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$^{50}Cr(p,\gamma)^{51}Mn$ Reaction from $E_p = 1\cdot45$ to $2\cdot07$ MeV

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Abstract

Proton resonances in the $^{50}Cr(p,\gamma)^{51}Mn$ reaction have been studied in the range E_p = 1450–2070 keV. Gamma-ray spectra, measured at 55° to the beam direction at each of the resonances at E_p = 1451, 1546, 1580, 1600, 1689, 1798, 1830, 2031, 2042 and 2067 keV with a high resolution 35 cm^3 Ge(Li) detector, have been used to derive the decay schemes of the resonant and bound levels in ^{51}Mn. Decays to the bound levels at 4·052, 4·729, 4·925, 5·073, 5·129, 5·174, 5·188, 5·203 and 5·506 MeV have been observed in the proton capture reaction for the first time, while new results have been obtained for the decay of some of these levels. The reported levels at 2·715, 2·892, 3·046, 3·051, 4·203, 4·887 and 5·223 MeV are confirmed. The energies of the excited levels in ^{51}Mn have been obtained with an accuracy of ±3 keV and the Q value for the reaction $^{50}Cr(p,\gamma)^{51}Mn$ has been found to be 5·269±0·002 MeV. From angular distribution measurements for the resonances at E_p = 2042 and 2067 keV, spins of 5/2 are proposed for each of the excited states at 7·270 and 7·295 MeV.

Introduction

The properties of the excited levels in ^{51}Mn were first investigated by Arnell (1962) from the reaction $^{50}Cr(p,\gamma)^{51}Mn$. He was able to identify 9 resonances in the energy range E_p = 900–1220 keV, using NaI detectors. Later work by Arnell and Sterner (1964) at 6 resonances for the same reaction in a similar range of E_p (and again using NaI detectors) established the existence of 11 levels below 4·0 MeV in ^{51}Mn and provided the first information on the decay properties of these levels. Subsequently, energy values to a better accuracy for 11 levels below 3·0 MeV excitation in ^{51}Mn were reported by Sterner *et al.* (1966), using 0·5 cm^3 Ge(Li) and NaI detectors. Wall and Erlandsson (1967) investigated the γ-ray decay schemes of 5 resonances for the $^{50}Cr(p,\gamma)^{51}Mn$ reaction in the energy region E_p = 1050–1970 keV. Excited levels up to 6·052 MeV in ^{51}Mn with an energy resolution of 30 keV were reported by Rapaport *et al.* (1967) from a study of the $^{50}Cr(^3He,d)^{51}Mn$ reaction at 12·0 MeV bombarding energy.

The principle source of information on the level decay scheme of ^{51}Mn has been the work of Forsblom *et al.* (1972). Those authors used a Ge(Li) detector to study 19 resonances from the $^{50}Cr(p,\gamma)^{51}Mn$ reaction in the energy range E_p = 1000–1700 keV and reported levels up to 5·585 MeV excitation in ^{51}Mn. Spins were assigned for some of the levels by Erlandsson (1967) and Forsblom *et al.* (1972) from measurements of the angular distributions. In addition, *l*-value assignments were made for certain levels from studies of the ^{50}Cr(^{3}He, d)^{51}Mn reaction by Rapaport *et al.* (1967) and the reaction ^{50}Cr(d, n)^{51}Mn by Nilsson and Erlandsson (1970).

As part of a program to investigate the decay schemes of radiative capture resonances with large Ge(Li) detectors, the present report deals with a study of the ^{50}Cr(p, γ)^{51}Mn reaction in the energy range E_p = 1450–2070 keV. The aims of this work were to look for any new resonances and bound levels, to verify the existence of certain doubtful levels, to derive the decay properties of the bound levels and to locate and study isobaric analogue states.

Experimental Procedure

The research work was carried out at two laboratories: The 2 MeV Van de Graaff accelerator of the Australian National University was used to locate the resonances and measure the γ-ray spectra, while the angular distributions were measured with the 4 MeV Van de Graff accelerator at the Centre de Recherches Nucleaires, Strasbourg.

Enriched ^{50}Cr targets were used. To minimize the contamination of occluded gases (especially ^{19}F), blanks of tungsten were heated in vacuum with an induction heater before being used as targets backings. Chromium powder 92% enriched with ^{50}Cr (obtained from the Oak Ridge National Laboratory) was evaporated onto the tungsten backings to produce targets of thicknesses 10 and 20 μg cm^{-2}. The thinner target was used for the determinations of the yield curves for the ^{50}Cr(p, γ)^{51}Mn reaction, while the thicker target was used to measure γ-ray spectra at different angles to obtain the angular distributions. The targets were water-cooled and a liquid nitrogen trap was placed in front of the target chamber to remove condensable vapours and to minimize carbon buildup.

