$ assignment unless a closely spaced doublet exists at this excitation energy. Kavaloski and Kossler,[16] assuming $J^\pi = 4^+$, report a transition rate of 1200 W.u. for the transition 3.224→2.420, a doubtful result since it requires an enhancement factor greater than Z^2. There is some confusion as to whether one or two levels exist[7,8,16] in the region of 3.335 MeV. Also, there are significant discrepancies among lifetime measurements for the 0.983-MeV first excited state.[16,19,20]

The present study was undertaken in an effort to resolve the above difficulties and to obtain electromagnetic-transition matrix elements of sufficient accuracy to test the predictions of the MBZ model. Most of this work utilized the reaction $^{48}Ti(p,p')$-^{48}Ti. However, α and ^{35}Cl beams were also used to excite the first two levels for Doppler-shift lifetime measurements, and the β^+ decay of ^{48}V was studied in an effort to resolve the problem of the 3.224-MeV level. Energies and branching ratios have been determined by precision Ge(Li) γ-ray spectroscopy, and nuclear lifetimes have been measured using the Doppler-shift attenuation method (DSAM).

II. EXPERIMENTAL PROCEDURE

A. General Experimental Arrangement

Targets of titanium metal enriched to 99% in ^{48}Ti were bombarded by particle beams from the Stanford University tandem Van de Graaff accelerator. Reaction γ rays were detected in a 32-cm^3 Ge(Li) diode, and, after amplification, pulse-height spectra were recorded with a 4096-channel analog-to-digital converter (ADC) interfaced with a PDP-7 computer. The detector was mounted on a platform which could be rotated about a vertical axis through the target for angular-distribution and lifetime measurements. Typically, the front face of the detector was 10 cm from the target. For most of the measurements, a stainless-steel target chamber was employed which incorporated a liquid-nitrogen cold trap to reduce contaminant buildup.

B. Excitation Energies and Branching Ratios

Excitation energies for levels with $E_x < 3.5$ MeV were obtained using the mixed-source technique. The $^{48}Ti(p,p')$ reaction was used to excite the ^{48}Ti levels at several bombarding energies in the neighborhood of 5 MeV. The target was a ^{48}Ti metal foil, 1 mg/cm^2 thick. Ge(Li) γ-ray spectra were measured at $\theta_\gamma = 90°$, and source lines from ^{54}Mn, ^{60}Co, and ThC'' were included in the spectra from which excitation energies were deduced. The energies of observed γ-ray transitions and the corresponding excitation energies derived from them are shown in Table I.

Branching ratios were determined in several steps, and in the course of these measurements rough γ-ray angular distributions were also obtained. γ-ray intensities for transitions from lev-

TABLE I. γ-ray energies and corresponding excitation energies. Uncertainties are statistical.

E_i (MeV)	E_f (MeV)	γ-ray energy (keV) $^{48}Ti(p,p')$	$^{48}V(\beta^+)$	Excitation energy (keV)
0.983	0	983.5 ± 0.15	983.2 ± 0.15	983.35 ± 0.10
2.296	0.983	1312.2 ± 0.10	1312.1 ± 0.10	2295.5 ± 0.15
2.420	0	2420.7 ± 0.20		2420.3 ± 0.15
	0.983	1436.8 ± 0.10		
2.997	0.983	2014.0 ± 0.20		2997.4 ± 0.25
3.224	0.983	2240.0 ± 0.30	2240.2 ± 0.20	3223.5 ± 0.20
	2.296	928.4 ± 0.60	928.0 ± 0.50	
	2.420	804.0 ± 1.2	801.5 ± 1.0	
3.240	2.296	945.1 ± 0.50	943.9 ± 0.30	3239.7 ± 0.35
3.359	0.983	2374.8 ± 0.80		3358.7 ± 0.65
	2.296	1064.0 ± 1.0		
3.371	0	3371.5 ± 1.2		3370.7 ± 0.30
	0.983	2387.3 ± 0.3		

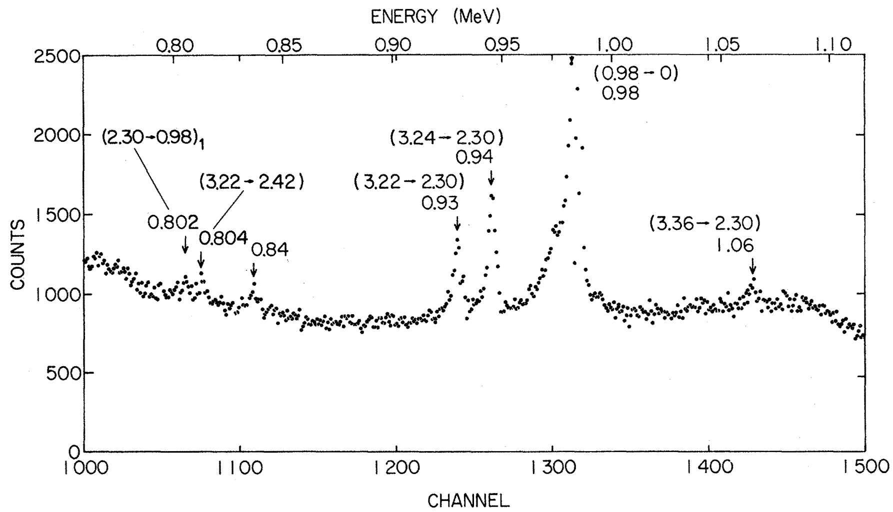

FIG. 1. A portion of the γ-ray spectrum resulting from proton bombardment of ^{48}Ti at $E_p = 6.4$ MeV in coincidence with 0.983-MeV γ ray. The line at 0.840 MeV could not be identified. All other lines can be identified with transitions in ^{48}Ti. The closely spaced doublet at 0.80 MeV contains the one-escape peak of the 2.296 → 0.983 transition, as well as the 3.224 → 2.420 transition.

