Gamma Decay of Analog Resonances in the $^{48}Ti(p, \gamma)^{49}V$ Reaction* †

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(Received 21 April 1969)

The γ decay of four prominent resonances in the $^{48}Ti(p, \gamma)^{49}V$ reaction have been studied using an 18-cc Ge(Li) detector. γ-ray angular distributions were obtained at resonant energies of 1.007, 1.013, 1.361, and 1.387 MeV. From these data, relative intensities, mixing ratios, and probable spins for resonant and secondary states are determined. The decay of the resonances indicate that the M1 γ decay of the analog resonances is strongly inhibited. It is found that the prominent resonance at 1.387 MeV is probably not an analog resonance, indicating that the identification of resonances as analog resonances simply on the basis of their strength in the (p, γ) reaction is highly questionable.

INTRODUCTION

THE excitation function of the $^{48}Ti(p, \gamma)^{49}V$ reaction has been studied between 870- and 2290-keV proton bombarding energies by Dubois[1] and Klapdor.[2] Some of the observed resonances are 3–10 times stronger than any neighboring resonances, and Klapdor suggests that the observed strength may be explained by interpreting these resonances as analog resonances. Fodor *et al.*[3] have measured spectra and angular distributions on the three lowest-energy strong resonances, interpreting them as analog resonances. They report extremely simple decay schemes for each of these resonances, with γ transitions to less than five states in ^{49}V observed for each resonance. Klapdor and Zausig[4] have measured γ spectra at four resonances, two of which were also studied by Fodor *et al.*[3] On the 1007-keV resonance, Klapdor and Zausig[4] report 10 primary transitions to states in ^{49}V ranging up to 4076 keV in excitation.

In this paper, we report on studies of the γ decay of the 1007-, 1013-, 1361-, and 1387-keV resonances in the $^{48}Ti(p, \gamma)^{49}V$ reaction. All of these resonances have been described as analog resonances by Fodor[3] and Klapdor.[2] Angular distributions were measured and probable spins assigned to the observed states of ^{49}V.

EXPERIMENTAL METHODS

Titanium oxide isotopically enriched to 99% ^{48}Ti was evaporated from a carbon boat by electron bombardment and deposited on Ta backing. Targets of thickness ranging 0.1–10 keV for 1-MeV protons were prepared. These targets were bombarded by protons from the University of Kansas 3-MeV Van de Graaff accelerator. Beam currents of 10–20 μA were used during the collection of these data.

The γ spectra were measured using an 18-cm^3 Ge(Li) detector. These spectra were analyzed by a 4096-channel analyzer. Normalization of data points was effected by beam-current integration and by using a NaI(Tl) detector as a monitor detector at a fixed angle of 55°. γ spectra were measured on and off resonance to ensure that the observed γ peaks were indeed a result of the $^{48}Ti(p, \gamma)^{49}V$ resonances.

Energy calibration of the spectra was accomplished by reference to standard-source γ rays, the 6.131-MeV γ decay of ^{16}O, and the 511-keV energy differences between full-energy, single-escape, and double-escape peaks. Analysis of these differences indicates a linear relationship between energy and channel number below 7-MeV γ-ray energy, but above 7 MeV definite nonlinearities appear. Therefore, γ energies quoted have a probable error of ±5 keV except for those energies over 7 MeV where the probable error rises to ±10 keV.

RESULTS

Excitation functions over the resonances studied are shown in Fig. 1. These show the yield of γ rays with energy greater than 6.5 MeV at 55°. Experiments with the thinnest targets established that the widths of the 1007- and 1013-keV resonances are less than 0.5 keV.

The high-energy γ spectra observed at the four resonances are seen in Fig. 2. All of the peaks displayed, with the exception of those from the ^{16}O 6131-keV γ decay, are a product of the decay of the ^{49}V resonances. Several weak medium-energy γ rays were observed which could not be assigned to γ decay through a definite state in the absence of coincidence measurements.