A 35 cm^3 Ge(Li) detector with a resolution of better than 3 keV for the 1173 keV γ-ray from ^{60}Co was placed at 55° to the beam direction to locate the resonances and to accumulate γ-ray spectra at each resonance. The spectra were stored in a 4096-channel Nuclear Data ND 2200 analyser. The spectra measured at 55° yielded the decay schemes and the branching ratios of both the resonances and the bound levels. The intensities of the γ-rays were derived from the calibrated intensity of the Ge(Li) detector using the 992 keV resonance from the ^{27}Al(p, γ)^{28}Si reaction and the γ-rays from a ^{56}Co radioactive source. The relative intensity errors vary from 5% for the prominent peaks to 15% for the smaller peaks. Where the decay scheme of a bound level could be determined from more than one resonance, the transition ratios were found to be consistent within experimental error.

The angular distributions were measured with an 80 cm^3 Ge(Li) detector at five angles, 0°, 30°, 45°, 60° and 90°. A fixed smaller volume Ge(Li) detector was used to normalize the angular distribution data. The results have been analysed in terms of even-order Legendre polynomials up to fourth order. For each spin combination, a value was computed of the sum of the squared and weighted differences between the experimental and theoretical number of counts divided by the number of free parameters. A computer program performed in the first step the normalization of the theoretical distributions and determined in the second step the best value of the mixing ratios. A 0·1% probability limit separated the acceptable from the unacceptable solutions. In the present case χ^2 was equal to 4·2 at the 0·1% limit. Often more than one value of χ^2_{min} was obtained.

Table 1. Branching ratios for decay of 10 resonances in $^{50}Cr(p, \gamma)^{51}Mn$

Bound level E_x (MeV)	Branching ratios (%) from resonances E_p = 1451	1546	1580	1600	1689	1798	1830	2031	2042	2067 keV
0	8		5	15	9	34	30	4	18	10
0·238	36			<1			2	11	5	
1·140										
1·817	8		26		4	1		17		
1·823		29		37	7	10	26		8	5
1·958		9			10	26		8	7	33
2·139		13		23	16	5		4	9	3
2·256	3		7		6		2		4	25
2·275			15		3		3	4		3
2·312	3		9				2		3	
2·416	17						1	2		
2·702	3		7					12	3	
2·715								2		
2·846					10	6	4		8	
2·892	2							2		
2·914	3	9	2	<1	5	5	1		1	
2·985			3	2	6		2		20	11
3·046	6									
3·051			3				2			
3·131	10	3	15				2	9		
3·294			3	3			2			
3·423					15					
3·556		9		4	6	5	3			2
3·694							3	1		
3·896	1	26				8	7		6	
4·052								1		
4·203				4				4	5	
4·355				8						
4·453			5	3						
4·729							2			
4·887									<1	2
4·925							3	1		<1
5·073							1	<1	2	1
5·129								4		
5·174								<1		<1
5·188							<1	13		
5·203					3					
5·223		2								
5·506										4

Results

The yield curves found by Wall and Erlandsson (1967) for the reaction $^{50}Cr(p, \gamma)^{51}Mn$ were used as a guide to identify the resonances up to E_p = 1830 keV. The proton energy of the resonances was obtained using the 992 keV resonance in $^{27}Al(p, \gamma)^{28}Si$ as a calibration point. The yield curve used for resonances above 2·0 MeV will be presented in a separate paper.