els at 3.371 and 2.420 MeV were extracted from spectra collected at $\theta_\gamma = 55°$, $E_p = 5.0$ MeV. Branching ratios were calculated from spectral intensities after correction for angular-distribution effects and γ-ray detector efficiency. The efficiency of the detector as a function of energy was determined from a calibration with a ^{56}Co source using the intensities quoted by Marion.[21]

It was suspected that some decays might exist with intensities too weak to be observed in the singles spectra, and so a γ-γ coincidence measurement was undertaken. Most of the low-lying levels in ^{48}Ti decay by γ-ray cascades which pass through the first excited state at 0.983 MeV. A proton bombarding energy of 6.4 MeV was chosen, and the second detector was a 10- ×12.5-cm NaI(Tl) counter. A single-channel analyzer was set on the full-absorption peak of the 0.983-MeV γ ray. Timing signals obtained from constant-fraction timing discriminators were used as the start and stop signals for a time-to-amplitude converter, resulting in a time spectrum with a width [full width at half maximum (FWHM)] of 10 nsec. The identification of weak branches followed easily from a comparison of the coincidence spectrum, a portion of which is shown in Fig. 1, with a singles spectrum taken at the same energy.

Figure 1 clearly shows the transitions 3.224 → 2.420 and 3.359 → 2.296, which could not be identified from the singles spectrum alone. In addition, the coincidence measurement established that a weak 2.35-MeV line present in the singles

TABLE II. Branching ratios for electromagnetic transitions in ^{48}Ti. Uncertainties are statistical.

E_i (MeV)	→	E_f (MeV)	^{48}Ti$(p,p'\gamma)$ [a]	Branch (%) ^{48}Ti$(p,p'\gamma)$ [b]	^{48}V(β^+) [b]	Adopted value
2.421		0	3.4 ± 1	5.0 ± 0.7		5.0 ± 0.7
		0.983	97 ± 1	95.0 ± 0.8		95.0 ± 0.8
3.224		0.983	65 ± 5	72.0 ± 2.2	69.7 ± 0.5	69.8 ± 0.5
		2.296	20 ± 3	24.3 ± 1.7	26.3 ± 0.4	26.2 ± 0.4
		2.421	15 ± 5	3.7 ± 0.8	4.0 ± 0.2	4.0 ± 0.2
3.240		0.983			<0.1	<0.1
		2.296	100		100	100
3.358		0.983	100	85.2 ± 0.7		85.2 ± 0.7
		2.296		14.8 ± 0.7		14.8 ± 0.7
3.371		0		13.5 ± 0.9		13.5 ± 0.9
		0.983	100	86.5 ± 1.0		86.5 ± 1.0

[a] Kavaloski and Kossler, Ref. 16.

[b] Present experiment.

spectrum at a bombarding energy of 6.4 MeV was not due to the transition 3.336 → 0.983 reported by Kavaloski and Kossler.[16] Branching ratios for transitions from the levels at 3.224 and 3.359 MeV were determined from the spectrum of Fig. 1. Information on all branching ratios is summarized in Table II.

An additional study of the ^{48}Ti level scheme was made through an investigation of the $^{48}V(\beta^+)^{48}Ti$ decay. A ^{48}V source approximately 5 μCi in strength was prepared by bombarding a 20-mg/cm^2 ^{48}Ti foil with 7-MeV protons for several hours. The γ-ray spectrum following the β^+ decay of ^{48}V has been extensively studied,[4] but the spectra reported in the literature have been taken with NaI(Tl) detectors or with small Ge(Li) detectors having a poor peak-to-Compton ratio for high-energy γ rays. A portion of the γ-ray spectrum obtained with the 32-cm^3 Ge(Li) detector after 18 h of counting is shown in Fig. 2. The γ rays identified with levels in ^{48}Ti were all observed to decay with the same lifetime as ^{48}V (16 days). The 0.804-MeV line from the weak branch 3.224 → 2.420 is present in the spectrum after a correction is made for the 1.31-MeV one-escape peak, and the occurrence of this branch is confirmed by the presence of a 1.438-MeV line with the proper intensity. This line can only occur via the cascade 3.224 → 2.420 → 0.983, since the 2.420-MeV level has $J^\pi = 2^+$ and the β^+ transition to this level is not allowed. γ-ray energies and branching ratios obtained from the ^{48}V spectrum are presented in Tables I and II, and may be compared with the corresponding quantities obtained from the $^{48}Ti(p, p')$ data. It is of particular interest to make this comparison for the 3.224-MeV level, since it has been proposed that this level is a closely spaced doublet.[17]

