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Reaction ^{48}Ti$(p,\gamma)^{49}$V from 1.75 to 2.50 MeV

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Resonances in the reaction ^{48}Ti$(p,\gamma)^{49}$V from 1.75 to 2.50 MeV have been observed with a resolution of 2 keV. Spins of 58 resonances are inferred from their γ-decay schemes, both by considering known final-state spins and by comparing branching patterns to those from resonances of known spin using multidimensional scaling. Limits to possible spins of 29 bound states, some observed here for the first time in γ spectra, are proposed. In the energy range studied, there are eleven ^{49}Ti levels of spin $<\frac{9}{2}$. Of the eight previously proposed analogs, two have directly measured spins. Among the remaining six, three appear to have spins incompatible with their parents. Three new analog candidates are proposed, along with new fragments of existing analogs.

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I. INTRODUCTION

The low-lying states of the low-Z f-shell nuclei—Ca to V—are of two types. In odd nuclei, the negative-parity states are generally well described within the context of an $f_{7/2}$ shell model, although there is some evidence for collectivity near midshell. As N nears 28, neutron excitations to the fp shell occur even among low-lying states. In addition, positive-parity states exist which are attributable to single particle-hole excitations involving the sd shell. On these in some cases are built well-developed rotational bands.

At high excitation, one must expect many-particle excitations, and indeed the high level density demonstrates this. Among the highly excited states, however, lie isobaric analogs of low-lying levels of neighboring nuclei. Thus, in ^{49}V near 9 MeV excitation, where the level density is very high—over 200 levels per MeV—analogs of low-lying ^{49}Ti states have been found. The simpler nature of these states is revealed by large proton stripping cross sections, though the expected proportionality of their spectroscopic factors to those for neutron stripping to the parent states is only approximately followed. Their γ decay is predominantly to lower levels of strong single-particle character. In this way, several $T=\frac{5}{2}$ analogs have been identified in the ^{49}Ti-^{49}V system [1–14]. The analog of the Ti ground state, at $E_x=6.416$ MeV in V, is bound and has only been observed in charge exchange reactions [2,3]. Higher-lying analogs have been identified using the (^{3}He,d) reaction [4] and resonant proton capture and scattering [7–14].

The first (p,γ) reaction study on Ti isotopes was conducted by Dubois [5] who measured yield curves in the proton energy range 0.8 to 1.4 MeV. Subsequently, analogs of the lowest strong $l=1$ states in Ti, presumably excitations of the form $f^{-1}p$, were identified [6–13]. Above these, strong resonances at appropriate energies have been suggested as analog states, though no supporting spin evidence is given [5,7]. In the study reported here, the proton energy regions from 1.0 to 1.4 and 1.75 to 2.5 MeV were surveyed. In the vicinity of potential analog resonances, γ-ray spectra were measured and spins are suggested on the basis of the decay branching.

II. EXPERIMENT

The methods of measurement and analysis followed closely those used in earlier measurements [15,16]. Proton beams of 15 to 20 μA from the King Saud University AK and McMaster University KN Van de Graaff accelerators struck 10 μg/cm^2 targets of $>99\%$ ^{48}Ti on high-purity thick tungsten backings. The (p,γ) excitation function was measured in steps of about 1.5 keV from 0.98 to 1.41 and 1.75 to 2.50 MeV at King Saud and McMaster Universities, respectively. Wide γ-ray windows 2–5 and 7–9 MeV were used. The latter contained mostly primary transitions to the lowest-lying states of ^{49}V while the former contained secondaries from higher states.

At the stronger resonances, spectra were accumulated using a high resolution HPGe detector close to the target at 55°. The γ-ray spectra were calibrated with radioactive sources, room background lines of K, Ra, and Th, and radiation from reactions—generally $(p,p'\gamma)$ and $(p,\alpha\gamma)$ on target contaminants, particularly F, Na, and Si. From the capture spectra at strong resonances, it was possible to calibrate the beam energy with an absolute precision of about 2 keV, using the known Q value of 6.758 MeV [1]. With a system resolution of 1.5 to 2.0 keV, the relative energies of neighboring resonances could be determined more precisely.

No angular distribution measurements were made. Spins were attributed to the resonances from the decay branching. The low-lying states of ^{49}V have a wide variety of spins (Table III) so considerable restriction on

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*Deceased.

resonance spin and parity could be made by assuming all strong decays to be either $E1$, $M1$, or $E2$. A multidimensional nonmetric scaling analysis [17] was applied as well, using the similarities of branching patterns (cross correlation) to classify resonances according to spin. A measure of similarity is found by treating the set of branching amplitudes from each resonance as a vector in a space of the final states and forming scalar products for all pairs of resonances. For two resonances, i and j, with branching intensities $(a_{ik})^2$ and $(a_{jk})^2$ to final states k, scalar products ("similarities") are

$$C_{ij}=\sum_k a_{ik}a_{jk} \ .$$

A "map" is formed in which each resonance is a point and the distances are related monotonely to dissimilarities. The set of positions in space (x_i) is sought such that the distance x_{ij} between points x_i and x_j increases as C_{ij} decreases. That is,

$$x_{ij} < x_{nm} \quad \text{if } C_{ij} > C_{nm} \ .$$

Programs which search for such arrangements have been developed largely to treat loosely correlated multivariate data in the social sciences. Such a program, MINISSA [18], was used in an earlier study of spectra from many resonances of conventionally determined spin [17]. There, an approximately linear dispersion in spin was found parallel to one of the axes. A resonance of unknown spin which fell in the map close to ones of known spin was assumed to have the same spin. The method appears to be insensitive to parity. Included in the present analysis are decay schemes of resonances (noted in Table I and its footnotes) measured only by others [9,12]. Among the low-lying resonances are those from which earlier angular distribution measurements give spin assignments, thus forming a calibration of the scaling analysis.