Angular distributions were measured for the known primary γ rays at each resonance. These angular distributions were then fit by the formula $W(\theta) = A_0 + A_2 P_2(\cos\theta)$. From these results, intensities, mixing ratios, and probable spins were determined. The mixing ratios were extracted using the phase-consistent formulas of Rose and Brink.[5]

* Work supported in part by U. S. Atomic Energy Commission under Contract No. AT(11-1)-1766.
† These data were obtained at the Nuclear Structure Laboratory of the University of Kansas, Lawrence, Kan., which is supported in part by the U. S. Atomic Energy Commission under Contract No. AT(11-1)-1120.

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Table I shows the results of these measurements. The states of ^{49}V for which primary transitions were observed, the intensity of these primary transitions, the ratio of A_2 to A_0, the mixing ratio, and the probable spin of the secondary state are listed. In cases where more than one spin is shown, the probable spin is underlined. The 1387-keV resonance is assigned a spin of $\frac{3}{2}$ on the basis that the observed anisotropy of the decay to the 747-keV state rules out a spin of $\frac{1}{2}$, and an assignment of $\frac{5}{2}$ yields improbable mixing ratios for the γ decay to the 89-keV state. A negative-parity assignment is favored on the basis of penetrability and the measured mixing ratios for the first three excited ^{49}V states. Higher spins are ruled out by penetrability arguments. The radiative widths shown in Table I are calculated under the assumption that $\Gamma_p/\Gamma=1$ and are probably accurate only within a factor of 2, due to difficulties in calibrating the Ge(Li) detector's efficiency and uncertainties in the assumptions used in the calculations. However, the values which can be compared are in good agreement with those of Fodor *et al.*[3] Since the major sources of errors have equal effects on all reported widths, the inaccuracies in the observed relative strengths of the γ rays reported here are estimated to be less than $\pm30\%$. As previously noted in the *f-p* shell,[6,3] the $M1$ transition strengths are much smaller than the Weisskopf estimates, particularly for the $\frac{3}{2}$ resonances, in contrast to the strong $M1$ γ decay of analog resonances observed in *s-d* shell nuclei.[7]

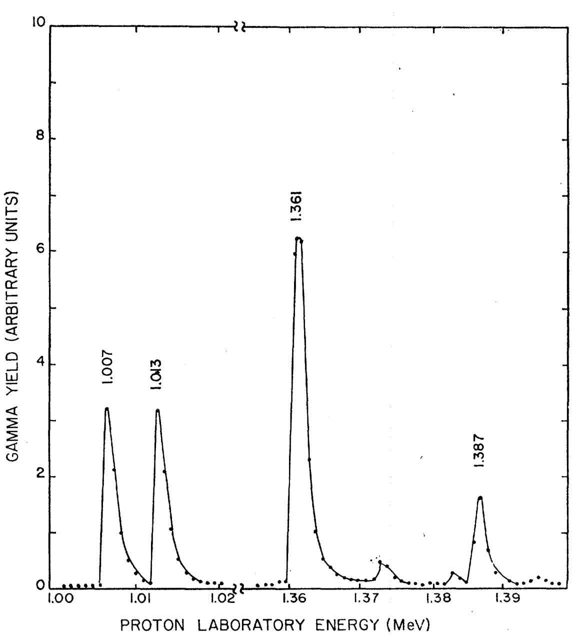

FIG. 1. Excitation curves for the ^{48}Ti(p, γ)^{49}V reaction in the vicinity of the resonances studies. These excitation curves were measured using a single-channel analyzer biased at 6.5 MeV to preclude interference from the ^{19}F(p, $\alpha\gamma$)^{16}O reaction.

An energy-level diagram of the states discussed in this paper is seen in Fig. 3. The ^{49}Ti levels[8] have been raised in energy by an amount $\Delta E_c-(M_n-M_H)c^2$, in order to allow easy comparison with the resonances observed in the ^{48}Ti(p, γ)^{49}V reaction. In addition, the ^{49}Ti states which show definite stripping patterns are drawn full-width while those whose angular distributions show no stripping patterns are drawn half-width.