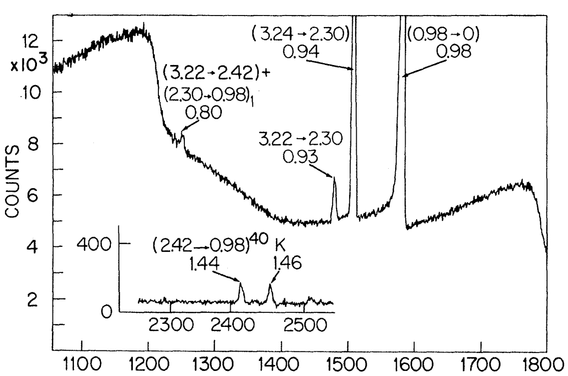

FIG. 2. A portion of the γ-ray spectrum following the $^{48}V(\beta^+)$ decay. The doublet at 0.80 MeV contains the one-escape peak of the 2.296 → 0.983 transition, as well as the 3.224 → 2.420 transition, which could not be seen in the spectra of Ref. 5. The 0.929-MeV line, barely evident in the spectra of Ref. 5, is a prominent feature.

C. Lifetime Measurements

The measurement of nuclear lifetimes by the DSAM is by now a standard technique. For a more complete discussion, reference should be made to a previous paper by the authors[22] or to standard works on the subject.[23-25] The mean lifetime, τ_m, is extracted from a measurement of the quantity F_m, defined as the ratio of the attenuated Doppler shift to the unattenuated shift:

$$F_m(\tau_m) = \Delta E_\gamma / E_{\gamma 0} . \quad (1)$$

In the analysis of the present measurements, the theoretical estimates of Lindhard, Scharff, and Schiøtt[26] for the stopping parameters K_e and K_n were used, and nuclear scattering was treated according to the method of Blaugrund.[27] The data of Ormrod, MacDonald, and Duckworth,[28] which indicate systematic deviations from the Lindhard estimates for K_n and K_e, do not extend as far as titanium, but the trend of the data suggests that departures from the Lindhard estimates should be small. The stopping parameter K_3 was estimated from the semiempirical compilation of Northcliffe and Schilling.[29] An uncertainty of 15% has been included in the final lifetime results to take into account uncertainties in the energy-loss parameters.

Lifetime measurements have been obtained for all levels in ^{48}Ti up to an excitation energy of 3.5

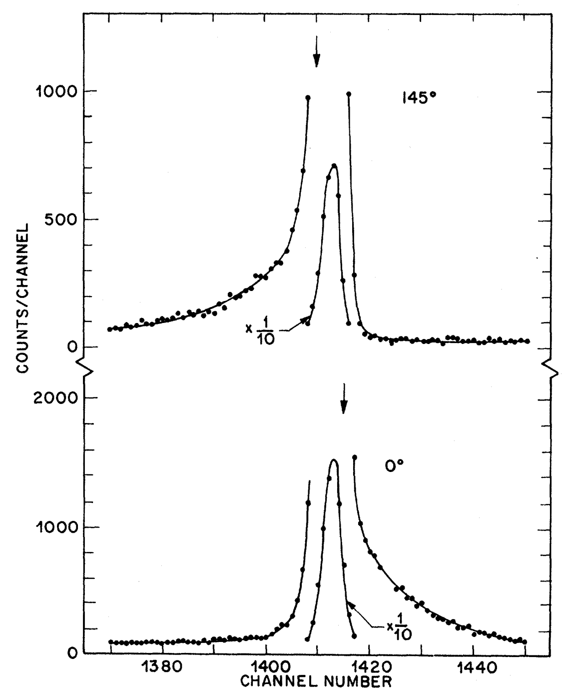

FIG. 3. Attenuated-Doppler-shift spectra for the 0.983-MeV γ ray excited by ^{35}Cl bombardment of ^{48}Ti. The arrows indicate the centroids of the peaks.

MeV with the exception of the 6^+ level at 3.332 MeV which was not excited at our bombarding energies. Different approaches were used in the determination of $\Delta E_{\gamma 0}$. The 0.983-MeV level was excited by Coulomb excitation using a 64-MeV beam of ^{35}Cl ions incident on a thick (20-mg/cm^2) ^{48}Ti foil. The spectrum is shown in Fig. 3. The known dependence of the Coulomb-excitation cross section on energy and angle was then used to calculate $\Delta E_{\gamma 0}$. Levels at 2.420, 3.224, and 3.371 MeV were excited in the $^{48}Ti(p,p')$ reaction ($E_p = 5.0$ MeV). The lifetimes for these levels were measured by comparing ΔE_γ for two media having different characteristic stopping times: a ^{48}Ti foil and a ^{48}Ti-^{197}Au alloy (10 at.% ^{48}Ti, $\rho = 16.2$ g/cm^3). This technique, first proposed by Warburton, Alburger, and Wilkinson,[23] circumvents the need for direct knowledge of $\Delta E_{\gamma 0}$. The mean lifetime is determined from the ratio

$$R(\tau_m) = \frac{(\Delta E_\gamma)_1}{(\Delta E_\gamma)_2} . \qquad (2)$$

Levels at 2.997, 3.240, and 3.359 MeV were excited in the reaction $^{48}Ti(p,p')$ ($E_p = 5.0$ MeV), and the 2.295-MeV level was excited in the $^{48}Ti(\alpha,\alpha')$ reaction ($E_\alpha = 5.0$ MeV). For these levels it was necessary to calculate $\Delta E_{\gamma 0}$ relying on the assumption of symmetry of the cross section about 90° in the center-of-mass system. An additional 10% uncertainty in F_m was allowed in these cases. The information on lifetimes is summarized in Table III. Curves of F_m vs τ_m used to extract the lifetimes in Table III are displayed in Fig. 4.