TABLE I. Resonances in ^{48}Ti$(p,\gamma)^{49}$V. A.D.: Spin assigned from angular distribution measurements. Decay: Spin inferred from decay to states of known spin. MDS: Spin inferred from multidimensional scaling analysis (see text).

Res. No.	E_p (MeV)	E_x (MeV)	J^π A.D.	J^π Decay	J^π MDS	J^π Adopted	
A	0.960	7.699		$\frac{3}{2},\frac{5}{2}$	$\frac{1}{2},\frac{3}{2}$	$(\frac{3}{2})$	a
1	0.992	7.730					
2	1.007	7.745	$\frac{3}{2}^-$			$\frac{3}{2}^-$	b,c,d
3	1.013	7.751	$\frac{3}{2}^-$			$\frac{3}{2}^-$	b,c,d
4	1.024	7.762		$\frac{1}{2}^-,\frac{3}{2},\frac{5}{2}$	$\frac{1}{2}$	$(\frac{1}{2}^-)$	a
5	1.034	7.771					
6	1.036	7.773					
7	1.049	7.786					
8	1.053	7.790					
9	1.062	7.798					
10	1.072	7.809					
11	1.084	7.820					
12	1.092	7.828					
13	1.103	7.839		$\frac{1}{2}^-,\frac{3}{2},\frac{5}{2}$	$\frac{1}{2}$	$(\frac{1}{2}^-)$	
14	1.120	7.855					
15	1.125	7.861					
16	1.132	7.868					
17	1.141	7.876		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{1}{2},\frac{3}{2}$	$(\frac{3}{2}^-)$	a
18	1.151	7.886					
19	1.164	7.899					
20	1.176	7.910		$\frac{1}{2}^-,\frac{3}{2},\frac{5}{2}$	$\frac{1}{2}$	$(\frac{1}{2}^-)$	
21	1.190	7.924					
22	1.196	7.930					
23	1.206	7.939					
24	1.210	7.943		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{3}{2}$	$(\frac{3}{2}^-)$	
25	1.229	7.962					
26	1.242	7.975					
27	1.255	7.988					
28	1.264	7.996					
29	1.271	8.003					
30	1.281	8.013		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{3}{2}$	$(\frac{3}{2}^-)$	

TABLE I. (*Continued*).

Res. No.	E_p (MeV)	E_x (MeV)	J^π				
			A.D.	Decay	MDS	Adopted	
31	1.288	8.020					
32	1.294	8.026					
33	1.310	8.042					
34	1.316	8.048					
35	1.321	8.052					
36	1.327	8.058		$\frac{3}{2},\frac{5}{2}^+$	$\frac{3}{2},\frac{5}{2}$	$(\frac{3}{2},\frac{5}{2}^+)$	
37	1.341	8.071		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$	
38	1.344	8.075					
39	1.352	8.083					
40	1.362	8.092	$\frac{1}{2}^-$			$\frac{1}{2}^-$	b,c,d
B	1.374	8.105	$\frac{1}{2}$			$\frac{1}{2}$	e
41	1.387	8.117	$\frac{3}{2}^-$			$\frac{3}{2}^-$	c
42	1.402	8.131		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{3}{2}$	$(\frac{3}{2}^-)$	
C	1.466	8.195		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{3}{2}$	$(\frac{3}{2}^-)$	a
D	1.543	8.270		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{1}{2},\frac{3}{2}$	$(\frac{3}{2}^-)$	a
E	1.564	8.289	$\frac{3}{2}^-$			$\frac{3}{2}^-$	e
43	1.764	8.486					
44	1.766	8.488					
45	1.779	8.501					
46	1.784	8.506					
47	1.794	8.516					
48	1.800	8.522					
49	1.804	8.526		$\frac{5}{2}$	$\frac{3}{2},\frac{5}{2}$	$(\frac{5}{2})$	
50	1.810	8.531					
51	1.814	8.535					
52	1.820	8.541					
53	1.830	8.551					
54	1.841	8.561					
55	1.851	8.572					
56	1.856	8.576					
57	1.861	8.581					
58	1.868	8.588					
59	1.871	8.591					
60	1.883	8.603					
61	1.887	8.607					
62	1.892	8.612					
63	1.903	8.622					
64	1.909	8.628		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{1}{2},\frac{3}{2}$	$(\frac{3}{2}^-)$	
65	1.914	8.633		$\frac{5}{2}$	$\frac{3}{2},\frac{5}{2}$	$(\frac{5}{2})$	
66*A*	1.922	8.640		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{3}{2}$	$(\frac{3}{2}^-)$	
66*B*	1.924	8.642		$\frac{3}{2}^-,\frac{5}{2}^+$	$\frac{3}{2},\frac{5}{2}$	$(\frac{3}{2}^-,\frac{5}{2}^+)$	
67	1.935	8.653					
68	1.942	8.660					
69	1.946	8.664					
70	1.952	8.670					
71	1.964	8.682		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$	
72	2.014	8.731					
73	2.024	8.740					

TABLE I. (*Continued*).

