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(t,^{3}He) reactions on ^{40,42,44}Ca, ^{46,48,50}Ti, ^{54}Cr, and ^{54}Fe

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The ^{40,42,44}Ca, ^{46,48,50}Ti, ^{54}Cr, and ^{54}Fe (t,^{3}He) reactions have been studied at $E_t=25$ MeV. Differential cross sections have been measured in the angular range $\theta_{lab}=5.5°-50°$. The angular distributions have been compared with coupled-channels calculations. J^π assignments have been made to a number of states in the residual nuclei ^{40,42,44}K, ^{46,48,50}Sc, ^{54}V, and ^{54}Mn.

I. INTRODUCTION

In two recent papers[1,2] we have discussed spectroscopic evidence obtained on the structure of ^{56,58}Mn and ^{58}Co, using the (t,^{3}He) reactions. The present paper extends the results to nuclei with $A=40-54$ and discusses the population of 1^+ states in these lower A nuclei to extend the results on the Gamow-Teller (GT) strengths we presented earlier.[1]

The experimental techniques were described in these earlier papers.[1,2] We mentioned there also the distorted wave Born approximation (DWBA) and coupled-channel Born approximation (CCBA) calculations which were used to derive the J^π assignments. The comparison here is made only with the CCBA calculations (CHUCK). Table I displays the target and reaction parameters.

II. RESULTS

A. States of ^{40}K

In Fig. 1 we present the spectrum of 47 ^{3}He groups we observe corresponding to states with $E_x<4800$ keV, and in Fig. 2 we display those angular distributions which we have fitted with CCBA curves. The J^π assignments are better known[3–6] in ^{40}K than in any of the other nuclei we have studied in this experiment; see Table II. We can thus compare how well the CCBA curves for known L transfers fit our angular distributions. Indeed the agreement is good to excellent when this comparison is made with the ground state of ^{40}K and the first three excited states at 30, 800, and 892 keV ($J^\pi=4^-$, 3^-, 2^-, and 5^-): see Fig. 2. (The experimental angular distributions for $J=4$ states consistently peak at lower angles in the reactions we are reporting.)

The quality of the fit to the lowest four states is encouraging, as these should have particularly simple configurations. Since ^{40}Ca represents a doubly closed shell, the (t,^{3}He) reaction, which changes a proton into a neutron, excites particle-hole states of rather pure nature at low excitation energy. The lowest four states arise from the neutron-proton configuration

$$[(\pi 1d_{3/2})^{-1}(\nu 1f_{7/2})]_{2^-,3^-,4^-,5^-},$$

with the $(\pi 1d_{3/2})$ shell being full and the $(\nu 1f_{7/2})$ shell

TABLE I. Target and reaction parameters.

Target	Q_m[a]	Isotopic enrichment[b] (%)	Target thickness[c] (μg/cm^2)
^{40}Ca	-1293.5 ± 1.3[d]	99.97	105
^{42}Ca	-3506.5 ± 1.9[d]	93.65 ^{42}Ca, 5.85 ^{40}Ca	74
^{44}Ca	-5641 ± 40[d]	95.35 ^{44}Ca, 4.58 ^{40}Ca	188
^{46}Ti	-2347.9 ± 1.8[d]	81.2 ^{46}Ti, 14.5 ^{48}Ti, 2.1 ^{47}Ti, 1.1 each ^{49}Ti, ^{50}Ti	142
^{48}Ti	-3975.5 ± 5.1[d]	99.1	140,223
^{50}Ti	-6870 ± 16[d]	67.72 ^{50}Ti, 24.1 ^{48}Ti, 2.99 ^{49}Ti, 2.71 ^{46}Ti, 2.48 ^{47}Ti	154
^{54}Cr	-7023 ± 15[e]	94.35 ^{54}Cr, 3.26 ^{52}Cr, 2.31 ^{53}Cr	97
^{54}Fe	-678.2 ± 2.3[d]	97.1 ^{54}Fe, 2.8 ^{56}Fe	99,189

[a]Q_m of the (t,^{3}He) reaction on target shown.
[b]Isotopes present as <1 percent are not shown.
[c]From comparison of elastic cross sections and DWBA calculations. We estimate the uncertainties in the target thicknesses as ±10 percent.
[d]From masses in Ref. 11.
[e]E. R. Flynn, J. W. Sunier, and F. Ajzenberg-Selove, Phys. Rev. C 15, 879 (1977).

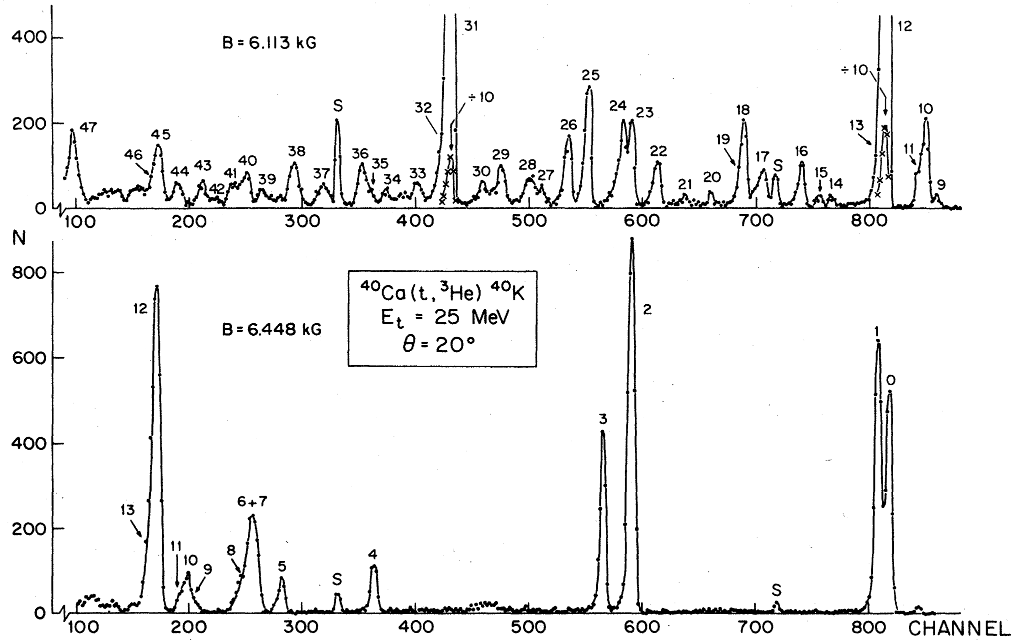

FIG. 1. Spectra of the ^{40}Ca(t,^{3}He)^{40}K reaction at $E_t = 25$ MeV, $\theta = 20°$ (lab) for two values of the magnetic field. N is the number of counts in a two-channel bin. The numbered groups correspond to the states displayed in Table II.

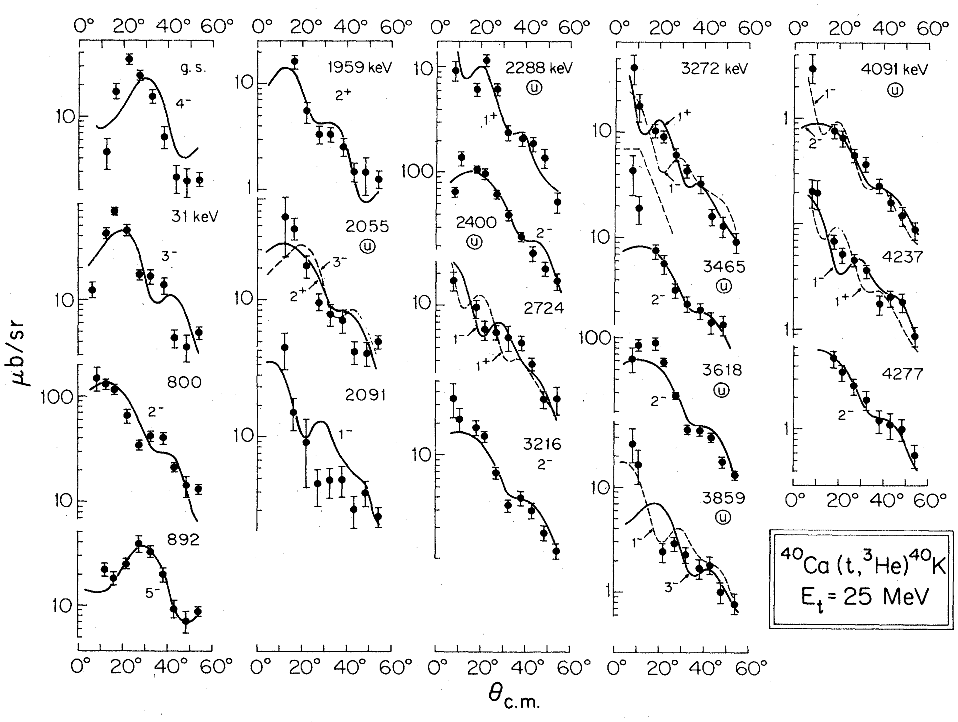

FIG. 2. Angular distributions of ^{3}He groups from the ^{40}Ca(t,^{3}He)^{40}K reaction. For each distribution the following information is given: the E_x (in keV) in ^{40}K (as displayed under "Present work" in Table II); the possible J^π from comparison with CCBA calculations plotted as a full line; the letter u, circled, designating states unresolved in this experiment. In cases where the experimental angular distribution could be reproduced by any of several theoretical curves these are shown. For comments see Table II and the text. Angular distributions were obtained to all the groups displayed in Table II. If they are not shown it is because there was no way to fit the curve theoretically, primarily in the case of unresolved and/or very weak groups. The error bars represent statistical errors only.

TABLE II. Energy levels of ^{40}K.

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L[c]	J^π	E_x (keV)	J^π
0	0	3+5	4^-	0	4^-
1	31 ± 5	3	3^-	29.8	3^-
2	800 ± 5	1+3	2^-	800.1	2^-
3	891 ± 5	5	5^-	891.4	5^-
4	1642 ± 8			1643.6	0^+
5	1959 ± 8	2	2^+	1959.1	2^+
6				2047.4	2^-
	2055 ± 15		d		
7				2069.8	3^-
8	2091 ± 20	1	1^-	2103.7	1^-
9	2265 ± 15^{e}			2260.4	3^+
10				2289.9	1^+
	2288 ± 20	0+2	1^{+d}		
11				2290.5	3^-
12	2390 ± 10			2397.2	4^-
		1+3	2^{-d}		
13	2411 ± 15			2419.2	2^-
14	2534 ± 15^{e}			2542.8	7^+
15	2566 ± 15			2576.0	2^+
16	2606 ± 15			2626.0	0^-
17	2724 ± 15	1	1^-	2730.4	1
	f			2746.9	$2^-,3^-$
				2756.7	$2^+,(3)$
18	2774 ± 20			2786.7	3^+
				2787.1	3,4,5
19	2807 ± 20				
				2807.9	$(1,2)^-$
20	2865 ± 20			2879.1	6^+
21	2938 ± 20			2950.7	
				2985.9	$2^-,3^+$
22	3017 ± 15^{g}		h		
				3028.0	2^-
				3100.2	$(4,5)^+$
23	3100 ± 15		h		
				3109.8	$(1,2)^+$
24	3120 ± 15		h		
				3128.4	$(2^- \text{-} 4^+)$
	f			3146.4	1
	f			3153.8	3^-
25	3216 ± 15	1+3	2^-	3228.7	2^-
26	3272 ± 15	(0+2)	$1(^+)$	3293	
27	3360 ± 15			3368.0	$(2,3)^-$
				3393.6	2^-
28	3391 ± 20^{g}				
				3414.4	2^+
				3439.2	$1^-,2^+$
29	3465 ± 15		$2^{-d,h}$		
				3486.2	2^-
30	3517 ± 15				
	e			3557.0	$(1^- \text{-} 4^+)$
				3599.2	2^-
31	3618 ± 15	1+3	$2^{-d,h}$		
				3629.9	$(2,3)^-$
32	3653 ± 20			3663.8	$(2^- \text{-} 4^+)$
				3711.1	(2^-)
33	3715 ± 15^{g}	e			
				3738.5	$1^+(2^-,3^+)$

TABLE II. (*Continued*).