III. DISCUSSION

A. Comparison with Previous Results

An energy level diagram of ^{48}Ti showing all γ-ray transitions is given in Fig. 5. The energies and branching ratios derived from the present data are summarized in Tables I and II. In general, the agreement with previous results is good with the present measurements offering improved precision in most instances. The γ-ray transitions $3.359 \rightarrow 2.296$ and $3.371 \rightarrow 0$ have not been reported previously. We have also verified the existence of the transition $3.224 \rightarrow 2.420$ reported by Kavaloski and Kossler[16] and have shown that the intensity of this transition explains the 1.438-MeV γ ray reported by Konijn, Lingeman, and deWit[5] in the spectrum of ^{48}V. Our value $(3.7 \pm 0.8)\%$ for the $3.224 \rightarrow 2.420$ branch disagrees with the value $(15 \pm 5)\%$ reported by Kavaloski and Kossler,[16] but the results for other branching ratios are in reasonable agreement with these authors.

We do not observe the transitions $3.336 \rightarrow 0.983$ and $3.336 \rightarrow 2.296$ on which Kavaloski and Kossler based their claim for a new level at 3.336 MeV.

TABLE III. Lifetimes of levels in ^{48}Ti. Mean lifetimes τ_m are expressed in psec. An asterisk indicates that a calculated value of $(\Delta E_{\gamma 0})$ was used to extract the value of τ_m.

Level energy (MeV)	γ-ray energy (MeV)	F_m(Ti)	F_m(Ti-Au)	R	τ_m	τ_m(other)
0.983	0.983	0.078 ± 0.002			6.0 ± 1.3*	$1.2^{+5.0}_{-0.3}$ [a]
						3.6 ± 1.5 [b]
						6.7 ± 0.4 [c]
2.296	1.313	0.056 ± 0.009			2.4 ± 0.6*	$1.2^{+2.0}_{-0.3}$ [a]
						$2.0^{+0.9}_{-0.7}$ [d]
2.421	1.438	0.740 ± 0.007	0.550 ± 0.008	0.743 ± 0.013	0.035 ± 0.007	$0.016^{+0.025}_{-0.016}$ [a]
2.998	2.015	0.365 ± 0.010	0.190 ± 0.020	0.522 ± 0.056	0.160 ± 0.032*	0.125 ± 0.025 [a]
3.224	2.241	0.685 ± 0.020	0.500 ± 0.040	0.730 ± 0.062	$0.042^{+0.018}_{-0.014}$	$0.024^{+0.016}_{-0.012}$ [a]
3.240	0.944	0.670 ± 0.080	0.520 ± 0.160	0.780 ± 0.250	$0.044^{+0.019}_{-0.016}$*	$0.100^{+0.080}_{-0.038}$ [a]
3.332	1.036					12.7 ± 1.2 [e]
3.358	2.375	0.186 ± 0.035	0.095 ± 0.039	0.510 ± 0.230	0.350 ± 0.087*	$0.250^{+0.040}_{-0.030}$ [a]
3.371	2.388	0.931 ± 0.023	0.770 ± 0.029	0.827 ± 0.037	0.018 ± 0.007	$0.022^{+0.013}_{-0.012}$ [a]

[a] Kavaloski and Kossler, Ref. 16.
[b] Booth, Chasan, and Wright, Ref. 19.
[c] Average of results of DeCastro Faria *et al.* and Häusser *et al.*, Ref. 20.
[d] A. F. Akkerman *et al.*, Zh. Eksperim. i Teor. Fiz. 45, 1778 (1963) [transl.: Soviet Phys.–JETP 18, 1218 (1964)].
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The 2.351- and 1.062-MeV γ rays which appear in our spectra have approximately the energies of the transitions reported by Kavaloski and Kossler, but these γ rays are attributed to new transitions $3.371 \to 0$ (2 escape) and $3.359 \to 2.296$, respectively. Belote *et al.*[13] also fail to find any evidence for a level at 3.336 MeV in ^{48}Ti(p,p') data recorded with a magnetic spectrograph at $E_p = 7.0$ MeV. The original suggestion by Barnes *et al.*[7] of a level with $1 \leq J \leq 4$ at about this energy has since been withdrawn after a reanalysis of the data.[8] Since the existence of a level at 3.336-MeV excitation energy is doubtful, this level is indicated as a dotted line in Fig. 5. The absence of the 6^+ level at 3.332 MeV from our spectra is expected; this level is not excited in the (p,p') reaction at these energies, presumably because of its high spin. Its existence, however, is well established by studies on the β^- decay of ^{48}Sc.