Res. No.	E_p (MeV)	E_x (MeV)	A.D.		J^π	
				Decay	MDS	Adopted
74	2.030	8.746				
75	2.042	8.758				
76	2.047	8.764				
77	2.055	8.771				
78	2.058	8.774				
79	2.063	8.780				
80	2.069	8.785		$\frac{3}{2}^-, \frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
81	2.073	8.789		$\frac{5}{2}^-$	$\frac{5}{2}$	$(\frac{5}{2}^-)$
82	2.085	8.801				
83	2.090	8.805				
84	2.096	8.812				
85	2.099	8.815				
86	2.111	8.826				
87	2.116	8.831				
88	2.124	8.838				
89	2.131	8.846				
90	2.137	8.852		$\frac{5}{2}^-, \frac{7}{2}^-$	$\frac{5}{2}, \frac{7}{2}$	$(\frac{5}{2}^-, \frac{7}{2}^-)$
91	2.145	8.859				
92	2.148	8.862				
93	2.153	8.867		$\frac{5}{2}^+$	$\frac{3}{2}, \frac{5}{2}$	$(\frac{5}{2}^+)$
94	2.163	8.877		$\frac{3}{2}^-, \frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
95	2.167	8.881		$\frac{5}{2}$	$\frac{5}{2}, \frac{7}{2}$	$(\frac{5}{2})$
96	2.177	8.891		$\frac{3}{2}^-, \frac{5}{2}$	$\frac{3}{2}$	$(\frac{3}{2}^-)$
97*A*	2.180	8.893		$\geq \frac{5}{2}^-$	$\frac{5}{2}$	$(\frac{5}{2}^-)$
97*B*	2.182	8.895		$\frac{5}{2}^+$	$\frac{3}{2}, \frac{5}{2}$	$(\frac{5}{2}^+)$
98	2.185	8.899				
99	2.189	8.903		$\frac{3}{2}^-, \frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
100	2.199	8.912		$\frac{3}{2}^-, \frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
101	2.205	8.918				
102	2.208	8.922		$\frac{5}{2}^+$	$\frac{5}{2}$	$(\frac{5}{2}^+)$
103	2.212	8.925		$\frac{5}{2}, \frac{7}{2}^-$	$\frac{7}{2}$	$(\frac{7}{2}^-)$
104	2.215	8.928		$\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
105	2.221	8.934				
106	2.227	8.940				
107	2.230	8.943		$\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
108	2.237	8.949				
109	2.243	8.956				
110	2.247	8.959				
111	2.253	8.965		$\frac{5}{2}^+$	$\frac{5}{2}$	$(\frac{5}{2}^+)$
112	2.258	8.970				
113	2.262	8.974				
114	2.270	8.981				
115	2.275	8.987				
116	2.287	8.998		$\frac{1}{2}^-, \frac{3}{2}, \frac{5}{2}$	$\frac{1}{2}$	$(\frac{1}{2}^-)$
117	2.297	9.008		$\frac{5}{2}^+$	$\frac{5}{2}$	$(\frac{5}{2}^+)$
118	2.302	9.013				
119	2.305	9.016				
120	2.313	9.024				

TABLE I. (*Continued*).

Res.	E_p	E_x			J^π	
No.	(MeV)	(MeV)	A.D.	Decay	MDS	Adopted
121	2.319	9.030		$\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
122	2.327	9.038		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
123	2.334	9.044		$\frac{3}{2}^-,\frac{5}{2},\frac{7}{2}^-$	$\frac{7}{2}$	$(\frac{7}{2}^-)$
124	2.341	9.051				
125	2.346	9.057		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
126	2.353	9.063				
127	2.362	9.072		$\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
128	2.366	9.076		$\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
129	2.369	9.079		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{3}{2}$	$(\frac{3}{2}^-)$
130	2.373	9.083		$\frac{3}{2},\frac{5}{2}$	$\frac{3}{2}$	$(\frac{3}{2})$
131	2.380	9.090		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{3}{2},\frac{5}{2}$	$(\frac{3}{2}^-,\frac{5}{2})$
132	2.385	9.095		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
133	2.390	9.100				
134	2.394	9.103				
135	2.397	9.107				
136	2.409	9.118		$\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
137	2.423	9.132		$\frac{5}{2}$	$\frac{3}{2},\frac{5}{2}$	$(\frac{5}{2})$
138	2.427	9.135		$\frac{3}{2}^-,\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
139	2.436	9.144				
140	2.440	9.149		$\frac{5}{2}$	$\frac{5}{2},\frac{7}{2}$	$(\frac{5}{2})$
141	2.446	9.154		$\frac{5}{2}^+$	$\frac{5}{2}$	$(\frac{5}{2}^+)$
142	2.453	9.161		$\frac{1}{2}^-,\frac{3}{2},\frac{5}{2}$	$\frac{1}{2},\frac{3}{2}$	$(\frac{1}{2}^-,\frac{3}{2})$
143*A*	2.460	9.168		$\frac{5}{2}^+$	$\frac{3}{2},\frac{5}{2}$	$(\frac{5}{2}^+)$
143*B*	2.461	9.169		$\frac{3}{2}^-,\frac{5}{2},\frac{7}{2}^-$	$\frac{1}{2},\frac{3}{2}$	$(\frac{3}{2}^-)$
144	2.467	9.174		$\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$
145	2.475	9.183		$\frac{3}{2}^-,\frac{5}{2},\frac{7}{2}^+$	$\frac{5}{2}$	$(\frac{5}{2})$
146	2.486	9.193		$\frac{3}{2}^-,\frac{5}{2},\frac{7}{2}^+$	$\frac{5}{2},\frac{7}{2}$	$(\frac{5}{2},\frac{7}{2}^+)$
147	2.488	9.195		$\frac{5}{2}$	$\frac{5}{2}$	$(\frac{5}{2})$

[a] From decay schemes of Ref. [12].
[b] Reference [9].
[c] Reference [10].
[d] Reference [11].
[e] Reference [12].

III. RESULTS

The yield curves for the ^{48}Ti$(p,\gamma)^{49}$V reaction from 1.0 to 1.4 and 1.75 to 2.50 MeV are shown in Figs. 1 and 2 and the resonances are listed in Table I. Several of the peaks are seen to be incompletely resolved and many are broadened, as is to be expected for an average spacing of under 5 keV [5,7].