The energies listed in Fig. 3 for the resonant ^{49}V states are those obtained by averaging the sum of the primary and secondary γ energies through various intermediate states. These excited-state energies then yield a measured value of 6757 ± 5 keV for the ^{48}Ti(p, γ)^{49}V Q value, in good agreement with the value of 6762 ± 3 keV listed by Maples *et al.*[9] Assuming that the 7742- and 7748-keV states are analogs of the ^{49}Ti 1384-keV state and that the 8089-keV state is an analog of the ^{49}Ti 1724-keV state[2,3] and using the value of -1384 ± 3 keV given for the ^{49}Ti(p, n)^{49}V Q value by Maples *et al.*,[9] one obtains a value of 7749 ± 10 keV for the Coulomb displacement energy ΔE_c, in reasonable agreement with the value of 7796 ± 30 keV listed by Sherr.[10]

DISCUSSION OF RESULTS

States in ^{49}V have been observed in the ^{52}Cr(p, α)^{49}V,[11] ^{50}Cr(t α)^{49}V,[12] and ^{48}Ti(^{3}He, d)^{49}V [12,13] reactions. Comparison of the results of these experiments with those of the present investigation allows one to identify states seen in the γ decay of resonant states with those observed in the particle-transfer reactions. From this identification, assignment of probable spins and parities for these states is usually possible.

Thus, the ground state, 89-, 152-, and 747-keV states in ^{49}V are known to have spins and parities of $\frac{7}{2}^-$, $\frac{5}{2}^-$, $\frac{3}{2}^-$, and $\frac{3}{2}^+$.[13] These assignments are in accord with the present measurements and, indeed, as has been mentioned previously, assisted us in making a spin-parity assignment of $\frac{3}{2}^-$ to the 1387-keV resonance. In referring to states seen in particle-transfer reactions, we shall use the excitation energies given by Brown and MacGregor.[11]

The 1639- and 1658-keV states in ^{49}V are observed in the γ decay of all four resonances studied. The 1639-keV state may be identified with the 1647-keV state,

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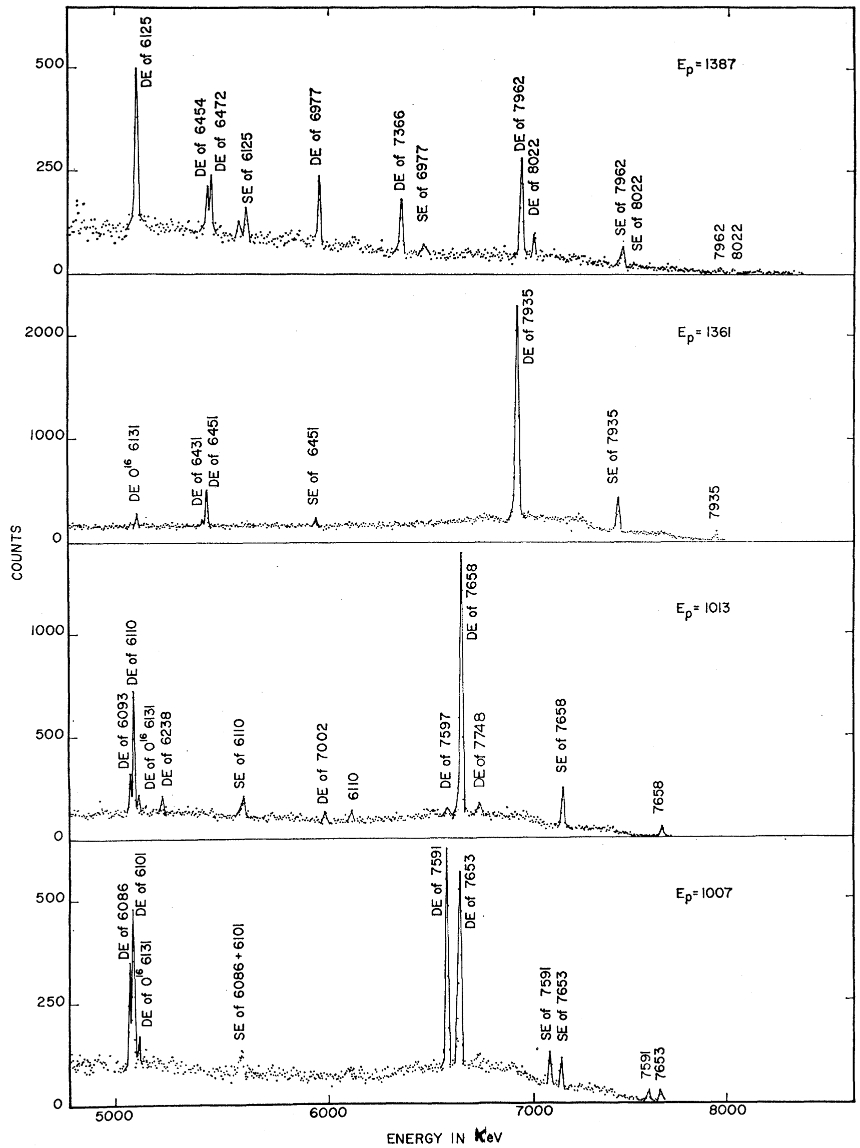