Table 2. Branching ratios and γ-ray energies in decay of bound levels in ^{51}Mn

Level No.	E_x (MeV)	Transition	E_γ (MeV)	Branching ratio (%)
0	0	g.s.		
1	0·238	1→0	0·238	100
2	1·140	2→0	1·140	10
		2→1	0·902	90
3	1·817	3→0	1·817	100
4	1·823	4→0	1·823	100
5	1·958	5→0	1·958	100
6	2·139	6→0	2·139	100
7	2·256	7→0	2·256	20
		7→1	2·018	80
8	2·275	8→3	0·458	70
		8→5	0·317	30
9	2·312	9→0	2·312	15
		9→1	2·074	85
10	2·416	10→0	2·416	6
		10→1	2·178	34
		10→2	1·276	37
		10→3	0·599	15
		10→6	0·277	8
11	2·702	11→2	1·562	2
		11→3	0·885	21
		11→5	0·744	26
		11→9	0·390	37
12	2·715	12→0	2·715	100
13	2·846	13→4	1·023	40
		13→5	0·888	60
14	2·892	14→0	2·892	35
		14→2	1·752	45
		14→3	1·075	20
15	2·914	15→0	2·914	100
16	2·985	16→0	2·985	20
		16→1	2·747	80
17	3·046	17→3	1·229	40
		17→7	0·790	45
		17→8	0·771	15
18	3·051	18→0	3·051	100
19	3·131	19→3	1·314	45
		19→7	0·875	12
		19→9	0·819	10
20	3·294	20→0	3·294	35
		20→1	3·056	65
21	3·423	21→5	1·465	100
22	3·556	22→0	3·556	100
23	3·694	23→0	3·694	20
		23→4	1·871	55
		23→6	1·555	25
24	3·896	24→0	3·896	100
25	4·052	25→16	1·067	100
26	4·203	26→0	4·203	20
		26→1	3·965	20
		26→4	2·380	60
27	4·355	27→0	4·355	45
		27→5	2·397	25
		27→22	0·799	15
28	4·453	28→4	2·630	45
		28→5	2·495	20
		28→9	2·141	35
29	4·729	29→0	4·729	85
30	4·887	30→5	2·929	13
		30→13	2·041	60
31	4·925	31→15	2·011	75
		31→16	1·940	25
32	5·073	32→3	3·256	15
		32→5	3·115	35
		32→8	2·798	50
33	5·129	33→9	2·817	75
		33→16	2·144	25
34	5·174	34→4	3·351	100
35	5·188	35→1	4·950	34
		35→14	2·296	18
		35→15	2·274	20
		35→18	2·137	28
36	5·203	36→0	5·203	70
37	5·223	37→1	4·985	50
		37→3	3·406	30
38	5·506	38→1	5·268	35
		38→25	1·454	65

Figs 1*a*–1*f* (pp. 267–72). Gamma-ray spectra measured at 55° with a 35 cm^3 Ge(Li) detector for resonances at E_p = 1689, 1798, 1830, 2031, 2042 and 2067 keV in the reaction ^{50}Cr(p, γ)^{51}Mn.