In Table II, the γ branching from 54 of the strongest capture resonances is given. All decay to two or more of the lowest five bound states shown in Table III. They also populate a majority of the known levels of low spin ($J<\frac{9}{2}$). Among the final states are a number of close doublets—at 1.64, 2.18, 2.81, and 3.24 MeV. These were distinguished in each spectrum using nearby lines (full energy or escape peaks) from transitions to well-established states. There are two known 1-keV doublets, at 3.13 and 3.39 MeV, which could not be distinguished with the overall calibration and measurement uncertainty of 2 keV. Above 3 MeV, 21 levels were observed for the first time in a γ-ray experiment. These are given in Table IV. Half are possibly levels which have been seen in reaction studies and reported in Ref. [1] with uncertainties of 5 to 10 keV. The remainder are new.

Although no angular distribution measurements were made, it is possible to place limits on the spins and parities of the resonances whose spectra were measured and on some of the bound final states. Assuming that the major decays from each resonance are $E1$, $M1$, and $E2$, the spin-parity values listed in Table I under "Decay" are found from the data of Tables II and III. The method of multidimensional scaling [17] does not require knowledge

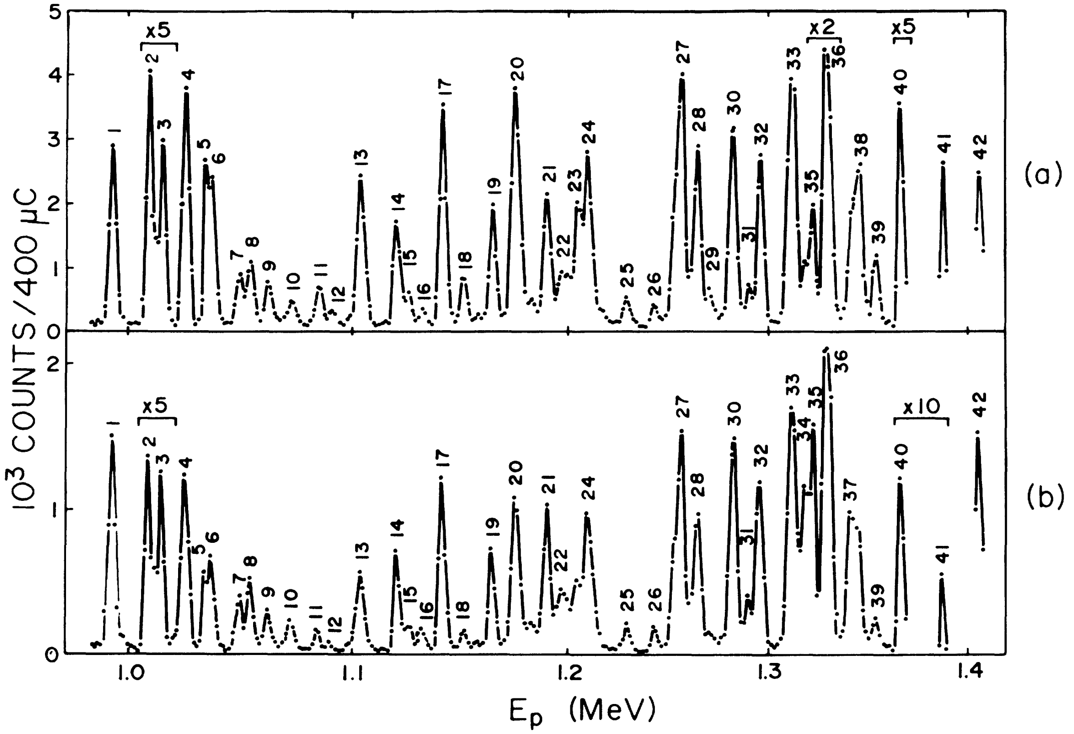

FIG. 1. Yield curve for the ^{48}Ti$(p,\gamma)^{49}$V reaction in the proton energy range 0.98 to 1.41 MeV, for (a) $2<E_\gamma<5$ MeV, (b) $7<E_\gamma<9$ MeV.

TABLE II. Decay branches for resonances in ^{49}Ti$(p,\gamma)^{49}$V.

Res. No.	13	20	24	30	36	37	40	42	49	64	65	66*A*	66*B*	71	80
0.0			2	14		20		1	1	1	1	1	2	22	31
0.091			14	3	4	13		2	37	1	9	15	18	3	22
0.153	8	24	13	9	23	41	90	7	9	4	24	35	8	44	6
0.748	11	15	2	62	7	2	2	5	7	27	7	23	18	4	8
1.140			4	3	10			34	9	27	9		9	1	5
1.155															
1.515					13			8	2		10	4	3	5	5
1.603									1		3				
1.643	43					15	6	10			4	6			
1.646		7			6					13			7	3	
1.662	20	15	15	4				7	21	6	3		10	4	9
1.995		11	5		2			5	2	10	3		3	2	5
2.179															
2.183											4				
2.235			2		10						3		3	1	
2.265	5	6	18		4	9				4			1	2	
2.310		15	9	4	4						7	1	1		
2.388					2			4			2		1	1	2
2.408									1					1	2
2.671															
2.680															
2.806												1			
2.811			3							7			1		
3.017												1	4		
3.134													1	1	
3.224				1	1		2								
3.239												2			
3.242					3			1					1		
3.259					1										
3.325													1	2	

TABLE II. (*Continued*).