FIG. 2. High-energy γ spectra measured at the four resonances studied. These spectra were obtained using an 18-cc Ge(Li) detector and contain all of the primary γ rays identified and discussed in this paper.

which is only weakly excited in proton stripping but is strongly excited in proton pickup with an $l=0$ angular distribution.[12] The observed γ decays are consistent with an assignment of $\frac{1}{2}^+$ for this state. The 1658-keV state may be identified with the 1644-keV state which is probably $\frac{3}{2}^-$, though neither the particle-transfer nor γ-ray data can rule out an assignment of $\frac{1}{2}^-$ for this state.

The 1138-keV state which is seen in the γ decay of the 1387-keV resonance may be identified with the 1140-keV state seen in particle-transfer reactions. This state is weakly excited by both stripping and pickup reactions, but Bachner *et al.*[12] report an $l=3$ angular distribution for the pickup reaction and suggest an assignment of $\frac{7}{2}^-$ for this state. However, the γ-ray angular distribution indicates that a spin assignment of $\frac{5}{2}$ is more probable, although an assingment of $\frac{7}{2}^-$ is not definitely ruled out.

The 1510-keV state which is seen in the decay of the 1013-keV resonance may be identified with the 1521-keV state which is weakly excited in pickup but not in stripping and for which no l assignment could be made.[12] The γ decay indicates that spin assignments of $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$ are all possible, and no convincing argument can be made for favoring one over the others.

The 1990-keV state seen in the decay of the 1387-keV resonance may be identified with the 1999-keV state which shows a weak $l=0$ pattern in the pickup reaction.[12] The γ decay is consistent with an assignment of $\frac{1}{2}^+$ to this state.

The 2237-keV state may be identified with the 2240-keV state which is weakly excited in the pickup reac-

TABLE I. γ decay of resonances.