The present value of 6.0 ± 1.3 psec for the lifetime of the 0.983-MeV level is in excellent agreement with two recent Coulomb-excitation measurements[20] and disagrees with earlier measurements employing DSAM and resonance fluorescence techniques.[16,19] It is reassuring to achieve agreement with the Coulomb-excitation result, which should be the more reliable one in this case. Other lifetimes reported in Table III are in good agreement with previous work, with the present measurements offering greater precision in most cases. The present result for the lifetime of the 3.24-MeV level differs from that reported by Kavaloski and Kossler[16] by about a factor of 2, but the measurements still overlap within the experimental uncertainties.

With the exception of the 3.224 and 3.240-MeV levels, the results of this experiment support previous spin and parity assignments. The observation of the transitions $3.359 \to 2.296$ and $3.371 \to 0$ is in accord with the assignments 3^- and 2^+ for the 3.359- and 3.371-MeV levels. An assignment of 5^+ for the 3.240-MeV level has been favored in the past[3] because of the absence of the transition $3.240 \to 0.983$. The situation with regard to this

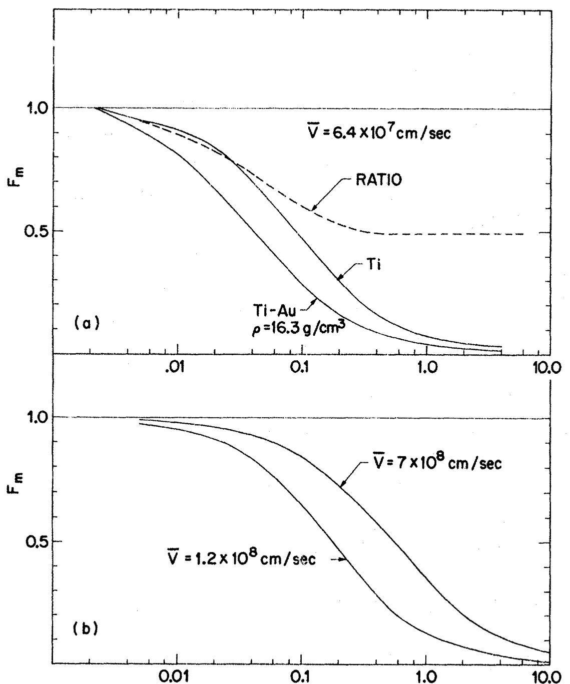

FIG. 4. (a) Plot of F_m vs τ_m for ^{48}Ti recoils stopping in ^{48}Ti and the ^{48}Ti-^{197}Au alloy. The ratio R vs τ_m is also shown. The velocity 6.4×10^7 cm/sec corresponds to the average velocity imparted to the ^{48}Ti recoils in the ^{48}Ti(p,p') reaction by 5.0-MeV incident protons. (b) Plot of F_m vs τ_m for ^{48}Ti recoils stopping in ^{48}Ti. The velocity 1.2×10^8 cm/sec corresponds to the average recoil velocity when a thick ^{48}Ti target is bombarded by 5.0-MeV α particles. The velocity 7×10^8 cm/sec corresponds to the average recoil velocity when a thick ^{48}Ti target is bombarded by 64-MeV ^{35}Cl ions.

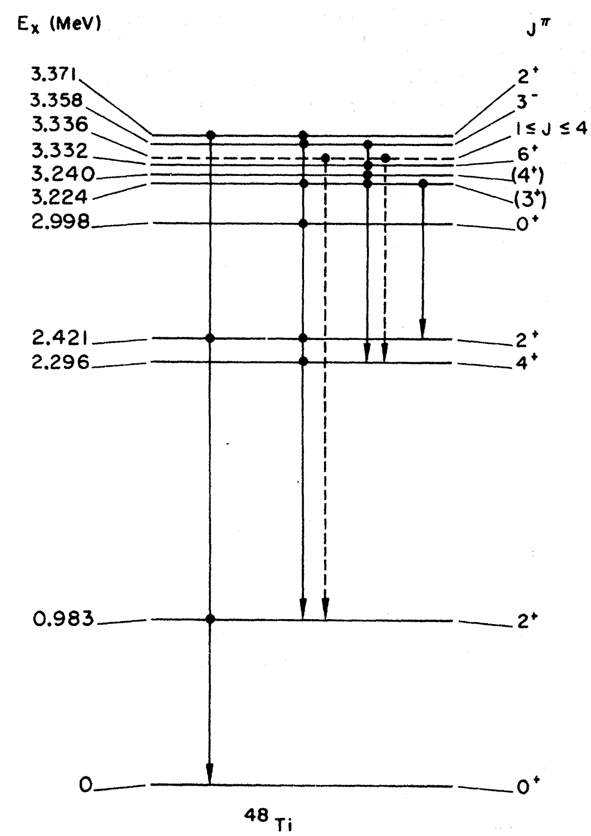

FIG. 5. Summary of level excitation energies, J^π assignments, and γ-ray transitions for ^{48}Ti levels. The existence of the 3.336-MeV level is considered doubtful, and it is therefore represented by a dotted line.

level is confusing. The spin and parity is given tentatively as (5^+) in Ref. 13, but as (4^+) in Ref. 5 which quotes Ref. 13 as supporting evidence. In any case, the failure of the ^{48}Sc β^- decay to populate this level and the ease with which it is excited in the ^{48}Ti(p, p') reaction at $E_p = 5.0$ MeV suggest a spin less than 5. In the next section, it will be shown that both the energy of the level and the strong $M1$ transition observed to the 2.296-MeV level are in serious disagreement with theory if $J^\pi = 5^+$. We suggest the assignment $J^\pi = (4^+)$ which resolves all of these difficulties. The transition $3.240 \rightarrow 0.983$, which is then an $E2$ transition connecting two levels with the same signature, is predicted by theory to be weak although not quite so weak as is experimentally observed.