Res. No.	13	20	24	30	36	37	40	42	49	64	65	66*A*	66*B*	71	80
3.342															
3.388	9	7	3		2			3			2		1		
3.464															
3.516											2				
3.521															
3.531			1					4							
3.603								3	5						
3.638												1		1	
3.671														1	
3.678			5												
3.694															
3.721												3			
3.741	4				8							1			
3.771															
3.782															
3.816			1												
3.841												1			
3.912			1									2			
3.927															
3.960									5		3	1	1		
4.002												1	2		
4.035															
4.088															
4.098															
4.129															
4.152											4				
4.218			1									1			
4.253			1												
4.259													1		
4.270													1		
4.289															
4.359															
4.373															
4.397															
4.422															
4.540															
4.635															

Res. No.	81	90	93	94	95	96	97*A*	97*B*	99	100	102	103	104	107	111
0.0	12	7	8	33	12	2	34	4	20	39	17	47	18	21	5
0.091	14	1	5	9	23	7	13	12	11	19	13	6	7	11	12
0.153	37	32	23	6		15	7	17	19	8	19	23	9	10	10
0.748	6		12	11		30	4	29	13	5	8		4	6	10
1.140	2	13	8	21	3		6	12	6	3	3	3	10	2	24
1.155	4	1					1								
1.515	2	3	4	2	3		3	4	2	1	4	2	2	3	9
1.603	1	1	1		2		3	2			10	7	2	3	
1.643									7						
1.646					4	13				1	8		15	13	
1.662			11	2		4	4	9	2	3		2	10	13	
1.995			1		5	3	3	2	4	3	4		2	3	
2.179											3				2
2.183	2				5		2				3				
2.235		8	2	4	3	2	6		6	3		2	7	1	
2.265			2			4	3	3		1					
2.310	2		5	1	3	3	2		3	1	8		4	6	
2.388	2	8	1	4										3	
2.408	2	2	1		1					1					2
2.671															

TABLE II. (*Continued*).

Res. No.	81	90	93	94	95	96	97*A*	97*B*	99	100	102	103	104	107	111
2.680	2														2
2.806		4					1								
2.811				1			1			4					
3.017	3	3	1	1	5				2				6	2	3
3.134			3	1											2
3.224	2	2		1											1
3.239				1					4	1					
3.242	1		1					2							
3.259															
3.325				1											
3.342															
3.388	3	5	1	1	2	2		2		1		2	4		3
3.464			1		3										
3.516															
3.521															
3.531															
3.603										1					
3.638			1				1								
3.671															
3.678															
3.694					1	1				1				3	
3.721															
3.741			2			3	1								4
3.771															
3.782												2			
3.816					1	1									2
3.841			2		1	1									
3.912		2	2		1		2			2					2
3.927															2
3.960						1									2
4.002					1										
4.035												1			
4.088															1
4.098						1									
4.129		2					1			1					
4.152															
4.218															1
4.253						1									1
4.259							1	2							
4.270						2									
4.289									1						
4.359															
4.373						2									
4.397							1			2					
4.422															
4.540															
4.635						2						1			

Res. No.	116	117	121	122	123	125	127	128	129	130	131	132	136	137	138
0.0		3	45	16	16	25	12	19	5		3	1	6	5	19
0.091		3	4	27	11	16	21	12	5	30	19	23	17	11	8
0.153	64	35	5	25	15	30	17	10	9	4	58	7	6	46	39
0.748	12	5	3	6		8	5	2	58	16	6	28	5	5	11
1.140		5	2	26	13	2	4	7		17		10	6		
1.155															
1.515					3	3	2	7	6			6	21		
1.603		1	1				2	5					3	8	
1.643			7					6	4	13					

TABLE II. (*Continued*).

Res. No.	116	117	121	122	123	125	127	128	129	130	131	132	136	137	138
1.646	7	1					6				2	10		11	8
1.662			3			3	5	6	4	8				4	15
1.995		5	5			6	4	6					10		
2.179															
2.183					11		2	2							
2.235			3		7		1					3	11		
2.265	17													6	
2.310		4	1		11	7	10	6				2	2	4	
2.388		10	2				2		6		4				
2.408		2	1					2							
2.671					3										
2.680															
2.806													5		
2.811							1								
3.017		4	3				2	3	3			4	7		
3.134			1												
3.224															
3.239			4												
3.242															
3.259					4										
3.325								2							
3.342		3													
3.388			1				1						1		
3.464															
3.516					2										
3.521							3								
3.531															
3.603			1												
3.638															
3.671		3	1												
3.678		3													
3.694								1				2			
3.721								1							
3.741		3										2			
3.771		2													
3.782															
3.816															
3.841															
3.912		5			2			2				2			
3.927															
3.960					2			1							
4.002		3													
4.035															
4.088		2													
4.098															
4.129															
4.152															
4.218															
4.253															
4.259															
4.270															
4.289															
4.359															
4.373															
4.397															
4.422															
4.540			2												
4.635															

TABLE II. (*Continued*).

Res. No.	140	141	142	143*A*	143*B*	144	145	146	147
0.0	4	5		13	4	35	2	20	21
0.091	13	9	11	4	2	6	20	22	5
0.153	9	11	57	10	59	17			4
0.748	20	22	5	3		14	32	24	19
1.140				4		8	43		16
1.155									
1.515	10	13		6	2		3		8
1.603	12			7	2	4			4
1.643			11	8	7				
1.646		5						10	
1.662		8		9	3	8			8
1.995	13			1	4			24	
2.179		3							
2.183	7								
2.235			9	1					
2.265		5	4	2					
2.310		13		8	3	3			3
2.388	7			2					3
2.408				2					3
2.671									
2.680									
2.806		3		3					
2.811									
3.017				2		5			3
3.134									
3.224		1	3		2				
3.239		2							
3.242				2					
3.259									
3.325									
3.342									
3.388				2	1				
3.464									
3.516									
3.521									3
3.531	5								
3.603				1					
3.638									
3.671									
3.678				1					
3.694				1					
3.721									
3.741				1	1				
3.771									
3.782									
3.816									
3.841									
3.912									
3.927									
3.960				2					
4.002									
4.035				1					
4.088									
4.098									
4.129									
4.152									
4.218									
4.253									
4.259									

TABLE II. (*Continued*).