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L[c]	J^π	E_x (keV)	J^π
34	3780±30[g]	i		3767.8	(1^--3)
				3797.6	1^+
	f			3821.4	2^-
35	3859±15	1	1^- [d]	3840.3	(1,2^+)
				3868.7	3^-,(2^-)
36	3883±15	i		3887.9	(1^--3)
				3902.1	
	f			3923.8	(1^--4^+)
37	3995±15[g]			3996	
				4020.4	(0-3)$^-$
38	4091±15[g]		2^-+(1^-)[d]	4076±5	
				4104.5	(1^--3^-)
				4110.9	(1^--3)
	f			4149.0	(2^--3)
39	4190±20[e]			4180.0	3^-
				4213.1	(2^-,3^+)
40	4237±15	1	1^-	4253.6	(1^-)
41	4277±15	1+3	2^-	4280.5	(2^-)
42	4335±15			4352	
43	4374±15			4365.6	8^+
				4384.0	0^+; $T=2$
	f			4395.9	(0-3)$^-$
	f			4419.4	(2^--4^+)
44	4455±15			4473.0	(2,3)$^-$
45	4508±15				
46	4535±15			4537.1	(2^-)
	e			4586.8	2^-
	f			4665.8	2^-
	f			4697	
				4744.1	(2^+)
47	4781±15	j		4761±5	(1^+)
				4788.9	(1^+)

[a]P. M. Endt and C. Van der Leun, Nucl. Phys. **A310**, 1 (1978); R. C. Shang *et al.*, *ibid.* **A366**, 13 (1981); D. J. Beale, A. R. Poletti, and J. R. Southon, Aust. J. Phys. **32**, 195 (1979); T. Von Egidy *et al.*, J. Phys. G **10**, 221 (1984).
[b]See Fig. 1.
[c]L transfers assumed in the theoretical CCBA curves shown in Fig. 2. L transfers are not shown if more than one value of J^π is possible.
[d]Angular distribution shown in Fig. 2 is of unresolved group.
[e]Observed at several angles: groups are generally weak.
[f]Not observed, but contributions of weak groups are not excluded.
[g]The width of this group indicates that it is due to unresolved states.
[h]See the text.
[i]Differential cross sections could not be obtained at $\theta_{c.m.} < 18°$, and therefore no comments can be made concerning the possibility of an $L=0+2$ or $L=1$ contribution.
[j]The angular distribution is not forward peaked.

being empty in the ^{40}Ca target nucleus.

Since the orbitals below the Fermi surface are all even parity, and those above are odd parity, we expect to excite only odd parity states in ^{40}K, with the exception of possible collective states. The appearance of 1^+ states is unexpected, as there are no unsaturated spin-orbit partners available to couple to 1^+. The observation of these states must be due to a fraction of the GT strength being excited collectively by the charge-exchange (t,^{3}He) reaction. One important consideration is that ^{40}Ca represents the extreme of the $N=Z$ nuclei and, even though ^{40}Ca should in principle be doubly closed, the Coulomb forces in this case distort the nucleus, producing deformed states. It is therefore possible that the (t,^{3}He) reaction may be sensing some of this collectivity.

For many of the groups at higher excitation energies an experimental problem made it impossible to extract the cross sections at some forward angles: the hydrogen contamination of the ^{40}Ca target gave an extremely intense background from the ^{1}H(t,^{3}He)n reaction. Thus, in a number of cases, definite J^π assignments could not be made. Another problem is that ^{40}K has many closely spaced states which we could not separate. At best (see Table II and Fig. 2) we determine the dominant L transfers.

We will comment first on angular distributions to unresolved states. Groups 6 + 7 correspond to 2^- and 3^- states at 2047 and 2070 keV: we show the combined angular distribution and the CCBA curves for these two assignments without any attempt to fit the sum of the two since we do not know the relative intensities of the two groups. The envelope is consistent with the known assignments. Groups 10 and 11 correspond to a 1^+ state at 2290 keV and to a 3^- state at 2291 keV: our unresolved angular distribution is clearly dominated by the 1^+ state. Groups 12 and 13 correspond to 4^- and 2^- states at 2397 and 2419 keV: our unresolved data are strongly dominated by the 2^- state. The angular distribution for group 22 [unresolved states at 2986 and 3028 keV with $J^\pi=(2^-,3^+)$ and 2^-] is not shown because the most forward angle was $\theta_{\mathrm{c.m.}}=18°$: the differential cross section decreases monotonically to 54°. Groups 23 and 24 were plotted without an attempt to resolve them since they correspond to three known states (see Table II): the differential cross section decreases exponentially from $\theta_{\mathrm{c.m.}}=8°$ to 54°. It is possible for one of the three states to have $J^\pi=1^+$ but there is no way to make an unambiguous determination without having independent information on the J^π of the other two states. Qualitatively, and assuming reasonable cross sections for all three states, the results are consistent with $J^\pi=5^+$, 1^+, and 2^- for $E_x=3100$, 3110, and 3128 keV, but this is a highly speculative comment. Group 29 corresponds to unresolved states at 3439 and 3486 keV with $J^\pi=(1^-,2^+)$ and 2^-: in Fig. 2 we show the 2^- CCBA curve but it is inconsistent with the two forward points at $\theta_{\mathrm{c.m.}}=8°$ and 11°, which could be due to the population of an unresolved 1^- state. Group 31, corresponding to the 3599 and 3630 keV states [$J^\pi=2^-$ and $(2,3)^-$] is quite well fitted by 2^- although 2^-+3^- is equally possible. Group 35 corresponds to the states at 3840 and 3869 keV; the former with $J^\pi=(1,2^+)$, the latter with $J^\pi=3^-,(2^-)$. We show the curves for $J^\pi=1^-$ and 3^- and suggest that the data are consistent with a 1^- state in addition, possibly, to a weakly populated 3^- state. Finally group 38, corresponding to the states at 4076 and 4105 keV (the latter 1^--3^-), is shown fitted with a 2^- distribution. The one high point at $\theta_{\mathrm{c.m.}}=8°$ suggests the possible involvement of a 1^- state, but this is a very weak argument based on one point, which we have, however, no cause to omit.

We will conclude this section by commenting on some other states. Group 8 [which corresponds to the 2104 keV, $(1)^-$ state] has an angular distribution which, within poor statistics, is indeed consistent with $J^\pi=1^-$. Group 14 (2543 keV, 7^+) (not shown in Fig. 2) has a constant $d\sigma/d\Omega$ of ~ 1.5 μb/sr from $\theta_{\mathrm{c.m.}}=18°$ to 43°, and then shows a decrease to 0.8 μb/sr at 54°. Group 16 (2626 keV, 0^-) could not be fitted by CCBA. Group 17 (2731 keV, 1) is fitted slightly better by 1^- than by 1^+. Group 20 (2879 keV, 6^+) which is not shown in Fig. 2 (no angles $<18°$) has an angular distribution at $\theta_{\mathrm{c.m.}}\geq 18°$ which is consistent with $J^\pi=6^+$. Group 26 (3293 keV, unknown J^π) appears to be a 1^+ state, although 1^- cannot be ruled out, while group 40 [4254 keV, (1^-)] is consistent with 1^-, although 1^+ cannot be totally ruled out. Finally the differential cross sections for group 43 (4366 + 4384 keV, $J^\pi=8^+$ and 0^+; $T=2$) decrease linearly from 5 μb/sr at $\theta_{\mathrm{c.m.}}=18°$ to 0.5 μb/sr at 54°. The 0^+ state thus appears to be dominant in the unresolved group.

B. States of ^{42}K

Several states of ^{42}K have unambiguously known[3,7,8] J^π values: they are the ones [see Table III) at 0, 106.8, 258.1, 638.5, 698.8, 783, 844.0, 1113.1, 1143.2, 1201, 1268, 1375.7, 1861.9, and 1947.4 keV with $J^\pi=2^-$, 3^-, 4^-, 3^-, 5^-, 2^-, 3^-, 3^+, 4^+, 4^-, 2^-, 6^+, 2^-, and 7^+. In a manner similar to ^{40}K, the lowest four states of ^{42}K will be dominated by

$$[(\pi 1d_{3/2})^{-1}(\nu 1f_{7/2})^3]_{2^-,3^-,4^-,5^-}$$

configurations. These will be somewhat weaker in ^{42}K than the analogous configurations in ^{40}K, due to the partial filling of the $f_{7/2}$ neutron shell (the Q-value effect also reduces the cross sections to these configurations). The presence of the extra two neutrons and their resulting collective vibrations causes an increase in the complexity of the ^{42}K spectrum relative to ^{40}K, due to particle-vibration couplings. However, as in ^{40}K, no low lying 1^+ states are expected because of the lack of proper orbitals, and the observation of some 1^+ strength indicates a collective character for such states.

In Fig. 3 we present the spectrum of the 61 ^{3}He groups we observe below $E_x=4160$ keV, and in Fig. 4 we display many of the angular distributions we have measured. The CCBA curves for the states with known J^π are in good to excellent agreement for the states at 0, 106.8, 258.1, 698.8, and 1143.2 keV. The ^{3}He groups corresponding to the states at 638.5 (3^-), 783 (2^-), 1375.7 (6^+), 1861.9 (2^-), and 1947.4 keV (7^+) are weak or not observed. The two

TABLE III. Energy levels of ^{42}K.

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L[c]	J^π	E_x (keV)	J^π
0	0	1+3	2^-	0	2^-
1	109 ±5	3	3^-	106.8	3^-
2	262 ±8	3+5	4^-	258.1	4^-
3	d			638.5	3^-
4	e			682.1	$1^+,(2,3)^+$
5	702 ±8	5	5^-	698.8	5^-
6	d			783±3	2^-
7	841 ±8			844.0	3^-
8	1107±15			1113.1	3^+
9	1145±10	4	4^+	1143.2	4^+
10	1201±10		$3^-,2^-$	1201±3	4^-
11	1259±20			1255.3	$(2,3)^-$
		1+3	2^-		
12	1277±15			1268	2^-
	e			1375.7	6^+
13	d			1378.4	$(0\text{-}3)^-$
14	1413±10			1408.3	$(1,3)^+$
				1463.6	
15	1469±10[f]				
				1483±12	
16	1539±15	2+4	3^+	1538.3	$(3,5)^+$
17	1688±15		$3^+,3^-$	1698±15	
18	1735±15			1749±15	
19	1810±20[f]			1787±12	
	e			1861.9	2^-
20	1926±15	3	3^-	1920±9	$0^-\text{-}3^-$
				1938	
21	1956±15	3+5	(4^-)		
				1947.4	7^+
	e			1994±15	
22	2067±20		$3^-,3^+$	2056±4	$(2\text{-}4)^-$
23	2088±20	1+3	2^-	2072	$(2,3)^-$
24	2193±15		$4^+,3^+$	2186±4	$(3,5)^+$
25	2219±20		$3^+,2^+,2^-$	2200±12	
26	2268±15[f]			2239	$0^-\text{-}3^-$
27	2328±15			2314±4	$(3,5)^+$
28	2373±15			2367	$0^-\text{-}3^-$
29	2409±15	2+4	3^+	2402	$(3,4)^+$
30	2434±15				
				2465±15	$(1^-,2^-)$
31	2496±15				
32	2570±15[f]			2544±15	$0^-\text{-}3^-$
33	2626±15			2632±15	$0^-\text{-}3^-$
34	2662±15[f]			2710±15	
35	2750±15			2749±15	
36	2780±15			2802±15	$(1^+\text{-}3^+)$
37	2824±15			2829±50	$(3\text{-}5)^+$
38	2862±10	0+2	1^+	2858±15	$(1^+\text{-}3^+)$
				2900±15	
39	2895±10		$3^+,3^-$		
				2916±15	$(1^-,2^-)$
40	2955±15[f]	g			
				3004±15	$(1^-,2^-)$
41	3032±10	2+4	3^+	3021±15	$(2^-\text{-}4^-)$
42	3056±15				
43	3097±15[f]	0+2	1^+	3093±15	
44	3132±15[f]				
				3193±15	$0^-\text{-}3^-$
45	3225±20[f]				
				(3217±15)	$(1^+\text{-}3^+)$

TABLE III. (*Continued*).