For the 3.224-MeV level, an assignment of (3^+) is suggested. The doublet hypothesis of Monahan *et al.*[17] seems unlikely, since the same centroids and relative intensities are obtained for the γ-ray transitions from this level regardless of whether the level is excited in the ^{48}Ti(p, p') reaction or in the ^{48}V (β^+) reaction (see Tables I and II). The γ-γ angular-correlation data of van Nooijen *et al.*[18] agree with a 3^+ assignment if the $E2/M1$ mixing ratio for the transition $3.224 \rightarrow 0.983$ has the value $\delta = -0.21 \pm 0.05$. The internal-conversion ratio for this transition favors a 4^+ assignment slightly, and this fact has been considered decisive in previous analyses.[4,18] The predicted value of N_e/N_γ is 0.16 $\times 10^{-4}$ for an $E2$ transition and 0.19×10^{-4} for an $M1$ transition, while the experimental result is $(0.14 \pm 0.01) \times 10^{-4}$. This result favors a pure $E2$ transition as opposed to a mixed transition which is predominantly $M1$, but we do not believe that it should be given much weight, since the theoretical predictions lie so close together. We have reanalyzed the data of Monahan *et al.*[17] and find that the p-γ correlation data on the transition $3.224 \rightarrow 0.983$ can be satisfactorily explained assuming a mixed $E2/M1$ transition with $J(3.224) = 3$ and $\delta = -0.26 \pm 0.05$. The χ^2 is 2.5 per degree of freedom, not so good a fit as was obtained by Monahan *et al.*[17] with a 2^+ assignment but well inside the customary 0.1% confidence limit. We conclude, therefore, that the available data can be explained satisfactorily by the assumption of a single level at 3.224-MeV excitation energy with $J^\pi = 3^+$. We note, in passing, that the strength of the transition $3.224 \rightarrow 2.420$ is no longer a problem since the transition is now a mixed $E2/M1$ transition rather than a pure $E2$ transition.

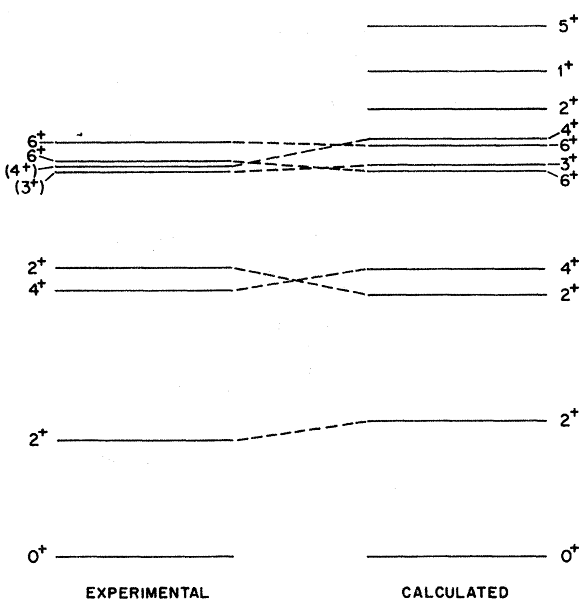

FIG. 6. Comparison of experimental and calculated level energies. Only levels expected to have pure $f_{7/2}$ configurations have been included in the experimental spectrum. The calculation is described in the text.

B. Comparison with Theory

Figure 6 shows the comparison between the experimental and theoretical level spectra. The two-body matrix elements of Vervier[30] were used rather than the ^{42}Sc matrix elements employed in the original MBZ calculation, but only slight changes in the predicted level spectrum result from this modification. Above 3 MeV, the possibility of core excitations and excitations of the $p_{3/2}$ shell produces many more levels than are predicted by the pure $f_{7/2}$ model. We have included in Fig. 6 only those experimental levels which are expected to be relatively pure $f_{7/2}$ configurations. The agreement between the experimental and theoretical level energies is reasonable and is improved considerably by the new spin assignments proposed for the 3.224- and 3.240-MeV levels. Otherwise, the predicted energy for the 3_1^+ level is too low, and the energy predicted for the 5_1^+ level is 1.3 MeV too high.

In Table IV, the electromagnetic-transition matrix elements derived from the experimental data in Tables II and III are summarized. We have relied on the data of other investigators for the lifetimes of the 3.332-MeV level and the $E2/M1$ mixing ratios for the transitions $2.420 \rightarrow 0.983$ and $3.224 \rightarrow 0.983$. All $M2/E1$ and $M3/E2$ mixing ratios have been assumed to be zero, and in three cases $M1$ matrix elements have been calculated assuming a zero $E2/M1$ mixing ratio, since no experimental data were available. (The calculated $E2$ width was less than 3% of the total width in these three cases.)