Proton resonance energy (keV)	Primary γ-ray energy (keV)	Final-state energy (keV)	A_2/A_0	Radiative width (eV)	Radiative width in Weisskopf units[a]	$J_i^{\pi_i}$	$J_f^{\pi_f}$	Mixing ratio δ
1007	7653	89	0.043±0.035	0.11	0.007	$\frac{3}{2}^-$	$\frac{5}{2}^-$	0.13±0.03 2.84±0.29
	7591	152	0.469±0.028	0.15	0.08	$\frac{3}{2}^-$	$\frac{3}{2}^-$	−0.05±0.02 −3.25±0.23
	6101	1639	−0.426±0.064	0.05	0.0002	$\frac{3}{2}^-$	$\frac{1}{2}^+$	−0.038±0.035 1.91±0.17
	6086	1658	0.04±0.06	0.05	0.01	$\frac{3}{2}^-$	$\frac{1}{2}^-$	−0.29±0.03 4.04±0.54
					0.05	$\frac{3}{2}^-$	$\frac{3}{2}^-$	0.23±0.04 −33.7±19.4
	5504	2237	−0.68±0.28	0.01		$\frac{3}{2}^-$	$\frac{1}{2}$	0.11±0.23 1.37±0.60
							$\frac{3}{2}$	No solution
							$\frac{5}{2}$	−0.28±0.33 −3.08±1.9
	5438	2303	0.403±0.103	0.03	0.01	$\frac{3}{2}^-$	$\frac{1}{2}^-$	−0.51±0.07 19.1±9.6
					0.05	$\frac{3}{2}^-$	$\frac{3}{2}^-$	0.00±0.07 −3.87±0.95
1013	7748	0	0.17±0.27	0.007	0.01	$\frac{3}{2}^-$	$\frac{7}{2}^-$	0.03±0.38 1.35±0.90
	7658	89	−0.030±0.20	0.17	0.01	$\frac{3}{2}^-$	$\frac{5}{2}^-$	0.058±0.019 3.61±0.28
	7597	152	0.58±0.23	0.009	0.005	$\frac{3}{2}^-$	$\frac{3}{2}^-$	−0.13±0.15 −2.51±0.95
	7002	747	0.4±0.4	0.005	0.0001	$\frac{3}{2}^-$	$\frac{3}{2}^+$	−0.07±0.27 −3.02±1.45
	6238	1510	−0.03±0.20	0.01		$\frac{3}{2}^-$	$\frac{1}{2}$	−0.25±0.11 3.5±1.0
							$\frac{3}{2}$	0.28±0.15 40±35
							$\frac{5}{2}$	0.06±0.18 3.6±1.6
	6110	1639	−0.469±0.043	0.06	0.0003	$\frac{3}{2}^-$	$\frac{1}{2}^+$	−0.02±0.03 1.80±0.10
	6093	1658	−0.089±0.093	0.02	0.004	$\frac{3}{2}^-$	$\frac{1}{2}^-$	−0.22±0.05 3.19±0.44
					0.02	$\frac{3}{2}^-$	$\frac{3}{2}^-$	0.32±0.07 16.4±8.3
	5445	2303	0.25±0.10	0.03	0.009	$\frac{3}{2}^-$	$\frac{1}{2}^-$	−0.41±0.06 7.1±2.0
					0.045	$\frac{3}{2}^-$	$\frac{3}{2}^-$	0.09±0.06 −6.2±1.8
1361	7935	152	−0.008±0.010	1.4	0.065	$\frac{1}{2}^-$	$\frac{3}{2}^-$	
	6451	1639	−0.08±0.06	0.17	0.0007	$\frac{1}{2}^-$	$\frac{1}{2}^+$	
	6432	1658	···	<0.02		$\frac{1}{2}^-$	$\frac{3}{2}^-$, $\frac{1}{2}^-$	

TABLE I (*Continued*)

Proton resonance energy (keV)	Primary γ-ray energy (keV)	Final-state energy (keV)	A_2/A_0	Radiative width (eV)	Radiative width in Weisskopf units[a]	$J_i^{\pi_f}$	$J_f^{\pi_f}$	Mixing ratio δ
1387	8022	89	-0.27 ± 0.17	0.009	0.0005	$\frac{3}{2}^-$	$\frac{5}{2}^-$	-0.14 ± 0.15
	7962	152	0.00 ± 0.05	0.05	0.025	$\frac{3}{2}^-$	$\frac{3}{2}^-$	0.26 ± 0.03
	7366	747	0.375 ± 0.079	0.03	0.0004	$\frac{3}{2}^-$	$\frac{3}{2}^+$	0.01 ± 0.05 -4.07 ± 0.80
	6977	1138	0.028 ± 0.085	0.03	0.002	$\frac{3}{2}^-$	$\frac{5}{2}^-$	0.11 ± 0.08 3.0 ± 0.7
					0.2	$\frac{3}{2}^-$	$\frac{7}{2}^-$	-0.12 ± 0.08 1.9 ± 0.4
	6472	1639	-0.15 ± 0.11	0.02	0.00008	$\frac{3}{2}^-$	$\frac{1}{2}^+$	-0.19 ± 0.06 2.9 ± 0.5
	6454	1658	-0.04 ± 0.12	0.02	0.004	$\frac{3}{2}^-$	$\frac{1}{2}^-$	-0.25 ± 0.06 3.5 ± 0.6
					0.020	$\frac{3}{2}^-$	$\frac{3}{2}^-$	0.28 ± 0.09 41 ± 31
	6125	1990	-0.17 ± 0.06	0.05	0.0002	$\frac{3}{2}^-$	$\frac{1}{2}^+$	-0.18 ± 0.03 2.9 ± 0.3