Res. No.	140	141	142	143*A*	143*B*	144	145	146	147
4.270									
4.289									
4.359				2					
4.373									
4.397									
4.422				1					
4.540									
4.635				1					

of the final-state spins, since it relies only on similarities of decay patterns. The two-dimensional MDS (multidimensional scaling) "map" (Fig. 3) for the decays measured in this and earlier studies includes the resonances for which angular distribution measurements allowed firm spin assignments. Those resonances, underlined in Fig. 3, form the calibration of the dispersion. Because the only directly measured spins are $\frac{1}{2}$ and $\frac{3}{2}$, the calibration is perhaps suspect at higher spins. The clustering of resonances seen in Fig. 3 suggests areas to which spins of $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ may be attributed. The MDS spin attributions, shown in Table I, are in all cases consistent with those found from decay, including the higher spin values.

TABLE III. Bound states of known J^π in ^{49}V.

E_f (MeV)	J^π	E_f (MeV)	J^π	E_f (MeV)	J^π
0.0	$\frac{7}{2}^-$	1.603	$\frac{7}{2}^+$	2.388	$\frac{5}{2}^+$
0.091	$\frac{5}{2}^-$	1.662	$\frac{3}{2}^-$	2.408	$\frac{7}{2}^-$
0.153	$\frac{3}{2}^-$	1.995	$\frac{3}{2}^+$	2.806	$\frac{5}{2}^+$
0.748	$\frac{3}{2}^+$	2.179	$\frac{9}{2}^+$	3.133	$\frac{9}{2}^+$
1.140	$\frac{5}{2}^+$	2.183	$\frac{7}{2}^-$	3.134	$\frac{7}{2}^-$
1.155	$\frac{9}{2}^-$	2.265	$\frac{5}{2}^-$	3.239	$\frac{7}{2}^-$
1.515	$\frac{5}{2}^-$	2.310	$\frac{3}{2}^-$	4.129	$\frac{5}{2}^-$

TABLE IV. Bound states newly observed in γ spectra.

E_x (MeV)[a,b]	E_x (MeV)[a,c]
3.242	3.516
3.603	3.521
3.638	3.721
3.671[d]	3.771
3.678[d]	3.782
3.694	4.035
3.927	4.259
4.152	4.270
4.397	4.289
4.422	4.359
4.540	

[a] Uncertainty 0.002 MeV.

[b] Previously observed only in particle spectra [1].

[c] Not previously reported.

[d] Single peak in (p,α) [1].

TABLE V. New spins for bound states in ^{49}V.

E_x (MeV)	J^π a	J^π b	
1.643	$\frac{1}{2},\frac{3}{2}^{(-)},\frac{5}{2}$	$\frac{1}{2}^+,\frac{3}{2},\frac{5}{2}^-$	
1.646	$\frac{1}{2}^{(+)},\frac{3}{2}^{(+)},\frac{5}{2}$	$\frac{1}{2}^+,\frac{3}{2},\frac{5}{2}^-$	
2.680		$\frac{3}{2},\frac{5}{2},\frac{7}{2}$	
3.224		$\frac{3}{2},\frac{5}{2}$	c
3.242		$\frac{3}{2},\frac{5}{2},\frac{7}{2}^-$	d
3.259		$\geq\frac{9}{2}$	e
3.325	$\frac{17}{2}^-$	$\frac{1}{2}^+-\frac{7}{2}^+$	d
3.342		$\frac{1}{2}^+-\frac{9}{2}^+$	f
3.388	$\leq\frac{7}{2}^-$	$\frac{3}{2}^-,\frac{5}{2}^-$	
3.464		$\frac{1}{2}^+-\frac{9}{2}^+$	f
3.516		$\frac{3}{2}^--\frac{9}{2}$	
3.521		$\leq\frac{9}{2}$	
3.531		$\leq\frac{7}{2}^-$	
3.638		$\frac{3}{2},\frac{5}{2},\frac{7}{2}^-$	
3.671		$\frac{1}{2}^+-\frac{9}{2}^+$	f
3.678		$\frac{1}{2}^+-\frac{7}{2}^-$	
3.721		$\leq\frac{7}{2}^-$	
3.771		$\frac{1}{2}^+-\frac{9}{2}^+$	
3.782		$\geq\frac{9}{2}$	e
3.841		$\frac{1}{2}^+-\frac{5}{2}$	c
3.912		$\frac{3}{2}^-$	
3.927		$\frac{1}{2}^+-\frac{9}{2}^+$	f
3.960		$\frac{3}{2}^-,\frac{5}{2},\frac{7}{2}^-$	
4.002		$\frac{3}{2}^-$	
4.035		$\frac{3}{2}^--\frac{9}{2}^+$	
4.098		$\leq\frac{7}{2}^-$	
4.218		$\frac{3}{2}^-$	
4.259		$\frac{3}{2},\frac{5}{2},\frac{7}{2}$	
4.397		$\leq\frac{9}{2}^-$	

[a] Reference [1].

[b] This work, combined with limits from Ref. [1].

[c] Including decay from $J=\frac{1}{2}$ resonance [12].

[d] Doublet, spin incompatible with state adopted by Ref. [1].

[e] Seen only at $J^\pi=\frac{7}{2}^-$ resonances.

[f] Seen only at $J^\pi=\frac{5}{2}^+$ resonances.