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L[c]	J^π	E_x (keV)	J^π
46	3297±10	0+2	1^+	3271±15	$(1^-,2^-)$
47	3329±10	0+2	1^+		
				3355±15	
48	3377±10	0+2	1^+		
				3402±15	$(1^- \text{-} 3^-)$
49	3425±15[f]		2^h		
50	3503±15			(3502±15)	
51	3587±15			(3543±15)	
52	3628±15[f]			3635±15	
53	3666±10				
54	3698±10				
55	3758±10			3766±15	
56	3793±15[f]				
57	3860±15			3873±15	$0^- \text{-} 3^-$
58	3887±15			3919±15	
				4002±15	
59	4042±15[f]			4039±15	$(1^- \text{-} 3^-)$
60	4121±15			4117±15	$(1^- \text{-} 3^-)$
61	4150±15[f]				

[a]P. M. Endt and C. Van der Leun, Nucl. Phys. **A310**, 1 (1978); J. Lichtenstadt *et al.*, *ibid.* **A311**, 61 (1978); A. M. Baxter *et al.*, *ibid.* **A390**, 29 (1982).
[b]See Fig. 3.
[c]L transfers assumed in the theoretical CCBA curves shown in Fig. 4. See the text and footnote c of Table II for additional comments.
[d]Observed at several angles: groups are generally weak.
[e]Not observed, but contributions of weak groups are not excluded.
[f]The width of this group indicates that it is due to unresolved states.
[g]L transfer curves are not significant because neither of the two unresolved states appears to be dominant.
[h]Dominant.

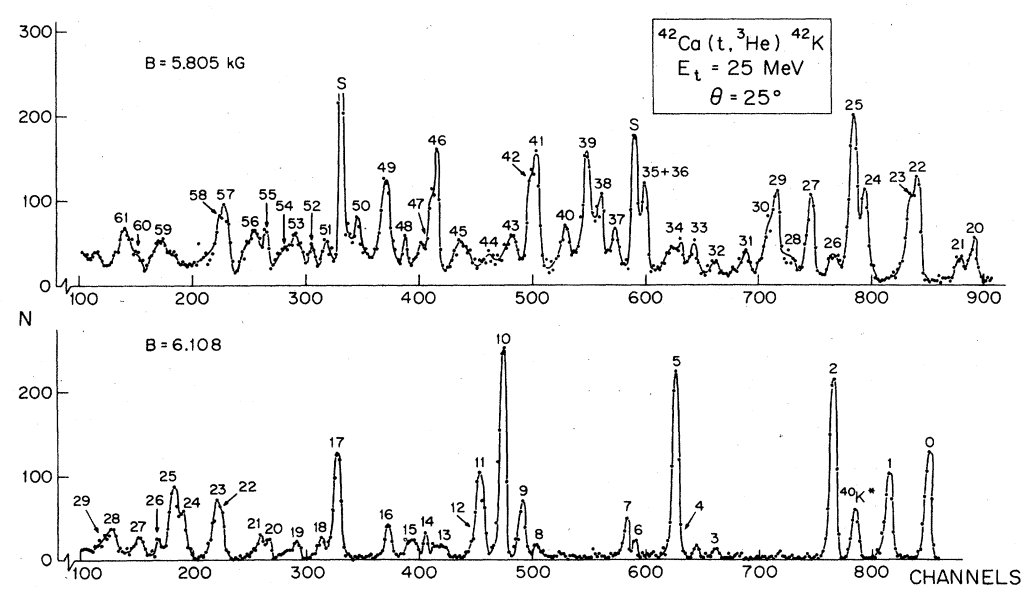

FIG. 3. Spectra of the ^{42}Ca(t,^{3}He)^{42}K reaction at $E_t=25$ MeV, θ(lab)=25°. The groups labeled S are spurious. See also the caption to Fig. 1, and Table III.

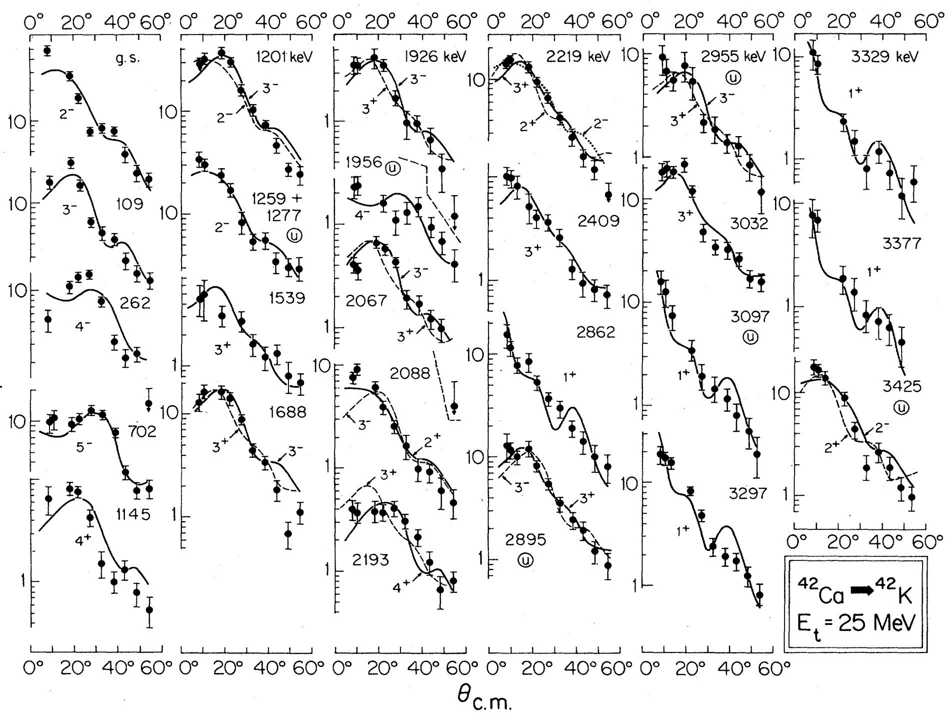

FIG. 4. Angular distributions of ^{3}He groups from the ^{42}Ca(t,^{3}He)^{42}K reaction. See also the caption of Fig. 2.

$J=4$ distributions (to the 258.1 and 1143.2 keV states) are experimentally more forward peaked than predicted, as was also the case in ^{40}K. Still the agreement between the experimental data and the CCBA curves are very good for those five states which are observed and whose J^π are known. We do disagree, however, with the 4^- assignment for the state at 1201 keV. Empirically the general agreement strengthens the validity of the assignments we make for those states for whom definite J^π assignments are not available: we display them in Fig. 4 and Table III and continue to comment here on only a few more complicated assignments.

A number of groups we observe correspond to unresolved states. For instance, groups 11 + 12, treated as a single group in Fig. 4, are made up of states at 1255.3 and 1268 keV with $J^\pi=(2,3)^-$ and 2^-: we find that an $L=1+3$ distribution ($J^\pi=2^-$) is dominant. The state at $E_x=1947$ keV is known to have $J^\pi=7^+$: this work does not resolve it from the state at 1938 keV, and the best fit to the angular distribution of group 21 is obtained with $L=3+5$, that is with $J^\pi=4^-$. Group 39 is best fit with $L=2+4$ or 3, that is with $J=3$ and undetermined parity, for the unresolved states at 2900 and 2916 keV.

In a number of cases this work can eliminate some possible J^π assignments: this is achieved for groups 16, 20, 23, 24, 29, and 38. In other cases we make J^π assignments for the first time.

$J^\pi=1^+$ states ($L=0+2$) have been located at $E_x=2862$, 3097, 3297, 3329, and 3377 keV (groups 38, 43, 46, 47, and 48, respectively): see Table III and Figs. 3 and 4. We shall discuss these further in Sec. III.

C. States of ^{44}K

Information[3] on the level structure of ^{44}K derives primarily from an early (t,^{3}He) paper[9] and from the ($\beta\gamma\gamma$) work of Huck *et al.*[10] The (t,^{3}He) work[9] reported excited states at 383, 520, 811, 966, 1070, and 1494 keV (the latter two possibly corresponding to unresolved states). The ^{44}Ar β-decay study[10] did not excite the states at 811, 966, and 1494 keV but reported additional states at $E_x=182.6$ and 1051.3 keV, as well as three 1^+ states at 1886.0, 2325.8, and 2754.2 keV. The only other definite J^π assignment is 2^- for the ground state of ^{44}K which stems[3] from the character of its β decay to states in ^{44}Ca. See Table IV for a display of the known information for $E_x<2.1$ MeV.

The ^{3}He groups observed in this experiment are displayed in Fig. 5 and in Table IV. The ^{3}He group corresponding to the 183 keV state is observed but is extremely weak at all angles. We have resolved states at 1048 and 1075 keV and at 1480 and 1500 keV, and we report a previously unknown state at 1003 keV. The very low population of the 183 keV state is difficult to understand. It is not populated directly in the ^{44}Ar β decay ($\log ft>6.9$) (and neither are any of the other states below 1460 keV, with the exception of the 383 keV state reached in a $\log ft=7.7$ transition). However, it is very strongly populated in the γ decay of most of the other states involved in the β-decay work. We shall return to this question. The other puzzle concerns the three 1^+ states at 1886, 2326, and 2754 keV whose assignments seem quite unambiguous. We observe no evidence whatsoever at any angle, in-

TABLE IV. Energy levels of ^{44}K.

Present results				Earlier work[a]	
Group No.[b]	E_x (keV)	L[c]	J^{π}[d]	E_x (keV)	J^{π}
0	0[e]	1+3	2^-	0	2^-
1	f			182.6	(1-3)
2	383±5	1+3	2^-	382.9	
3	520±5	3+5	4^-	519.8	
4	811±5	5	5^-	811	
5	969±5	2+4	3^+	966	
6	1003±12	4	4^+		
7	1048±10		$4^+,3^-$	1051.3	
8	1075±10	1+3	2^-	1076.7	
9	1480±10	(0+2)	(1^+)	1459.5	(0,1)
10	1500±15			1494	
	g			1886.0	1^+
11	1990±20[h]				
12	2060±20[h]		$5^+,4$		

[a]P. M. Endt and C. Van der Leun, Nucl. Phys. **A310**, 1 (1978); A. Huck *et al.*, Phys. Rev. C **18**, 1803 (1978).
[b]See Fig. 5.
[c]L transfers assumed in the CCBA curves shown in Fig. 6. See the text and footnote c of Table II for additional comments.
[d]See also the text.
[e]$Q_0 = -5672 \pm 20$ keV.
[f]Group observed but very weak at all angles; E_x is not calculated.
[g]Group not observed at any angle.
[h]May be due to unresolved states.

cluding the forward ones, for the 1886 keV state: in Fig. 5 it would lead to a ^{3}He group at channel 180. Its differential cross section at $\theta_{c.m.} = 8°$ is < 1 μb/sr. While the data are not shown in Fig. 5, we also investigated the ^{3}He ions at θ(lab)$=12°$ and 25° at energies corresponding to the 2326 and 2754 keV states. At 25° we do observe groups to states at these energies, as well as to a large number of other states, but at 12° these states if they are populated (the background is high) are populated more weakly than at 25°. We were not able to repeat these runs and to obtain additional information. We can just report that the 1^+ states at 2326 and 2754 keV are weakly populated in this reaction, at $E_t = 25$ MeV, if they are populated at all.

Let us turn now to the angular distributions displayed in Fig. 6. The $L = 1+3$ CCBA fit to the 2^- ground state group is rather poor (compare with Figs. 2 and 4). No other J^{π} assignments are known. From systematics (see Tables II and III) one would expect $J^{\pi} = 3^-$, 4^-, and 5^- in the vicinity of the ground state. The next state we observe is at 383 keV and it is best fitted with L values corresponding to $J^{\pi} = 2^-$, although the fits for 3^+ or 3^- cannot be excluded. However, either $J = 3$ assignment is impossible in view of the logft value of 7.7 ± 0.3 from the 0^+ ground state of ^{44}Ar. The unique first-forbidden nature of the $0^+ \rightarrow 2^-$ decay would be expected to lead to a

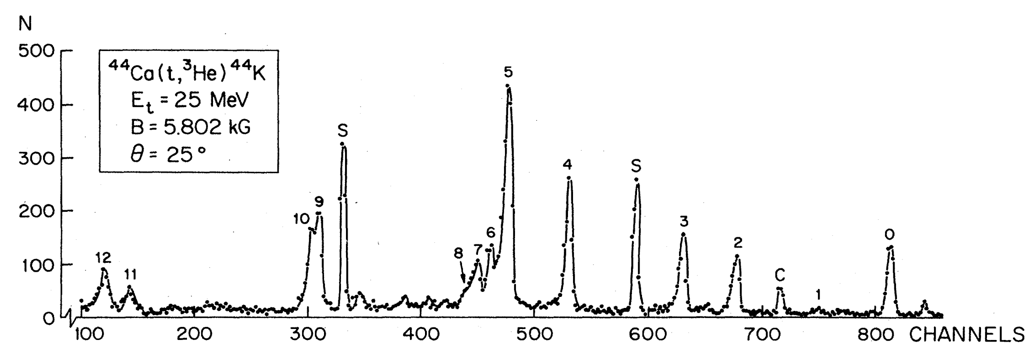

FIG. 5. Spectrum of the ^{44}Ca(t,^{3}He)^{44}K reaction at θ(lab)$=25°$. The groups labeled S are spurious. The group labeled C is due to a contaminant.