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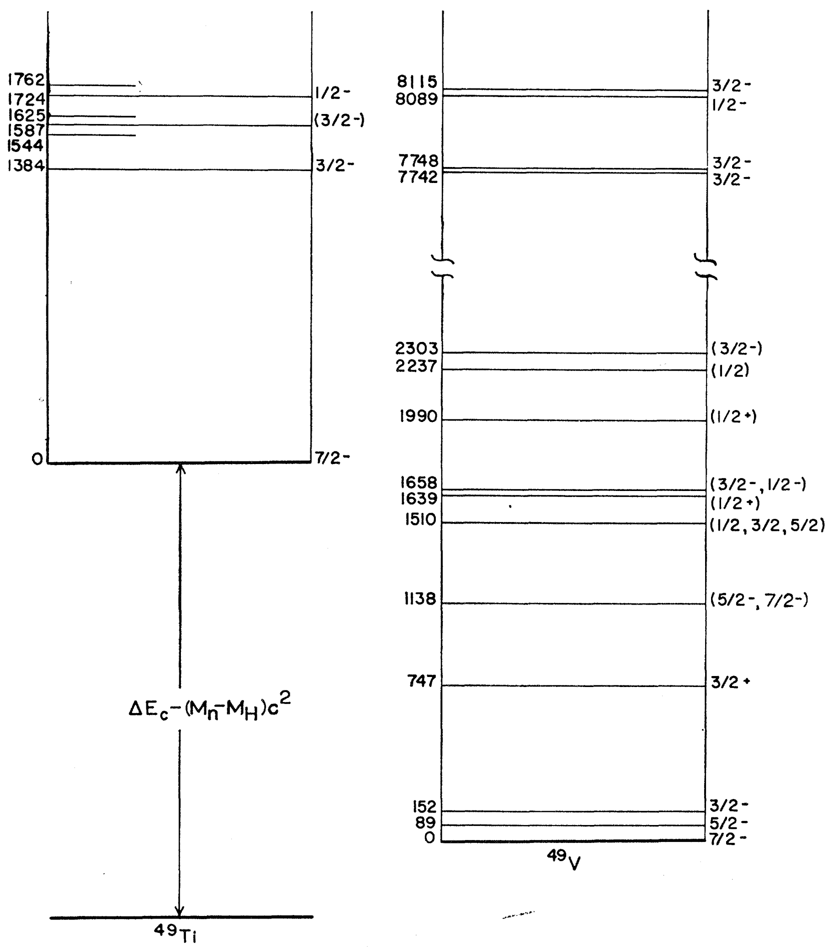

FIG. 3. Energy levels of ^{49}Ti and ^{49}V of interest in this paper. Only those levels of ^{49}V below 2.5-MeV excitation energy are shown which were observed in the γ decay of the four resonances studied. The levels in ^{49}Ti have been raised in energy by $\Delta E_c-(M_n-M_H)c^2$ to allow easy comparison with their analogs in ^{49}V.

tion but shows no definite stripping pattern. The γ-decay data indicates that a spin assignment of $\frac{1}{2}$ for this state is highly favored.