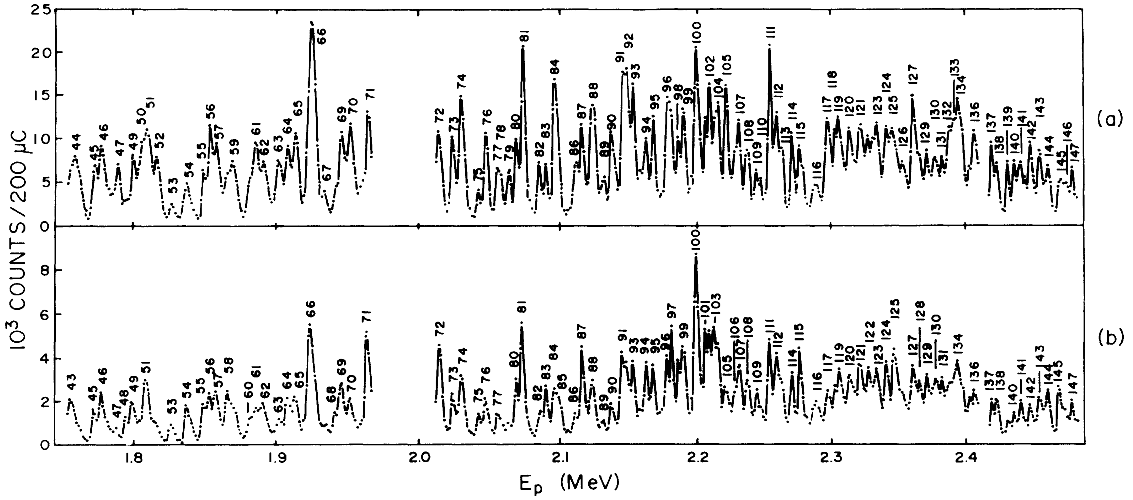

FIG. 2. Yield curve in the proton energy range 1.75 to 2.50 MeV, (a) and (b) as in Fig. 1.

TABLE VI. $T=\frac{5}{2}$ analog states in $A=49$.

^{49}Ti E_x (MeV)	^{49}Ti J^π	Res. No.	^{49}V E_x (MeV)	^{49}V J^π	ΔE_C (MeV)	Ref.
0.0	$\frac{7}{2}^-$		6.416	$(\frac{7}{2}^-)$	7.800	[2,3]
1.382	$\frac{3}{2}^-$	2	7.745	$\frac{3}{2}^-$	7.747	[4,7–13]
		3	7.750	$\frac{3}{2}^-$	7.752	
1.586	$\frac{3}{2}^-$	24	7.943	$(\frac{3}{2}^-)$	7.741	
		30	8.013	$(\frac{3}{2}^-)$	7.812	
1.623	$\frac{5}{2}^- - \frac{9}{2}^-$	37	8.071	$(\frac{5}{2})$	7.832	
1.723	$\frac{1}{2}^-$	40	8.092	$\frac{1}{2}^-$	7.753	[4,7,9,11,13]
		B	8.105	$\frac{1}{2}$	7.766	[12]
1.762	$\frac{5}{2}^-$					
2.261	$\frac{5}{2}^-,\frac{7}{2}^-$	65	8.633	$(\frac{5}{2})$	7.756	
2.471	$\frac{5}{2}^-,\frac{7}{2}^-$	80	8.785	$(\frac{5}{2})$	7.698	
		81	8.789	$(\frac{5}{2}^-)$	7.702	[7]
2.504	$\frac{1}{2}^+$		8.870	$\frac{1}{2}^+$	7.750	[14]
			8.876	$\frac{1}{2}^+$	7.756	[14]
		94	8.877	$(\frac{5}{2})$	7.748	
2.513	$\frac{5}{2}^-$	97*A*	8.893	$(\frac{5}{2}^-)$	7.764	
		99	8.903	$(\frac{5}{2})$	7.774	
		100	8.912	$(\frac{5}{2})$	7.783	[4,7,9]
2.517						
2.664	$\frac{3}{2}^+$	130	9.083	$(\frac{3}{2})$	7.803	
2.721						
3.175	$\frac{1}{2}^-$		9.568	$(\frac{1}{2})^-$	7.777	[4,14]
3.261	$\frac{3}{2}^-$		9.662	$\frac{3}{2}^-$	7.785	[4,14]
3.847	$\frac{5}{2}^-$		10.230	$\frac{5}{2}^-,\frac{7}{2}^-$	7.767	[4]
4.505	$\frac{5}{2}^+$		10.925	$(\frac{5}{2})^+$	7.804	[4]
4.770	$\frac{9}{2}^+$		11.150	$(\frac{7}{2}^+,\frac{9}{2}^+)$	7.764	[4]

The final column lists most likely spins attributable to each resonance.

Most of the decay strength from the resonances studied leads to bound levels of well-established J^{π} (Table IV). The majority of the remaining bound states are fed from only a few resonances. However, in some cases, the spins of the initial states are sufficiently disparate to allow some restriction of the spins of final states. For instance, each of the 1.64-MeV pair of states is fed from resonances ranging in spin from $\frac{1}{2}^-$ to $\frac{5}{2}^+$, allowing a spin-parity range of $(\frac{1}{2}^+,\frac{3}{2},\frac{5}{2}^-)$ under the above assumptions of dipole and $E2$ transitions. Similarly, the 2.235-MeV level, fed from resonances ranging in spin from $\frac{3}{2}^-$ to $\frac{7}{2}^-$, may be presumed to have a spin in the range $(\frac{3}{2}^-,\frac{5}{2},\frac{7}{2}^-)$. Table V summarizes the bound levels for which some contribution has been made to narrowing the range of possible spins and parities.