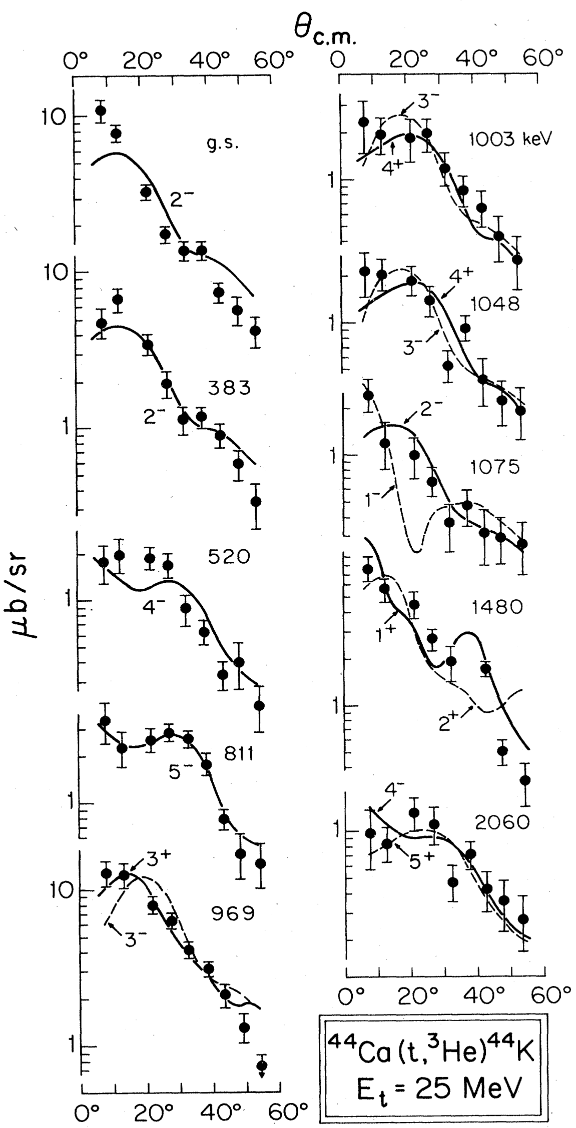

FIG. 6. Angular distributions of the ^{3}He groups from the ^{44}Ca(t,^{3}He)^{44}K reaction. See also the caption of Fig. 2.

somewhat higher logft value but the angular distribution precludes $J<2$. (The β transition to the ground state has a log$ft>6.9$.)

The CCBA predictions for $L=3+5$ and $L=5$ have similar shapes, though not absolute cross sections. We suggest 4^- and 5^-, respectively, for the states at 520 and 811 keV. An alternate 5^-, 4^- sequence is not completely excluded by the angular distributions but the suggested assignment of 4^- to the lower state is consistent with the observed[10] γ branchings. The 969 keV state is fitted with $L=2+4$ ($J^\pi=3^+$) although $L=3$ ($J^\pi=3^-$) is not totally excluded. 4^+ is more likely than 3^- for the new state at 1003 keV, and 3^+ is excluded. The 1051 keV state can be fit either by $J^\pi=4^+$ or by 3^-. We assign 2^- to the 1077 keV state and, possibly, 1^+ to the 1460 keV state. The latter is populated in the β^- decay of ^{44}Ar with log$ft=6.9\pm0.2$ which would imply a first-forbidden transition and thus $\Delta J=0$ or ±1, and a change in parity. However, an $L=1$ distribution, if J^π were 1^-, does not fit the data (see the CCBA curve for 1^- shown for the 1077 keV state). In any case neither $J^\pi=1^+$ or 1^- would explain the relative strength of the 1460$\rightarrow$1051 keV transition. The (possibly) unresolved angular distribution to the state at 2060 keV can be fitted if $J^\pi=5^+$ or 4 (the 4^+ distribution is not shown but cannot be excluded).

Finally we determine $Q_0=-5672\pm20$ keV which, together with the earlier value[11] of -5641 ± 40 keV, leads to a weighted average of -5666 ± 18 keV. The atomic mass excess of ^{44}K is then $-35\,785\pm18$ keV.

D. States of ^{46}Sc

The level structure of ^{46}Sc has been studied in many reactions.[12] Its ground state ($J^\pi=4^+$) decays by both β^- and β^+ to ^{46}Ca and to ^{46}Ti. Its first excited state, at 52.01 keV, is an isomeric state with $J^\pi=(6)^+$. Table V shows the previously known level structure of ^{46}Sc below $E_x<4680$ keV. Figure 7 shows one of the ^{3}He spectra we observed, and Table V displays the characteristics of the level structure derived from the 74 ^{3}He groups which we studied. In view of the high level density in ^{46}Sc, a number of them clearly correspond to unresolved states.

We will comment here on some of the angular distributions shown in Fig. 8. The ground state, $J^\pi=4^+$, experimental angular distribution peaks at a smaller angle than the appropriate CCBA curve: this is a characteristic of $L=4$ distributions throughout our work, as we commented earlier. The distribution to the first excited state is in good agreement with $J^\pi=6^+$. The group corresponding to the 1^- state at 143 keV is very weak: within very poor statistics it does peak at forward angles. The distribution to the state at 228 keV is in good agreement with $J^\pi=3^+$. The unresolved groups 4 and 5 correspond to a $(5,6)^+$ state at 280.7 and to a 2^- state at 289.5 keV. In Fig. 8 we show the unresolved distribution and 2^- and 5^+ CCBA distributions (the 6^+ distribution could certainly fit the larger angle data as well as does the 5^+ distribution).

Because in ^{46}Ti there are two protons in the $f_{7/2}$ shell, the (t,^{3}He) reaction can be expected to excite a multiplet of even parity states. This is the result of charge exchange of the $f_{7/2}$ proton into an $f_{7/2}$ neutron. The multiplet will have J^π of 0^+ through 7^+. The ground and first excited states presumably are dominated by this configuration, as their angular distributions confirm a J^π of 4^+ and 6^+, respectively. The 2^+ member of this multiplet is not clearly assigned and may be either at 446 or 586 keV. The 0^+ member is considerably reduced in strength here because of the $(2J+1)$ factor, and is not seen. The $(\pi d_{3/2}^{-1}\nu f_{7/2})$ configurations evidently mix into the same energy region as evidenced by the 2^- state at 288 keV, reminiscent of ^{40}K. One also now expects direct excitation of GT 1^+ states due to the presence of protons in the $f_{7/2}$ shell, and 1^+ levels at 990 and 1848 keV may contain such strength.

We assign definite J^π (see Table V) to 16 states whose

TABLE V. States of ^{46}Sc.

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L[c]	J^{π}[d]	E_x (keV)	J^{π}
0	0	4	4^+	0	4^+
1	52±5	6	6^+	52.0	$(6)^+$
2	143±5			142.5	1^-
3	228±5	2+4	3^+	227.8	$(3)^+$
4				280.7	$(5,6)^+$
	288±8	1+3[e]	$2^-+(5,6)^+$		
5				289.5	2^-
6	446±5	2	2^+	444.1	$(2)^+$
7	586±5		$2^+,3^-$	584.8	3^-
8	625±8	3+5	4^-	627.5	$(4)^-$
9	772±5	4+6	5^+	774.0	$(5)^+$
10	826±15	4	4^+	835.3	$(4)^+$
11	981±10			977	$(7)^+$
		0+2	1^{+}[e]		
12	997±15			991.3	$(1)^+$
13	1092±15	2+4	3^+	1088.4	$(3,4)^+$
				1121	$\pi=+$
14	1130±15				
		3+5[d,e]	4^-	1124.2	4^-
15	1150±15			(1141±6)	
16	1274±10[g]	1+3	2^-	1270.6	$(2)^-$
17	1322±20[g]	1+3	2^-	1321.3	2^-
18	1392±15	2	2^+	1393.6	$\pi=+$
19	1427±10	1+3	2^-	1430	(2^-)
20	1525±15			1526.3	
21	1642±10		$3^-,4^-$	1642.0	$(3^-,4^-)$
	f			1677±6	$\pi=+$
	f			1692±6	$(3^-,4^-)$
22	1708±10		$3^-,2^-$	1708.1	(2^-)
23	1735±20			1753±6	$(\pi=+)$
	f			1765±6	$(\pi=+)$
				1799.4	$\pi=+$
24	1802±10				
				1804±8	(2^-)
25	1848±10	(0+2)	(1^+)	1852	(1^+)
	f			1887	$(1)^+$
26	1917±10	2	2^+	1920.1	$(2,3)^+$
27	2047±15			2063	(4^-)
28	2074±15			2071±6	$\pi=+$
29	2113±15		$3^+,2^+$	2126	$(2)^+$
	f			2174±6	
				2208±6	
30	2210±15	2	2^+		
				2222.5	$(1,2)^+$
31	2246±15	2+4	3^+	2255±15	$(3^+,4^+,5^+)$
32	2287±15	1+3	2^-	2295	(2^-)
				2307±6	$\pi=+$
33	2320±20	2	2^+		
				2334±6	$\pi=+$
	f			2366±6	$\pi=+$
34	2397±20	2+4	3^+	2410.0	$(3,4)^+$
				2441.7	
35	2434±20[g]	2+4	3^+		
				2455±6	$(3)^+$
	h			2533±6	+
36	2557±15	4	4^+	2566±6	$(3,4,5)^+$
37	2585±15[g]		$3^-,4^-$	2589.0	$(3^-,4^-)$

TABLE V. (*Continued*).

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L[c]	J^{π}[d]	E_x (keV)	J^{π}
				2646	$(3^-,4^-)$
38	g,h			2670±8	(1^+)
				2705.1	$(3,4)^+$
39	2734±15	2	2^+	2733±8	$\pi=+$
				2770±15	$(3^+,4^+,5^+)$
40	2770±20[g]				
				2786	$3^-,4^-$
41	2814±15			2813±8	$\pi=+$
				2833.7	$3^-,4^-$
42	2851±20[g]				
				2863.1	$(2,3)^+$
43	2882±15[g]				
				2897±8	$\pi=+$
				2939±8	$(3^-,4^-)$
44	2950±20[g]				
				2956.8	
45	2974±15		$(2,3)^+$	2971	$(3,4)^+$
				3005±8	
46	3016±15	0+2	1^+		
				3017.3	
	f			3032±8	
	f			3061±8	
				3087±8	$\pi=+$
47	3100±30[g]	0+2	1^+		
				3116±15	(1^+)
	f			3142±8	$3^-,4^-$
48	3185±20			3183±8	$\pi=+$
49	3220±15			3224±15	(1^+)
				3241±8	$\pi=+$
50	3268±15[g]				
				3287±8	$(2,3)^+$
51	3335±15			3321±8	$(2,3)^+$
52	3377±15	0+2	1^+	3391±8	$\pi=+$
53	3420±15			3420±8	$\pi=+$
54	3446±15			3449±8	$\pi=+$
				3472.2	$\pi=+$
55	3489±15[g]				
				3493.0	$\pi=+$
				3539±8	$\pi=+$
56	3523±20[g]	0+2	1^+		
				3544±15	(1^+)
	h			3586±8	$\pi=+$
57	3607±15			3604±15	(1^+)
				3618±8	$\pi=+$
58	3648±15[g]			3630±15	
				3661±8	$\pi=+$
	f			3672±15	(1^+)
				3695±8	
59	3700±20[g]				
				3715±8	
60	3745±20[g]	2+4	3^+	3771±8	$\pi=+$
61	3784±20[g]			3785.9	$\pi=+$
	h			3822±8	$\pi=+$
62	3860±20			3839±8	
63	3899±20[g]			3878±8	
	h			3941±8	$\pi=+$
	f			3960±8	
64	3980±15			3980±8	
65	4010±15[g]				

TABLE V. (*Continued*).

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L^c	$J^{\pi d}$	E_x (keV)	J^π
66	4070±15				
67	4098±15				
68	4136±15				
69	4167±15			4170±20	$(0^+,1^+)$
70	4220±20			4240±20	
71	4257±20				
	h			4320±20	
72	4509±15				
73	4650±20			4620±20	
74	4700±20			4680±20	

[a]R. L. Auble, Nucl. Data Sheets **24**, 1 (1978).
[b]See Fig. 7.
[c]L transfers assumed in the theoretical CCBA curves shown in Fig. 8. See the text and footnote c of Table II for additional comments.
[d]See also the text.
[e]Angular distribution shown in Fig. 8 is of unresolved group.
[f]Not observed, but contributions of weak groups are not excluded.
[g]The width of this group indicates that it is due to unresolved states.
[h]Observed at several angles: groups are weak.