Finally, the 2303-keV state which is seen in the decay of the 1007- and 1013-keV resonances may be identified with the 2312-keV state which is strongly excited in the stripping reaction with an $l=1$ distribution.[12,13] The γ-decay data indicate that a $\frac{3}{2}^-$ assignment is strongly favored for this state.

Thus we find that the γ decay of these resonances is generally more complicated than reported by Fodor *et al.*[3] We have observed γ decay to six or more states at excitations under 2.5 MeV for every resonance but the $\frac{1}{2}^-$ resonance, and every spectrum showed evidence of decay to higher excited states. However, we find generally better agreement in ^{49}V states' excitation energies with Fodor *et al.*,[3] and with the particle-transfer reaction, than we do with Klapdor and Zausig.[4]

We also are forced to conclude that the 1387-keV resonance is not an analog resonance. First, its location would require an alteration of 12 keV in ΔE_c from the value found for the other resonances if it were considered to be the analog of the 1762-keV state in ^{49}Ti. In addition, the assignment of $\frac{3}{2}^-$ to this resonance would then imply that the 1762-keV state was a $\frac{3}{2}^-$ state for which no stripping pattern could be observed. Although McCullen *et al.*[14] predict a $\frac{3}{2}^-$ state in this region formed by $(f_{7/2})^n$ wave functions coupling to spin $\frac{3}{2}$, the observed weak $l=1$ stripping to the ^{49}Ti 1587-keV state[8] makes it likely that the 1587-keV state may be identified with the predicted state. Finally, it should be noted that Dubois[1] and Klapdor[2] have observed equally strong (p, γ) resonances at excitations which correspond to no known states in ^{49}Ti, while Dubois observed no similarly strong resonance corresponding to the ^{49}Ti 1587-keV state.[1]

Since the resonant states' widths are less than 1 keV, the yield of γ rays using a target thicker than 1 keV will be approximately proportional to $\Gamma_p\Gamma_\gamma/\Gamma$, and Γ_p/Γ may be assumed to be approximately 1 since neutron decay of the resonances is forbidden. Thus, the yield will be approximately proportional to Γ_γ, and assuming that a strong (p, γ) resonance is an analog state implies an assumption that the analog-state radiative width is much larger than its neighboring $T=T_z$ states. Since measurements show that the $M1$ decay of the analog state is severely inhibited, this is a very dangerous assumption to make in this mass region. Thus, the assignment of strong (p, γ) resonances as analog resonances needs confirmation from proton elastic scattering and resonance spin assignments.

Finally, we note the striking difference in decay of the two fragments of the $\frac{3}{2}^-$ analog resonance at 1007- and 1013-keV bombarding energies. The effect, a strong decay to the 152-keV $\frac{3}{2}^-$ state by the 1007-keV resonance and the almost total absence of this decay for the 1013-keV resonance, is similar to that seen by Chasman *et al.*[6] However, there is an important difference in that the 152-keV state can not be identified as the anti-analog state. Rather, the states at 1658 and 2303 keV would share this identification since they possess the major $l=1$ spectroscopic factors measured in the ^{48}Ti(^{3}He, d)^{49}V reaction.[12,13] Although there is some variation in decay to these states, it is not nearly so striking. However, these variations are again indications that the $M1$ analog to anti-analog transition is severely inhibited and of the same order of strengths as transitions from the $T=T_z$ neighboring states with much more complicated configurations. This leads to the interesting speculation that the inhibition of the $M1$ strength is a characteristic feature of $\frac{3}{2}^-$ analog states in the $1f$-$2p$ shell nuclei.

ACKNOWLEDGMENTS

It is indeed a pleasure to thank the faculty, Dr. R. W. Krone and Dr. F. W. Prosser, and the graduate students at the University of Kansas nuclear laboratory for their hospitality and assistance. Without the great cooperation of all, this experiment would not have been possible. Finally, we gratefully acknowledge the assistance of Dr. G. Seaman and R. Tapphorn for assistance in data acquisition.

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