The experimental matrix elements are compared with theory in Table V. Best agreement in the case of the $E2$ matrix elements was achieved by using effective charges $e_p = 1.5e$, $e_n = 0.7e$. (The values $e_p = 1.5e$, $e_n = 0.5e$ are typically employed for p-shell nuclei.[31]) Best agreement between the experimental and theoretical $M1$ matrix elements was obtained by using effective g factors for the neutron and proton such that $(\mu_p - \mu_n + 3) = 4.5$. This result is typical of other $M1$ transitions in the $f_{7/2}$ shell.[32] The agreement between experimental and theoretical matrix elements in Table V is strikingly good. Without exception, transitions predicted to be weak are found experimentally to be weak, and transitions predicted to be strong are found to be strong. Because of the special configuration $(\pi)^2(\nu)^{-2}$ assumed for the low-lying ^{48}Ti levels, it is also possible to predict relative transition strengths on the basis of simple selection rules which involve the signature of the wave functions. $E2$ transitions between levels with the same signature have transition matrix elements proportional to $(e_p - e_n)$ and are therefore retarded in comparison with transitions between levels with opposite signatures which have matrix elements proportional to $(e_p + e_n)$. This selection rule has been discussed previously by Lawson[2] and by Zamick,[33] and holds very well for the $E2$ transitions shown in Table V. An even stronger rule applies in the case of $M1$ transitions: $M1$ transitions between levels of the same signature are strictly forbidden. This rule also holds very well for the transitions in Table V. The transition $3_1^+ \to 2_1^+$, which connects two levels with the same signature, is the weakest of the observed $M1$ transitions, and the strong transitions $3_1^+ \to 4_1^+$, $2_2^+ \to 2_1^+$, and $4_2^+ \to 4_1^+$ all occur between levels with opposite signatures.

The identification of the levels at 3.224 and 3.240 MeV as 3_1^+ and 4_2^+, respectively, is essential to achieve any reasonable agreement between the experimental and calculated matrix elements. The previous assignment of 4_2^+ for the 3.224-MeV level would imply a strength of 32 W.u. for the $4_2^+ \to 2_1^+$ transition compared to a theoretical prediction of 0.13 W.u. The previous assignment of 5_1^+ for the 3.240-MeV level leads to even greater difficulties, an experimental $M1$ transition strength of 0.80 W.u. for the $5_1^+ \to 4_1^+$ transition which is strictly forbidden by the theory.

The three levels at 2.997, 3.359, and 3.371 MeV probably involve more complicated configurations and have not been included in Fig. 6. The 2.997-

TABLE IV. Transition strengths (in W.u.) for electromagnetic transitions in ^{48}Ti. All $M3/E2$ and $M2/E1$ mixing ratios are assumed to be zero in the absence of experimental information. [The definition of the W.u. follows that of Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic, New York, 1960), Part B, pp. 859, 860.]

E_i (MeV) → E_f (MeV)	$J^\pi{}_i \to J^\pi{}_f$	δ	$\Gamma(E1)$	$\Gamma(M1)$	$\Gamma(E2)$
0.983 → 0	$2^+ \to 0^+$	0			14.1 ± 2.2
2.296 → 0.983	$4^+ \to 2^+$	0			8.5 ± 2.5
2.421 → 0	$2^+ \to 0^+$	0			1.34 ± 0.33
→ 0.983	$\to 2^+$	−0.14 ± 0.08 [a]		0.28 ± 0.06	$6.1^{+9.6}_{-4.9}$
2.998 → 0.983	$0^+ \to 2^+$	0			14.7 ± 2.9
3.224 → 0.983	$3^+ \to 2^+$	−0.26 ± 0.05 [b]		$0.043^{+0.014}_{-0.018}$	$1.5^{+0.6}_{-0.9}$
→ 2.296	$\to 4^+$	0 [c]		$0.24^{+0.08}_{-0.10}$	
→ 2.421	$\to 2^+$	0 [c]		$0.053^{+0.018}_{-0.023}$	
3.240 → 2.296	$4^+ \to 4^+$	0 [c]		$0.80^{+0.29}_{-0.35}$	
→ 0.983	$\to 2^+$	0			≤0.05
3.332 → 2.296	$6^+ \to 4^+$	0			5.2 ± 0.5
3.358 → 0.983	$3^- \to 2^+$	0	$(1.35 \pm 0.34) \times 10^{-4}$		
→ 2.296	$\to 4^+$	0	$(2.80 \pm 0.70) \times 10^{-4}$		
3.371 → 0	$2^+ \to 0^+$	0			1.35 ± 0.52

[a] Average of results of Monahan *et al.*, Ref. 17, and Matin, Church, and Mitchell, Ref. 14.
[b] Reanalysis of angular-distribution data of Monahan *et al.*, Ref. 17.
[c] Assumed to calculate $M1$ matrix element.

TABLE V. Comparison between experimental and calculated transition strengths for transitions in ^{48}Ti. Notation $2_1^+(-)$ denotes the first excited state having $J^\pi = 2^+$ and negative signature. Effective charges $e_p = 1.5e$, $e_n = 0.7e$ were used in the calculation of the $E2$ matrix elements; $M1$ matrix elements were calculated using the value 4.5 for $(\mu_p - \mu_n + 3)$.