IV. DISCUSSION

The yield curves of Figs. 1 and 2 and the resonances listed in Table I may be compared directly with the earlier results. The most extensive excitation function measurements are those of Dubois [5] from 0.88 to 1.37 MeV and of Klapdor [7] from 1.34 to 2.29 MeV. The agreement is excellent. It is more difficult to compare the present results with those obtained by Prochnow *et al.* [14] for elastic and inelastic scattering at higher resolution. Those results extend from 1.8 to 3.1 MeV. Such experiments at low proton energies yield extensive data on $l=0$ and $l=1$ resonances but are insensitive to higher l levels. The two methods are therefore more complementary than competitive. Some connection can be made at strong $l=2$ levels. There the agreement seems good.

In the few cases where spectra can be compared with those from earlier studies agreement is found. The greater sensitivity and resolution of the detectors used in the present work allowed more weak branches to be found. In no case do the spin values found from this work conflict with earlier values.

The region studied covers a range of excitation energies in ^{49}V from 7.7 to 9.2 MeV, corresponding to an isobaric parent excitation energy range 1.3 to 2.7 MeV (Table VI). In this range there are ten ^{49}Ti states with spins less than $\frac{9}{2}$ and two of unknown spin. Other workers have identified eight analog candidates but only two have spin measurements confirming the assignment. The $\frac{3}{2}^-$ doublet at 7.745 and 7.750 MeV, corresponding to the first excited state of Ti, is well studied, as is the $\frac{1}{2}^-$ resonance at 8.092 MeV. The 8.105-MeV spin-$\frac{1}{2}$ resonance detected by Kiuru [12] may be another fragment of this analog. Above this the assignments already made have been based on resonance strength and no spin values have been suggested, except by analogy with the supposed parent states. The 8.115-MeV level suggested by Refs. [5,7] appears to have spin $\frac{3}{2}^-$, not $\frac{5}{2}^-$, the parent state spin. Similarly, the V levels at 8.640 and 8.642 MeV, previously proposed as analogs [5], seem to have spins different from their supposed parent at 2.261 MeV in Ti. A potential alternative, with likely spin $\frac{5}{2}^-$, is at 8.633 MeV.

The next level in Ti is also $l=3$. Reference [5] suggests as its analog the 8.789-MeV level. The present results confirm spin $\frac{5}{2}$ for this level and for a companion state at 8.785 MeV. Analogs for the $\frac{1}{2}^+$ and $\frac{5}{2}^-$ levels at 2.5 MeV in Ti have been suggested at 8.914 and 8.915 MeV, respectively. A pair of $\frac{1}{2}^+$ resonances has been found at $E_p=2.156$ and 2.163 MeV in elastic scattering [14]. The present results show no low-spin resonance and five spin-$\frac{5}{2}$ resonances from 8.877 to 8.912 MeV. Four of these decay to states of large single-particle strength, while the fifth, Resonance 95, does not. This dissimilarity in decay is reflected in Fig. 3. The proposed analog of the Ti $\frac{3}{2}^+$ level at 2.664 MeV, at 8.968 MeV in V [5] appears to be a $\frac{5}{2}^+$ level. No sure $\frac{3}{2}^+$ candidate has been found, but there is a spin-$\frac{3}{2}$ level of undetermined parity at 9.083 MeV.

In addition, there are two low-energy Ti levels, at 1.586 and 1.623 MeV, with small stripping strengths. Possible analog candidates of the first of these $(\frac{3}{2}^-)$ are at 7.943 and 8.013 MeV. The 70-keV separation is large for these to be fragments and they should be considered as alternates. The higher resonance, No. 30, has a much greater tendency to decay to single-particle states and may therefore be preferred. The spin-$\frac{5}{2}$ resonance at 8.071 MeV may be the analog of the 1.623-MeV Ti level, although the parent state spin is uncertain [1].

The above cases, and five higher analogs proposed by others, are included in Table VI. The consistency of the Coulomb energy differences ΔE_C is evident.

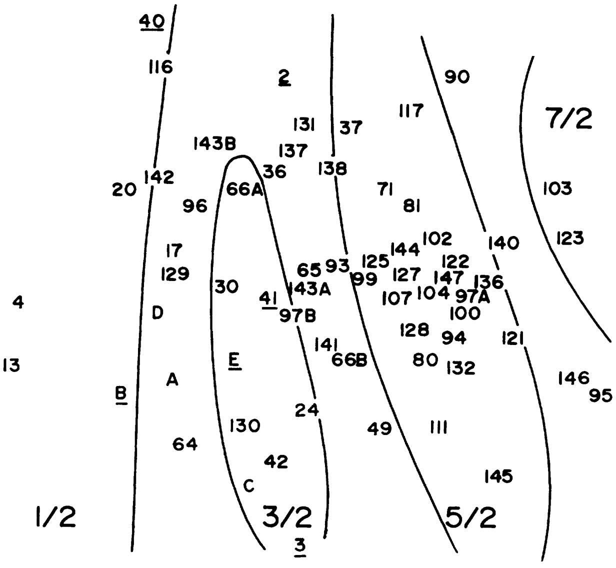

FIG. 3. Two-dimensional nonmetric scaling "map" of resonances, identified by their number. The six underlined numbers indicate resonances whose spins have been determined using angular distribution measurements (B and 40: $\frac{1}{2}$; 2, 3, 41, and E: $\frac{3}{2}$). The boundaries outline the regions within which single most likely spin values have been attributed.

V. CONCLUSIONS

In spite of the high level density, it has been possible to select by decay characteristics likely spins of many resonances in the $^{48}\mathrm{Ti}+p$ system, and to identify a number of new isobaric analog state candidates.

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