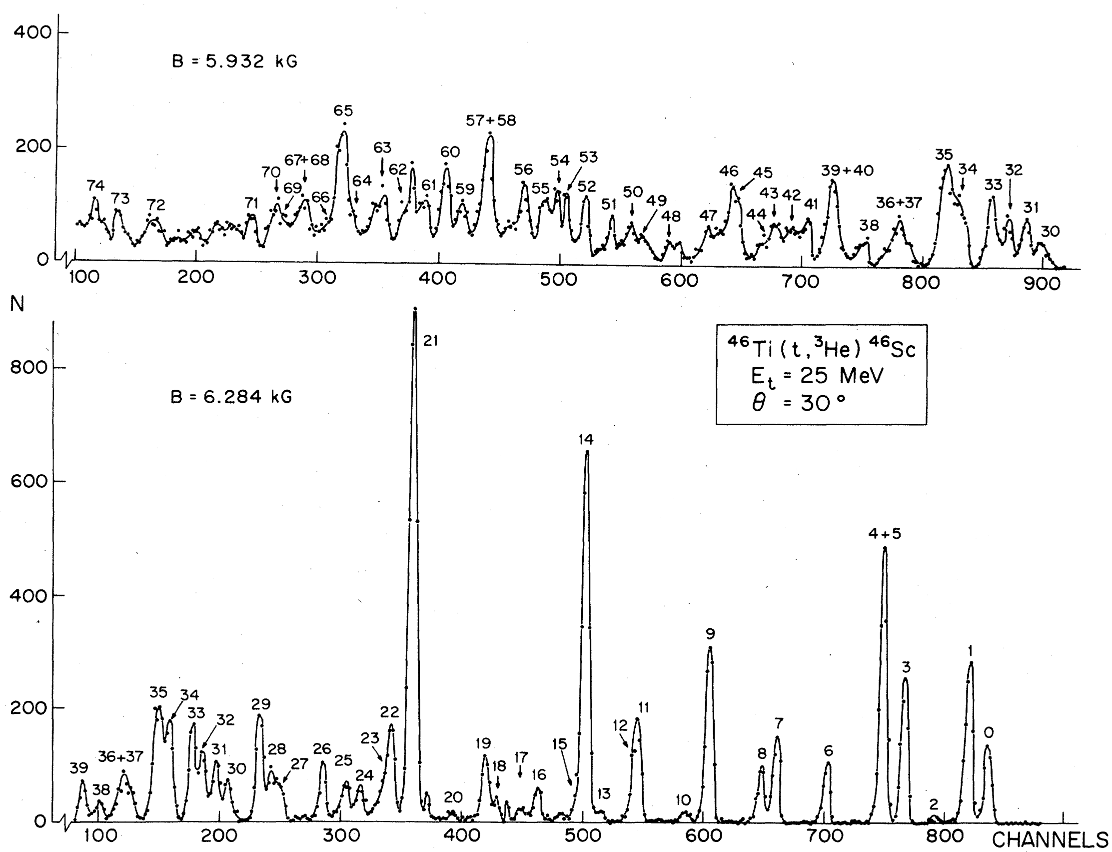

FIG. 7. Spectrum of the ^{46}Ti(t,^{3}He)^{46}Sc reaction at θ(lab)=30°.

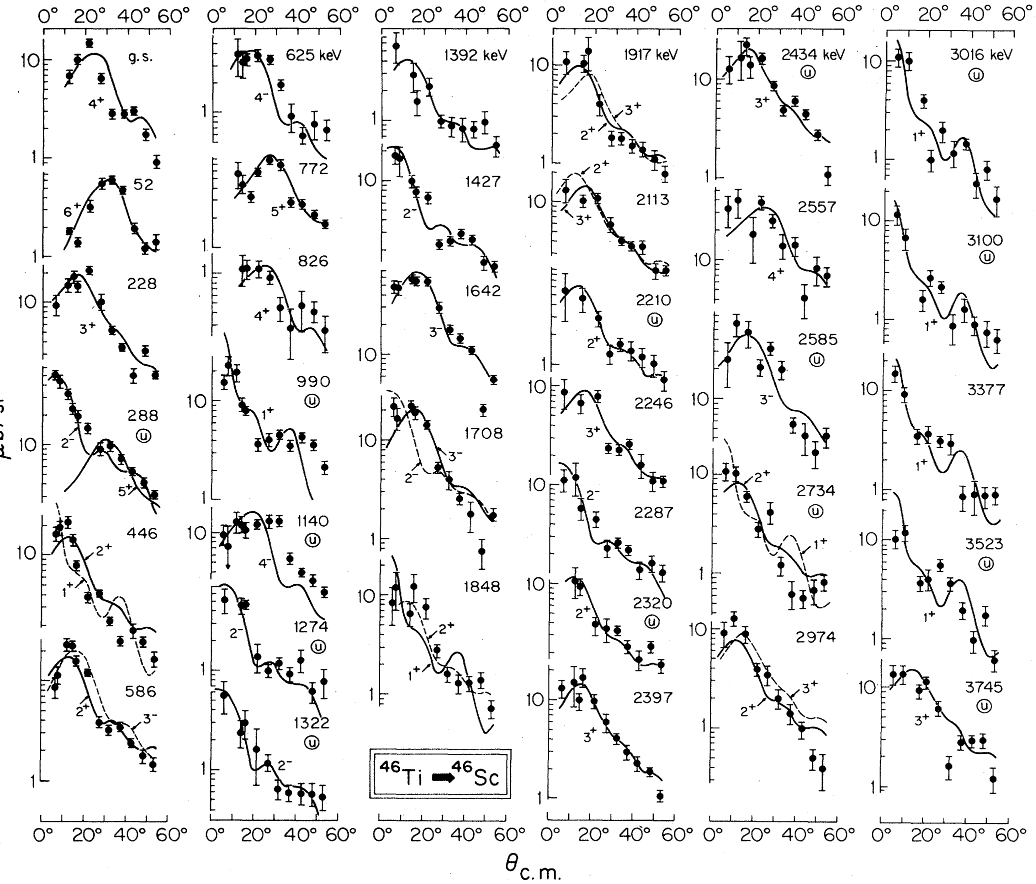

FIG. 8. Angular distributions of the ^{3}He groups from the ^{46}Ti(t,^{3}He)^{46}Sc reaction. See also the caption of Fig. 2.

J^π had been uncertain. In other cases our results open the possibility of other J^π values [i.e., 2^+ for the 3^- state at 586 keV; 3^- or 2^- for the (2^-) state at 1708 keV; 3^+, 2^+ for the $(2)^+$ state at 2126 keV; $(2,3)^+$ for the $(3,4)^+$ state at 2974 keV], or confirm previous assignments [$3^-,4^-$ for the $(3^-,4^-)$ states at 1642 and 2589 keV].

In the case of unresolved groups we are able to identify the dominant state: 1^+ for groups 11+12, 4^- for groups 14+15, 2^+ for groups 30 and 33, 3^+ for group 35, and 1^+ for groups 46, 47, 52 (not unresolved), and 56. We also confirm the suggestion of (1^+) for the state at 1852 keV.

Finally we will summarize our comments on the 1^+ states which we have identified, in all but one case in unresolved groups (in these the data are dominated by $L=0+2$). These are groups 12, 46, 47, 52, and 56 to the states at $E_x=991$, 3016, 3100, 3377, and 3523 keV, in addition to group 25 (1848 keV) whose 1^+ assignment is not certain. Very weak groups due to 1^+ states could of course have been missed and, in a number of cases not shown in Fig. 8 (particularly above $E_x=3.5$ MeV), we were not able to obtain forward angle data, which is essential to pick out the 1^+ states: see Sec. III.

E. States of ^{48}Sc

The level structure of ^{48}Sc derives[13] principally from studies of the ^{46}Ca(^{3}He,p) and ^{46}Ca(α,d) reactions as well as from more recent studies[14,15] of the ^{48}Ca(p,n) and of the ^{48}Ca(^{3}He,t) reactions; see Table VI. The first six states are identified[13] as states with wave functions dominated by

$$(\pi 1f_{7/2})^{+1}(\nu 1f_{7/2})^{-1} .$$

Figure 9 displays the observed ^{3}He groups and Fig. 10 the ^{3}He angular distributions to many of these groups. Additional distributions have also been obtained but they could not be fitted by CCBA: many of those are distributions to unresolved states.

It was not possible to obtain data at forward angles for groups 0 to 6. Fortunately the J^π of these first seven states are known, and the angular distributions to these states, shown in Fig. 10, are consistent with the previous work.

Many of the L assignments are obvious. We will comment here on some of the more complicated or interesting ones. The 1892 keV state previously had a J^π assignment

TABLE VI. Energy levels of ^{48}Sc.

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L[c]	J^π	E_x (keV)	J^π
0	0	d	6^+	0	6^+
1	132±5	4+6	5^+	130.9	5^+
2	252±5	4	4^+	252.4	4^+
3	621±5	2+4	3^+	622.6	3^+
4	1091±8	d	7^+	1096	7^+
5	1144±8	2	2^+	1142.9	2^+
6	1404±5	1+3	2^-	1402.4	2^-
	e			1592±20	
7	1892±8		$2^-,3^-$	1892	$(2^-,3^-,4^-)$
8	2061±10	4+6	5^+	2063	(1,2)
	f			2080	
9	2101±10	3	3^-	2104	(4^-)
10	2158±10		$4^-,5^-$	2165	$(4,5,6)^-$
				2191	
11	2195±15[g]	2+4	3^+	2210±20	
				2230±20	
12	2280±15	2	2^+	2278	(2^+)
13	2390±20	2	2^+	2391	(2^+)
14	h	d		2519	1^+
				2551	
15	2567±20				
				2561	
	f			2619	
	f			2626	
	f			2639	
	f			2650	
				2672	
16	2677±15	d			
				2695±14	(1^+)
17	2739±10	1+3	2^-	2728	
18	2789±10	2	2^+	2784	
19	2813±10			2810	
	f			2893	$(2)^-$
20	2934±10			(2925)	
21	2969±10			2978	
22	2989±10	0+2	1^+	2985	1^+
				3054	1^+
23	3064±10[g]	0+2	1^+		
				3068±10	(1^+)
				3152	
24	3160±10				
				3164	$(3^+,4^+)$
25	3230±15[i]			3220	(4^+)
	f			(3258±6)	
				3270±10	
26	3281±10				
				3289	
	f			3305	
	f			3329	
	f			3343±10	
	f			(3353±10)	
	f			(3372)	
27	3393±10			3387	$(0,1,2)^-$
		1+3	2^-[g]		
28	3421±15			3455±10	
	f			3481	(3,4)
29	3495±15		$2^-,1^-$	3496	
	f			3510	
	f			3526	

TABLE VI. (*Continued*).

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L[c]	J^π	E_x (keV)	J^π
				3564	
30	3576±15				
				3573	
	f			3620	
	f			3659	
				3675	
31	3679±15[i]				
				3690	
32	3719±15	0+2	1^+	3709	(1^+)
33	3751±15			3742	
	f			3776	$(3^+,4^+,5^+)$
34	3797±10			3806	
	f			3838±7	
				3871±7	
35	3887±15				
				3919±10	
				4005±20	(1^+)
36	3999±15[i]				
				4026	
	f			4062	
				4071±7	
37	4112±15[i]				
				4142	
				4159±8	
38	4170±15				
				4174	(1^+)
39	4236±15			4246	
40	4268±20			4289	
	f			4330±20	$1^+,0^+$
	f			4396±8	
41	4424±15			4450±15	
42	4550±20[i]			4566±15	

[a]J. R. Beene, Nucl. Data Sheets **23**, 1 (1978); B. D. Anderson *et al.*, Phys. Rev. Lett. **45**, 699 (1980); C. Gaarde *et al.*, Nucl. Phys. **A334**, 248 (1980).
[b]See Fig. 9.
[c]L transfers assumed in the CCBA curves shown in Fig. 10: see the text and footnote c of Table II for additional comments.
[d]See the text.
[e]Not observed.
[f]Not observed, but contributions of weak groups are not excluded.
[g]Angular distribution shown in Fig. 10 is of unresolved group.
[h]Observed at several angles: groups are weak.
[i]The width of this group indicates that it is due to unresolved states.

of $(2^-, 3^-, 4^-)$: the data favor 2^- over 3^- and exclude 4^-. The 2063 keV state was suggested to have $J=(1,2)$. Our data are inconsistent with either of these values: the best fit is for $J^\pi=5^+$ but in any case $J\geq 4$. $J^\pi=(4^-)$ had been suggested for the 2104 keV state: these data strongly favor 3^-. For the 2165 keV state $(4,5,6)^-$ was suggested. We cannot distinguish between 5^- or 4^- (only the 5^- curve is shown in Fig. 10), but can exclude 6^-. For the unresolved triplet at $\sim$2200 keV (no known J^π) we find that $L=2+4$ (3^+) fits the composite data.