Transition	Γ (M1) (W.u.) Experimental	Γ (M1) (W.u.) Calculated	Γ (E2) (W.u.) Experimental	Γ (E2) (W.u.) Calculated
$2_1^+(-) \to 0^+(+)$			14.1 ± 2.2	5.95
$4_1^+(+) \to 2_1^+(-)$			8.5 ± 2.5	7.30
$2_2^+(+) \to 0^+(+)$			1.34 ± 0.03	0.32
$2_2^+(+) \to 2_1^+(-)$	0.28 ± 0.06	0.30	$6.1^{+9.6}_{-4.9}$	6.1
$3_1^+(-) \to 2_1^+(-)$	$0.043^{+0.014}_{-0.018}$	0	$1.5^{+0.6}_{-0.9}$	0.48
$\to 4_1^+(+)$	$0.24^{+0.08}_{-0.10}$	0.20		
$\to 2_2^+(+)$	$0.053^{+0.018}_{-0.023}$	0.063		8.50
$6_1^+(-) \to 4_1^+(+)$			5.2 ± 0.5	5.50
$4_2^+(-) \to 2_1^+(-)$			<0.05	0.13
$\to 4_1^+(+)$	$0.80^{+0.29}_{-0.35}$	0.52		0.31
$5_1^+(+) \to 4_1^+(+)$		0		0.26

MeV level has been assigned $J^\pi = 0^+$ from the (t, p) work of Hinds and Middleton.[10] The present results verify a previous measurement of the lifetime of this level but do not contribute any additional knowledge about its structure. Lawson[2] has satisfactorily explained the energy of this level by assuming the core-excited configuration $(\pi d_{3/2})^{-2}(\pi f_{7/2})^4(\nu f_{7/2})^{-2}$. The 3.359-MeV level has been given the assignment $J^\pi = 3^-$ by Bernstein *et al.*[11] and presumably represents a collective octupole excitation. Soga, Horoshko, and Van Patter[34] have predicted a strong enhancement for the $E1$ transition $3^- \to 2_2^+$ relative to the transition $3^- \to 2_1^+$, if the wave function for the 3^- level is predominantly isoscalar in character. The selection rule operating is similar to that for $E2$ transitions but is much stronger, since the proton and neutron-effective charges can almost completely cancel in the case of an $E1$ transition. For example, in ^{46}Ti the enhancement of the $3^- \to 2_2^+$ transition over the $3^- \to 2_1^+$ transition by a factor $>3 \times 10^4$ is attributed to this selection rule, and similar enhancements are predicted in ^{48}Ti. This prediction is not realized; the transition $3^- \to 2_2^+$ cannot even be identified in our spectra. Allowing for the possibility that it could be obscured by the 0.944-MeV γ ray, its enhancement relative to the $3^- \to 2_1^+$ transition is certainly less than a factor of 2. A similar conclusion is reached in Ref. 17. These transitions are quite weak, however, and small impurities in the wave functions may mask the effects of the selection rule. The 2^+ level at 3.371 MeV may be identified with the 2_3^+ state predicted by the model, although the agreement between the experimental and theoretical energies is not particularly good. However, there are several levels of unknown spin and parity between 3.5- and 4.1-MeV excitation energy, some of which are probably also 2^+ levels, and we should expect the 2_3^+ level to be mixed with other configurations.

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(p, t) and $(p, {}^3\text{He})$ Reactions on ^{27}Al at $E_p = 27$ MeV*

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Levels in ^{25}Al and ^{25}Mg were populated via the (p, t) and $(p, {}^3\text{He})$ reactions with 27-MeV protons on a ^{27}Al target. Angular distributions of emitted tritons and ^{3}He were measured simultaneously with a detector telescope. Zero-range distorted-wave Born-approximation (DWBA) calculations with simple shell-model configurations for the two transferred nucleons provided satisfactory fits for several of the observed diffraction patterns. A sharp rise in cross section at forward angles was a good indication of the presence of $L=0$ transfer even though transitions occurred with a mixture of L values. Compound-nucleus calculations reproduced the smooth angular-distribution shapes observed for higher excited levels but predicted cross sections consistently larger than those observed. For the first $\frac{1}{2}^+$ levels neither DWBA, compound-nucleus, nor a direct two-step (p, d) (d, t) calculation were able to give a satisfactory description of the data.

I. INTRODUCTION

The (p, t) reaction has been utilized with considerable success to determine energies, spins, and parities, and to check nuclear wave functions in even-A nuclei. In a recent study of the (p, t) reaction on even-A titanium isotopes Baer *et al.*[1,2] carefully investigated the advantages as well as the limitations of the (p, t) reaction. However, use of the (p, t) reaction on odd-A targets for spectroscopic purposes has not been extensive. One reason may be that the high level density in the residual odd-A nucleus requires relatively better energy resolution. Also the determination of the spins and parities of residual states from the triton angular distributions can be difficult because several L values may be mixed.

In order to assess the impact of L mixing and other complexities on the interpretation of the two-nucleon transfer reaction on odd-A target nuclei, we selected $^{27}_{13}$Al as the target. The energies, spins, and parities of low excited states in