The 1^+ state reported at 2519 keV is observed here at only five angles, including the forward ones. If it is a 1^+ state it is very weakly populated: at least a factor of 2 less than the state at 2985 keV. Group 16, which corresponds to two unresolved states one of which, at 2695 keV, may be a 1^+ state, has an angular distribution (not shown in Fig. 10) which is roughly constant at 2 μb/sr to $\theta_{c.m.}=30°$ and then decreases monotonically to 54°. If a 1^+ state is involved, in addition, say, to a strongly populated state with $J\geq 3$, we can on the basis of the forward differential cross sections also set the upper limit of its intensity as a factor of 2 less than the 2985 keV state. Group 22 ($E_x=2985$ keV) is well fitted by $L=0+2$. Group 23 represents the unresolved states at 3054 (1^+) and 3068

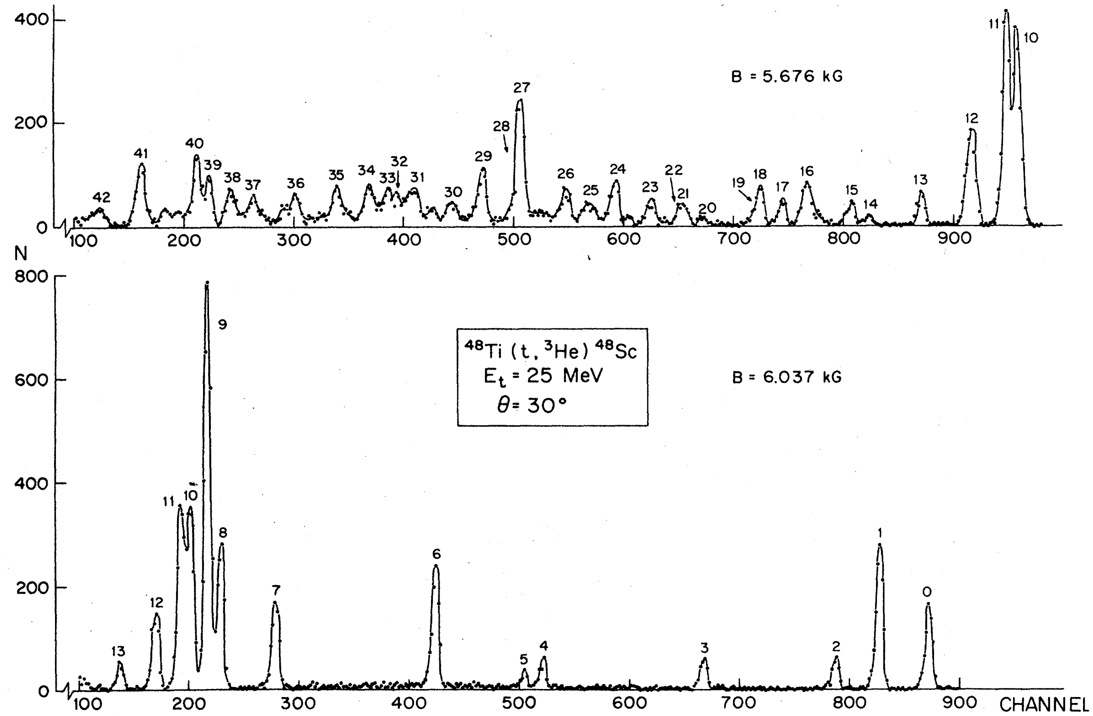

FIG. 9. Spectrum of the ^{48}Ti(t,^{3}He)^{48}Sc reaction at θ(lab)$=30°$.

(1^+) keV: the data are fitted with $L=0+2$ as expected either if both states have $J^\pi=1^+$ or if the one which is not 1^+ (unless it is 1^- in which case the composite distribution would not be substantially different) is weakly populated. Group 32 ($E_x=3709$ keV) is well described by $L=0+2$.

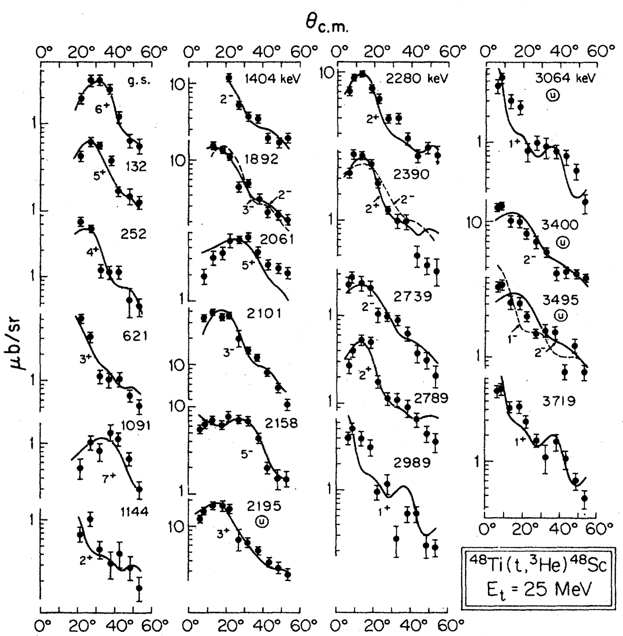

FIG. 10. Angular distributions of the ^{3}He groups from the ^{48}Ti(t,^{3}He)^{48}Sc reaction. See also the caption of Fig. 2.

We find a good fit with $L=1+3$ (2^-) for the unresolved doublet at 3387 $[(0,1,2)^-]$ and 3455 keV, and 2^- (or 1^-) for the state at 3496 keV. We assign $J^\pi=1^+$ to the (1^+) state at 3709 keV. We should note that most of the strength of the 1^+, $T=3$ states appears to be located[14,15] above $E_x=6$ MeV in ^{48}Sc. We have also obtained angular distributions to other states shown in Table VI, but have not been able to fit the curves with CCBA. Many of the states are unresolved, and the angular distributions are not dominated by a single L assignment. However, the unresolved group 36 could be due to a 1^+ state of intensity similar to that of the 2985 keV state, in addition to a state with $J\geq 2$.

F. States of ^{50}Sc

Information on the states of ^{50}Sc derives[16] mainly from studies of the β^- decay of ^{50}Ca and ^{50}Sc, and from the ^{48}Ca(^{3}He,p) reaction: see Table VII. Figure 11 displays the observed ^{3}He groups. Unfortunately ^{50}Ti could not be obtained highly enriched: the target contained (see Table I) 24.1 percent ^{48}Ti and 67.72 percent ^{50}Ti, in addition to smaller amounts of other Ti isotopes. For instance the groups at channels 560, 525, and 214 (in the $B=5.644$ kG run) were definitely assigned to the ^{48}Ti(t,^{3}He)^{48}Sc reaction. At higher E_x, the states in ^{48}Sc are not well enough known to permit assignments of ^{3}He groups to them here. Groups above group 6 were assigned to the ^{50}Ti(t,^{3}He)^{50}Sc reaction on the basis of their intensities and the known states in ^{50}Sc shown in Table VII.

Figure 12 shows the observed angular distributions to the first nine states of ^{50}Sc. The only unambiguous J^π assignment previously made to excited states was to the 1^+

TABLE VII. Energy levels of ^{50}Sc.

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L[c]	J^{π}[d]	E_x (keV)	J^{π}
0	0[e]	4+6	5^+	0	5^+
1	257±5	2+4	$3^{+\,d}$	256.9	$2^+,3^+$
2	331±8	2+4	3^+	328.5	
3	764±10	4	4^+	756±8	
4	1852±10	0+2	1^+	1847.8	1^+
5	2225±10	2+4	3^+	2226±5	
6	2327±10	2+4	3^+	2331±8	
7	2527±10		1		
8	2614±10	0+2	1^+		
9	3028±15				
	f			3089±5	
10	3250±20[g]			3259±7	
11	3300±20[g]			3287±5	
12	3355±15			3380±20	
13	3388±15				
14	3475±20[g]			3510±20	
15	3556±15[g]				
16	3598±15[g]			3617±15	
17	f			3682±5	

[a]D. E. Alburger, Nucl. Data Sheets **42**, 369 (1984).
[b]See Fig. 11.
[c]L transfers assumed in the CCBA curves shown in Fig. 12: see the text and footnote c of Table II for additional comments.
[d]See also the text.
[e]$Q_0 = -6878 \pm 20$ keV: see also Table I.
[f]Observed at several angles: groups are weak.
[g]The width of this group indicates that it is due to unresolved states.

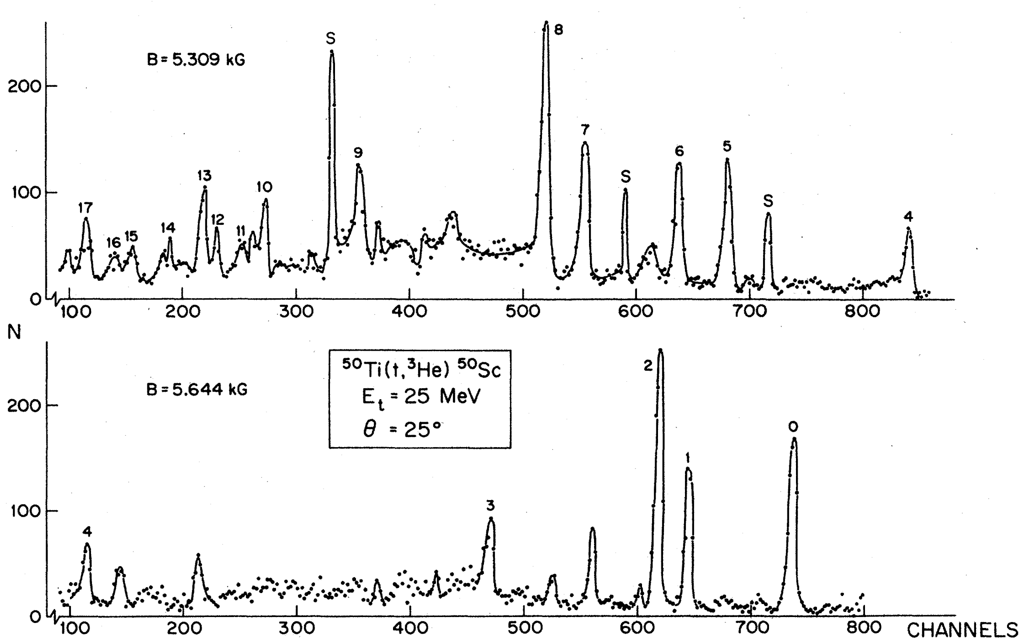

FIG. 11. Spectrum of the ^{50}Ti(t,^{3}He)^{50}Sc reaction at θ(lab) = 25°. The groups labeled S are spurious. See also the comments in the text.

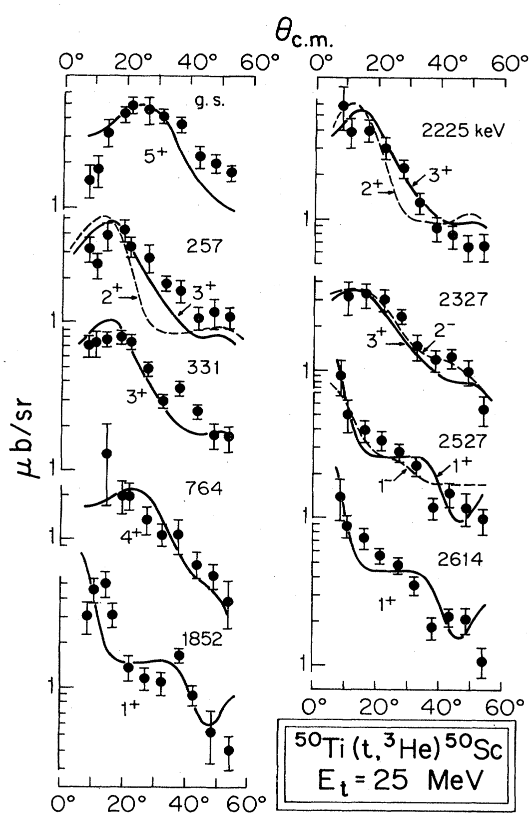

FIG. 12. Angular distributions of the ^{3}He groups from the ^{50}Ti(t,^{3}He)^{50}Sc reaction. See also the caption of Fig. 2.

state at 1848 keV. From the β^- decay of ^{50}Sc, $J^\pi = 5^+$ for the ground state: our results agree with this assignment. The first excited state, at 257 keV, is an isomeric state: its lifetime suggests 2^+ if $J^\pi = 5^+$ for the ground state, although $J^\pi = 3^+$ is possible.[16] The angular distribution is better fitted by $L = 2+4$ ($J^\pi = 3^+$) (compare with the $L = 2$ curve which is also shown). For the 760 keV state we find $J^\pi = 4^+$ and we confirm the assignment of 1^+ for the 1848 keV state. We suggest 3^+, but cannot exclude 2^+, for the 2226 keV state (we do, however, exclude 1^+), and we assign 3^+ for the 2329 keV state. $J^\pi = 2^-$ is excluded by the L value in the (^{3}He,p) reaction. The 2527 keV state is equally well fitted by $L = 1$ or by $L = 0+2$ and we do not determine its parity: $J = 1$. However, the 2614 keV distribution assigns $J^\pi = 1^+$ to that state. Angular distributions were obtained, but are not displayed in Fig. 12, for the higher states of ^{50}Sc displayed in Table VII. Most of the groups corresponded to unresolved states, and all were incomplete distributions: generally information could not be obtained at forward angles due to background problems. Finally we obtain $Q_0 = -6878 \pm 20$ keV, in excellent agreement with the Wapstra value quoted in Table I.

G. States of ^{54}V

The level structure of ^{54}V has previously been studied by Flynn *et al.*[17] using the ^{54}Cr(t,^{3}He) reaction and 23 MeV tritons: their results are displayed in Table VIII. An example of the present data is shown in Fig. 13. We endeavored to study the angular distributions to these earlier reported states. Unfortunately the background at θ(lab) $< 20°$ was extremely high and precluded our obtaining differential cross sections. We found, as in the previous paper,[17] that the differential cross sections were generally very low, which is not surprising in view, among other factors, of the very negative Q value of the reaction ($Q_0 = -7.02$ MeV). The low level background comes in part from the ^{52}Cr(t,^{3}He) reaction, as discussed earlier.[17]

We do not show the differential cross sections since they are for $\theta_{c.m.} \gtrsim 21°$ and since, as a result, no definite J^π assignments can be made. However, we will comment that those groups for which $L = 0+2$ ($J^\pi = 1^+$) is *not excluded* (in all cases other L values are possible) are groups 1, 4, 7, 17, and 18 (the latter two due probably to unresolved states), which correspond to the states at 116, 447, 745, 1934, and 1987 keV. Group 11 (968 keV) is isotropic for $\theta_{c.m.} = 21°$ to 54°.

Finally in this work we determine $Q_0 = -7006 \pm 20$ keV. In the previous work[17] $Q_0 = -7023 \pm 15$ keV. The weighted mean of these two values is -7017 ± 12 keV leading to an atomic mass excess of $-49\,895 \pm 12$ keV for ^{54}V, based on the t, ^{3}He, and ^{54}Cr masses listed by Wapstra and Audi.[11]

TABLE VIII. Energy levels of ^{54}V.

Group No.[b]	Present results E_x (keV)	Previous work[a] E_x (keV)
0	0[c]	0[d]
1	116±5	111±8
2	245±8	238±8
3	e	(291±10)
4	447±8	442±10
	e	495±10
5	540±8	532±10
6	703±10	694±10
7	745±8	739±10
8	770±10	
9	847±10	840±15
10	940±15[f]	930±15
11	968±15	960±15
12	1208±20[f]	1200±10
13	1540±20[f]	1533±15
14	1675±15	1662±15
15	(1752±15)	
16	1865±15	1852±10
17	1934±20[f]	(1920)
18	1987±15[f]	(1980)
19	2123±15	(2130)

[a]E. R. Flynn, J. W. Sunier, and F. Ajzenberg-Selove, Phys. Rev. C **15**, 879 (1977).
[b]See Fig. 13.
[c]Q_0 derived from the present work is -7006 ± 20 keV.
[d]$J^\pi = 5^+$ from systematics.
[e]Observed at several angles: groups are weak.
[f]The width of this group indicates that it is due to unresolved states.

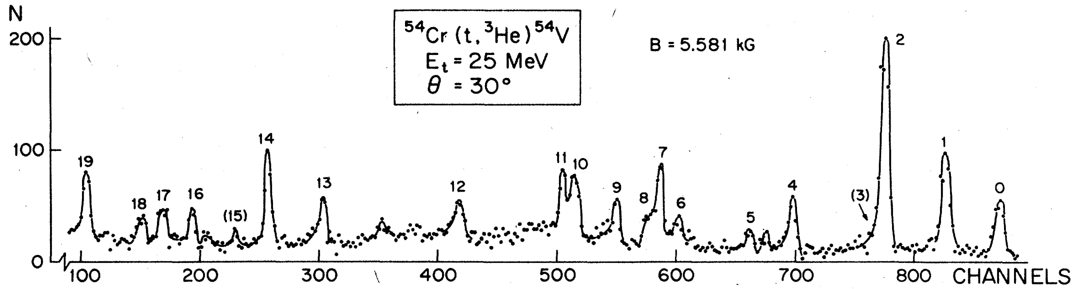

FIG. 13. Spectrum of the ^{54}Cr(t,^{3}He)^{54}V reaction at θ(lab)$=30°$.

TABLE IX. States of ^{54}Mn.

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L[c]	J^π	E_x (keV)	J^π
0	0	d		0	3$^+$
1	54±3	d		54.6	2$^+$
2	160±5	4	4$^+$	156.3	4$^+$
3	374±8	d		367.9	5$^+$
4	414±8	d		407.4	3$^+$
5	842±8	d		838.7	4$^+$
6	1007±10			1009.4	3$^+$
		d,e	3$^+$+6$^+$		
7	1040±20			1073.0	6$^+$
8	1130±10	4+6	5$^+$	1136.6	5$^+$
				1374.5	2$^+$
9	1353±20[e]	2[f]	2$^+$		
				1375.5	
10	1377±20	0+2	1$^+$	1390.5	1$^+$
11	1430±20	0+2[g]	(1$^+$)	1454.2	1$^+$
12	1454±20		4$^+$,5$^+$	(1461)	
13	1506±10	h		1508.3	2$^+$
14	1538±10	h,i		1543.7	3$^+$
				1634.1	2$^+$,3$^+$
15	1632±20[d,f]	j,k			
				1650.8	1$^+$
	l			1679	0$^+$
				1784	7$^+$
16	1789±15	m			
				1784.5	2$^+$,3$^+$
	n			1852.7	3$^+$
				1921.7	1$^+$
17	1923±15[e]	0+2[f]	1$^+$		
				1925.7	7$^+$
18	2051±15		4$^+$(5$^+$)	2050	2$^+$,4$^+$
				2110	0$^+$
19	2112±15[e]	4[k]	4$^+$		
	l			2113	1$^+$-6$^+$
20	2140±20	k		2133.4	(1$^+$)
21	2270±20		4$^+$,5$^+$	2267.4	2$^+$-5$^+$
22	2300±20	h		2291.0	2$^+$-4$^+$
	l			2320	5$^+$
23	2360±15	h		2354.3	
24	2500±15	(4)	(4$^+$)	2497.9	
25	2560±15		4$^+$,5$^+$	2566	
26	2620±15			2620	
27	2670±15			2695	
28	2705±15				
29	2775±15	4 + 6[k]	5$^+$	2815	1$^+$-6$^+$

TABLE IX. (*Continued*).

Present results				Previous work[a]	
Group No.[b]	E_x (keV)	L[c]	J^{π}	E_x (keV)	J^{π}
				2857	8^+
30	2880±20[e]	4 + 6[k]	5^+		
				2868	
31	2905±15	h		2910	
32	2985±20			2980	
33	3015±15	4[k]	4^+	3023	1^+-6^+
	n			3067	1^+-6^+
34	3115±20	4 + 6	5^+	3080	
35	3200±15	4 + 6[k]	5^+	3207	1^+-6^+
36	3220±20	4 + 6	5^+	3244	9^+
37	3300±15	4 + 6	5^+	3305	
38	3335±20	4 + 6	5^+	3313	
	k,n			3422	1^+-6^+
	k,n			3552	1^+-6^+
39	3600±20				
40	3655±15				
41	3707±15[p]				
				3720	0^+-5^+
42	3730±20		$1^+,2^+$		
43	3780±30				
44	3830±20[o]				
45	3900±30				
				3939	6^+-9^+
46	3950±30[o]				
47	4020±30[o]				
48	4050±30[0]				
				4100	
49	4130±30[o]				
50	4160±30[o]			4160	
51	4220±30[o]			4210	
52	4240±30[o]				
53	4290±30				
54	4320±30[o]			4332	
55	4440±30[o]			4415	
56	4490±30[o]			4465	
57	4590±30[o]			4542	
58	4620±30[o]			4670	

[a]See H. Verheul and R. L. Auble, Nucl. Data Sheets **23**, 455 (1978); A. A. Pilt, J. A. Cameron, and J. A. Kuehner, Phys. Rev. C **22**, 462 (1980); J. A. Cameron *et al.*, Nucl. Phys. **A365**, 113 (1981).
[b]See Fig. 14.
[c]L transfers assumed in the theoretical CCBA curves shown in Fig. 15. See the text and footnote c of Table II for additional comments.
[d]See the text.
[e]Angular distribution shown in Fig. 15 is of unresolved group.
[f]Dominant.
[g]Consistent with $L=0+2$ except for most forward angles.
[h]Very poor agreement with CCBA.
[i]The group is weak and nearly isotropic. When groups 13 and 14 are plotted together, which improves the errors due to the peak fitting procedure, the composite group still shows very poor agreement with $J^{\pi}=2^{+}+3^{+}$.
[j]The unresolved group is weak and nearly isotropic at ~ 2 μb/sr to $\theta_{\rm c.m.}=40°$, decreasing to 0.6 μb/sr at $\theta_{\rm c.m.}=54°$.
[k]There is no evidence of a strong forward contribution characteristic of a 1^+ state.
[l]Not observed, but contributions of weak groups are not excluded.
[m]The angular distribution is not shown in Fig. 15 but it is consistent with weakly populated 7^+ and (2^+ or 3^+) states.
[n]Observed at several angles: groups are weak.
[o]The width of this group indicates that it is due to unresolved states.
[p]Neither this state nor any of the higher energy states have been observed at forward angles.

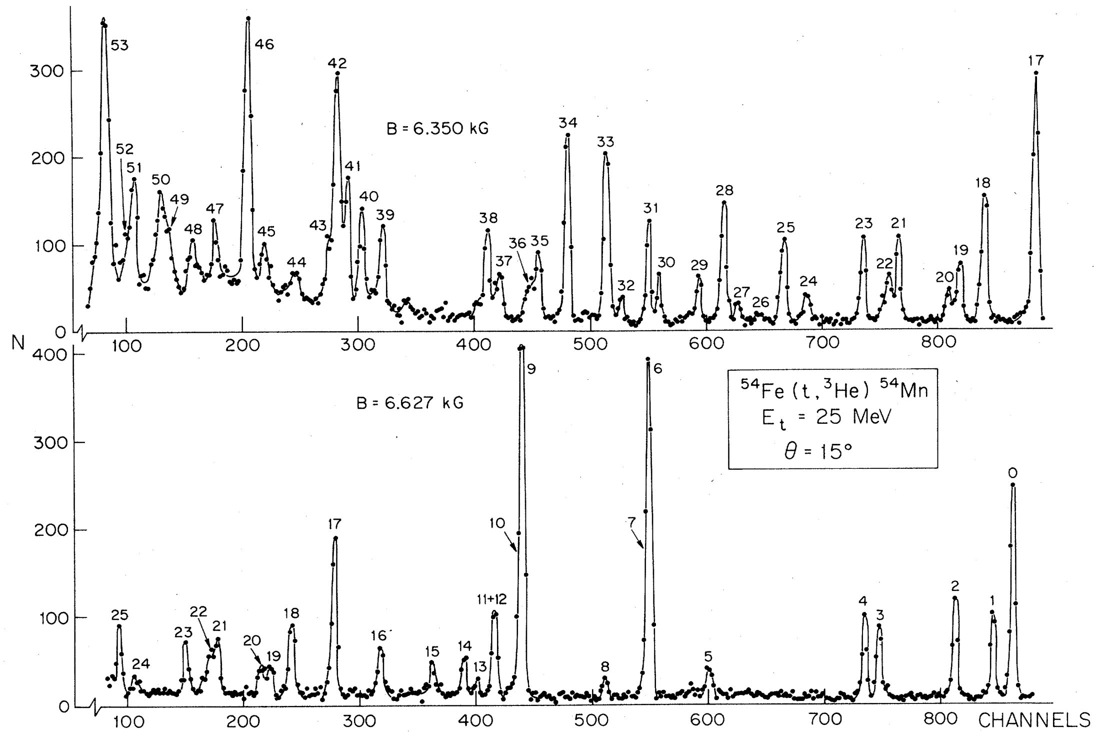

FIG. 14. Spectrum of the ^{54}Fe(t,^{3}He)^{54}Mn reaction at $\theta_{lab}=15°$.

H. States of ^{54}Mn

The level structure of ^{54}Mn is discussed in the review by Verheul and Auble.[18] More recently Pilt, Cameron, and Kuehner,[19] and Cameron *et al.*[20] have reported on studies of the ^{56}Fe($\vec{d}$,α) and ^{55}Mn($\vec{d}$,t) reactions, respectively. The evidence from these three papers is displayed in Table IX. The evidence for the J^π assignments for the first six states of ^{54}Mn is very strong: the ground state and the states at 55, 156, 368, 407, 839, 1009, and 1073

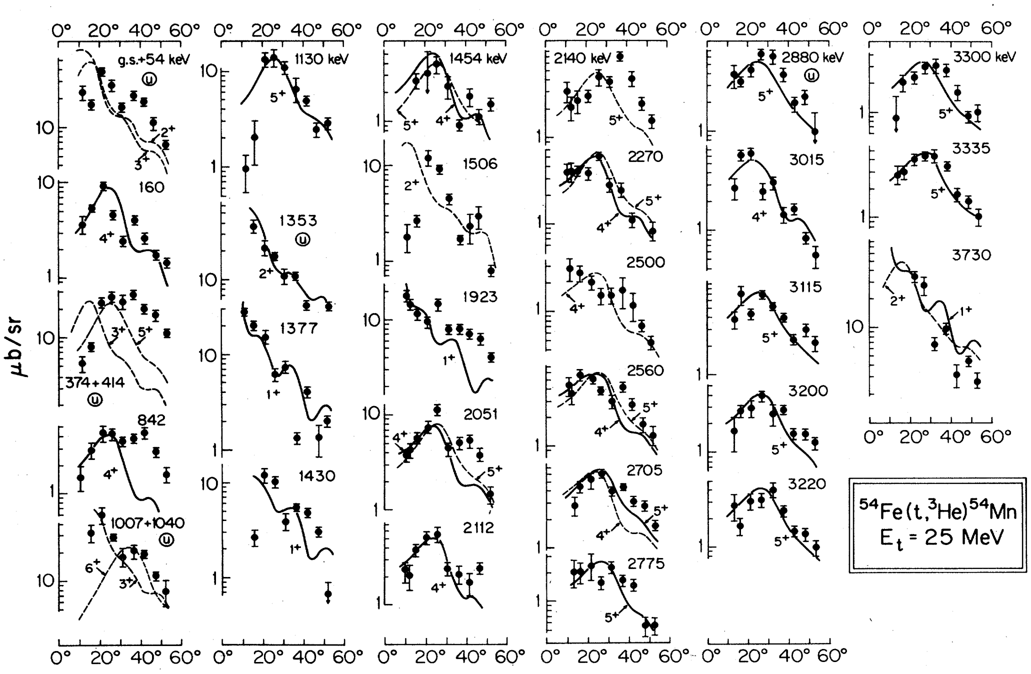

FIG. 15. Angular distributions of the ^{3}He groups from the ^{54}Fe(t,^{3}He)^{54}Mn reaction. See also the caption of Fig. 2.

keV have, respectively, $J^{\pi}=3^+, 2^+, 4^+, 5^+, 3^+$, and 4^+.

Figure 14 shows the spectra of the ^{3}He groups from the ^{54}Fe(t,^{3}He) reaction, and Fig. 15 shows some of the angular distributions we obtained as well as CCBA calculations. In contrast with the results presented in Ref. 1 and in the earlier part of this paper, we find very poor agreement between the CCBA curves using the known values of L for the J^{π} of five of these six states and the experimental curves. The exception is the angular distribution to the 156 keV state which is in good agreement with $L=4$. We cannot account for the differences in the other cases, i.e., for the unresolved groups to the ground state and the 55 keV state $(3^+ + 2^+)$ and to the 368 and 407 keV states $(5^+ + 3^+)$, as well as for the group to the 4^+ state at 839 keV. The disagreement is as striking when we plot the angular distributions to the individual states

TABLE X. Population of the 1^+ states.[a]

^{40}K		^{42}K		^{46}Sc	
E_x[b] (keV)	σ_{rel}[c]	E_x[d] (keV)	σ_{rel}[c]	E_x[e] (keV)	σ_{rel}[c]
2288[j]	0.24±0.04	2862	0.53±0.11	991[j]	0.48±0.09
3272[k]	0.51±0.13	3097[j]	0.42±0.11	1848[l]	0.36±0.09
	0.75±0.14	3297	0.82±0.16	3016[j]	0.34±0.10
		3329	0.33±0.11	3100[j]	0.31±0.08
		3377[j]	0.31±0.11	3377	0.46±0.07
			2.41±0.27	3523[j]	0.61±0.12
					2.56±0.23
^{48}Sc		^{50}Sc		^{54}Mn	
E_x[f] (keV)	σ_{rel}[c]	E_x[g] (keV)	σ_{rel}[c]	E_x[h] (keV)	σ_{rel}[c]
2989	0.27±0.06	1852	1.20±0.12	1377	0.74±0.08
3064[j]	0.29±0.08	2614	3.1±0.5	1430	0.65±0.06
3719	0.69±0.14		4.3±0.5	1923[j]	1.1±0.2
	1.25±0.17			3730[l]	2.8±0.6
					5.3±0.6
^{56}Mn		^{58}Mn		^{58}Co	
E_x[i] (keV)	σ_{rel}[c]	E_x[i] (keV)	σ_{rel}[c]	E_x[i] (keV)	σ_{rel}[c]
111	≡1	180	1.11±0.27	1050	1.08±0.22
1166	0.87±0.09	298	0.82±0.22	1377	0.16±0.02[o]
1560	0.54±0.14	651	1.54±0.33	1436	0.23±0.02[o]
(1674)[m]	0.54±0.16	745	1.03±0.26	1729	1.06±0.19
1833	0.92±0.13	816	1.46±0.30	1865	1.93±0.23
2159	0.64±0.13	1040	1.39±0.39	2249	0.25±0.05
2519	0.58±0.15	1275	1.99±0.45	n	
2626	0.35±0.09		9.3 ±0.9		4.7 ±0.4
2780	0.74±0.16				
2855[j]	0.81±0.17				
	7.0±0.4				

[a]See Sec. III for a discussion of the 1^+ states observed in this work and in a previous paper (Ref. 2) and of the problems involved in identifying weak and unresolved 1^+ states.
[b]See Fig. 2 and Table II.
[c]Cross sections for $0° < \theta < 53°$ (c.m.) divided by the total cross section over that angular range predicted by DWBA calculations, and relative to that for the 111 keV state of ^{56}Mn taken to be 1.
[d]See Fig. 4 and Table III.
[e]See Fig. 8 and Table V.
[f]See Fig. 10 and Table VI.
[g]See Fig. 12 and Table VII.
[h]See Fig. 15 and Table IX. See also Table I of Ref. 1.
[i]See Table I of Ref. 1. See also Ref. 2.
[j]The 1^+ state is dominant in an unresolved angular distribution. The σ_{rel} shown is an upper limit.
[k]1^+ assignment is uncertain; this could be a 1^- state.
[l]1^+ assignment is uncertain: see the text.
[m]This is a possible 1^+ state; the assignment is not certain. The σ_{rel} shown is an upper limit.
[n]See also Table IV in Ref. 2.
[o]Uncertainty shown in Ref. 1 was in error.

which we were in fact able to resolve clearly at most (but not at all) angles. While there are ways in which the experimental distributions to the 368 and 407 keV states and to the 838 keV states might be understood [3^+ state weak in the first set; unresolved, and previously unreported, high J state ($J \geq 6$) in the second], these are only *ad hoc* explanations.

At higher excitation energies the agreement between CCBA for known states and the experimental data improves somewhat. We observe 1^+ states at $E_x = 1377$, (1430), 1923, and (3730) keV: see Tables IX and X. However, we do not observe the strong forward distributions characteristic of 1^+ states for the known 1^+ state at 1651 keV and the possible 1^+ states at 2113, 2133, 2815, 3023, 3067, 3207, 3422, and 3552 keV (most of them have possible assignments $J^\pi = 1^+ - 6^+$). We do not observe the 9^+ state at 3244 keV but report a 5^+ state at 3220 keV.

I. The 1^+ states

In an earlier paper[1] we discussed the location of Gamow-Teller states with T_0+1 isospin in ^{54,56,58}Mn and in ^{58}Co. We summarize in Table X the data we have obtained on the population of 1^+ states in ^{40,42}K, ^{46,48,50}Sc, and ^{54}Mn relative to that of the 1^+ state at 111 keV in ^{56}Mn (see Table I in Ref. 1).

In ^{40}K (see Table III) a 1^+ state is known at 2290 keV: we do not resolve it from the 3^- state at 2291 keV, but the unresolved angular distribution shown in Fig. 2 is dominated by $L = 0+2$. There is a possibility that the state at 3110 keV has 1^+ but this is a highly speculative statement (see Sec. II A) and we do not display this state in Table X. The state at 3272 keV appears to be a 1^+ state although 1^- cannot be definitely ruled out. The only even parity states that should arise in ^{40}K are from deep hole or high lying particle states, and these should primarily be weak or should obtain their strengths from admixtures of giant resonances. Additional comments are made in Sec. II A.

In ^{42}K we assign five groups, to 1^+ states at $E_x = 2862$, 3097, 3297, 3329, and 3377 keV. Two of these groups (see Table III), the ones corresponding to 3097 and 3377 keV, appear to correspond to unresolved states. Their relative populations are shown in Table X. In ^{44}K we do not observe the population of the three 1^+ states known to be located at 1886, 2326, and 2754 keV and we discuss this problem in Sec. II C. The state at 1886 keV would have been well resolved, and we do not understand why it is not populated.

In ^{46}Sc we report the population of six 1^+ states in Table X. However, all but one of the ^{3}He groups (that to the state at 3377 keV) are due to unresolved groups or to a group ($E_x = 1848$ keV) whose 1^+ assignment is not certain. Additional comments are made in Sec. II D. ^{3}He groups to three 1^+ states are reported in ^{48}Sc, one of which, to states at 3064 keV, may correspond to two unresolved 1^+ states: see Table VI. The state at 2519 keV, which has previously been assigned 1^+, is very weakly populated here: see Sec. II E. Most of the strength of the 1^+, $T=3$ states appears to be located[9,10] above $E_x = 6$ MeV in ^{48}Sc.

In ^{50}Sc we observe ^{3}He groups to two 1^+ states at 1852 and 2614 keV. Finally in ^{54}Mn, in addition to the two 1^+ states at $E_x = 1377$ and 1430 keV whose relative population was given in Ref. 2, we now assign 1^+ to one of the unresolved states at 1923 keV (see Table IX) and, possibly, to a state at 3730 keV. Table X summarizes these data and displays as well the earlier information shown in Ref. 1.

III. CONCLUSIONS

This is the second of two papers[1] reporting on the comprehensive use of the (t,^{3}He) reaction as a tool for determining J^π assignments and Q values. J^π assignments have been made to many states in ^{40,42,44}K, ^{46,48,50}Sc, and ^{54}Mn. In addition, we report on the relative population of 1^+ states in these nuclei.

ACKNOWLEDGMENTS

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[2]F. Ajzenberg-Selove, R. E. Brown, E. R. Flynn, and J. W. Sunier, Phys. Rev. C **31**, 777 (1985).

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