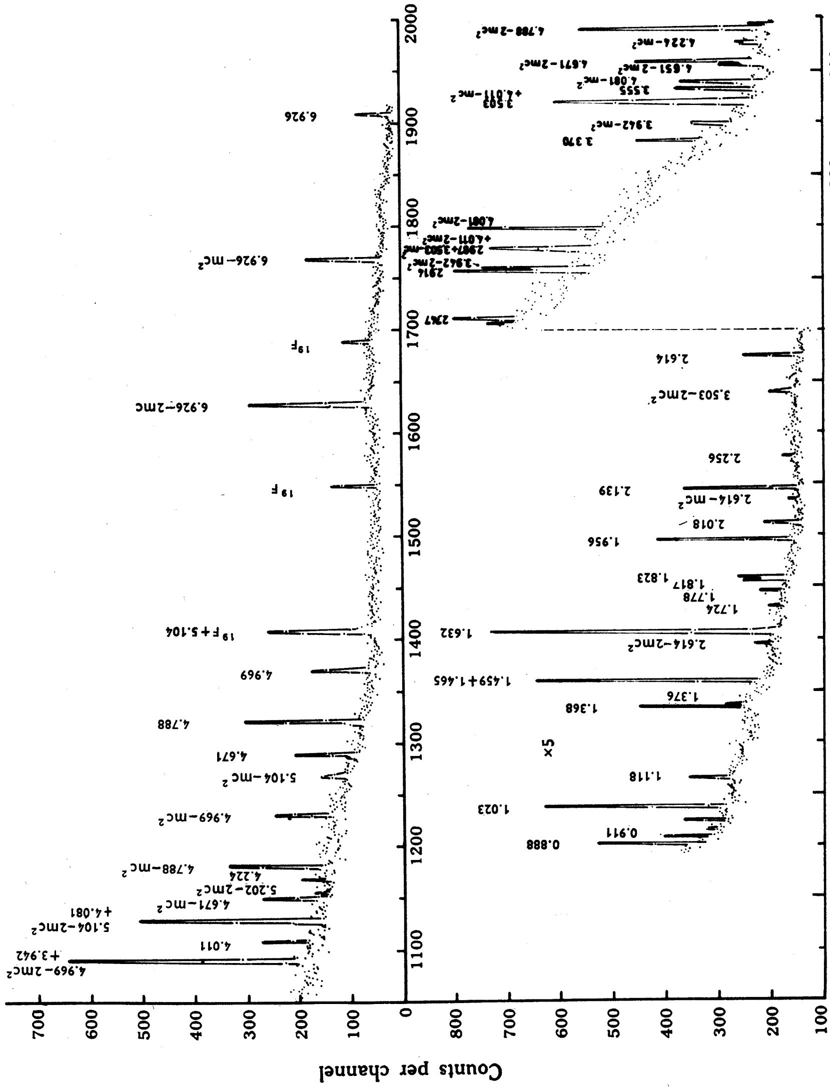

Fig. 1a. $E_p = 1689$ keV. Decay to the $3\cdot423$ MeV level was observed with the $3\cdot503$ MeV primary γ-ray.

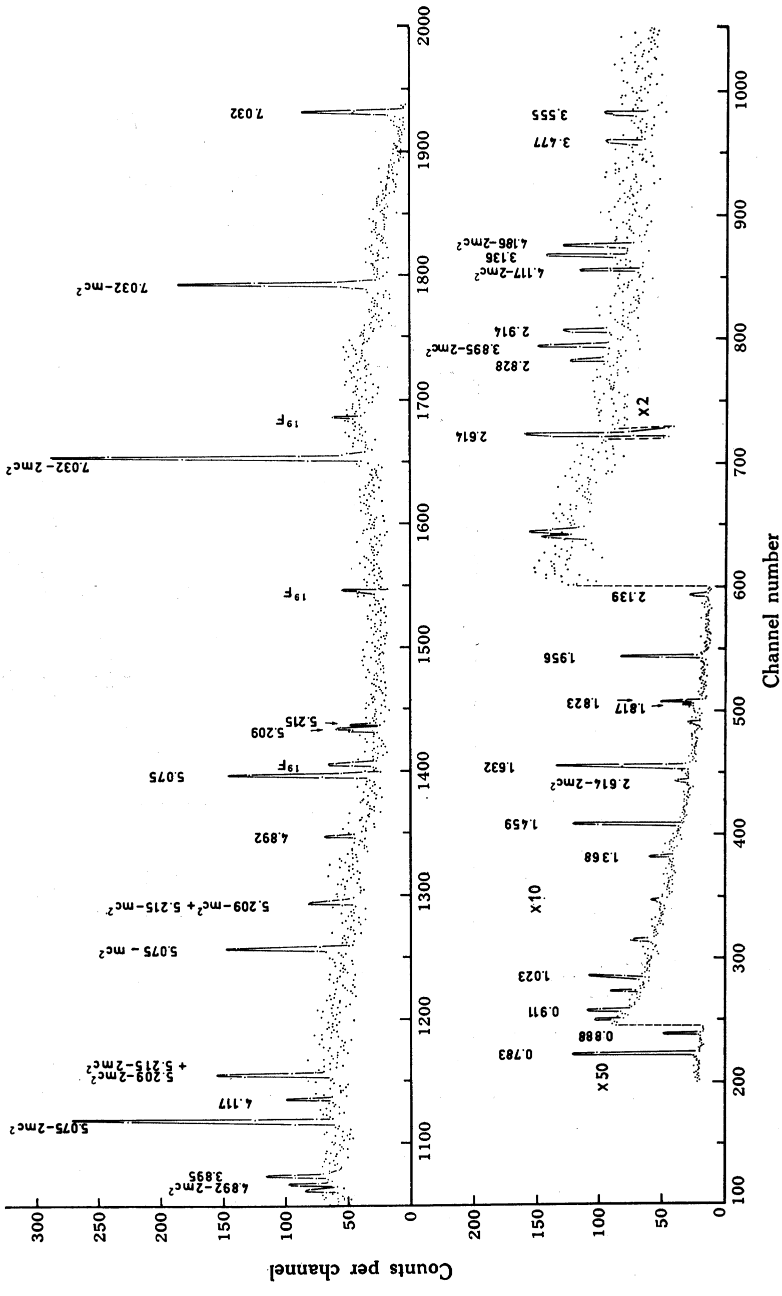

Fig. 1*b*. $E_p = 1798$ keV. It was found to be necessary to revise the decay scheme of Wall and Erlandsson (1967).

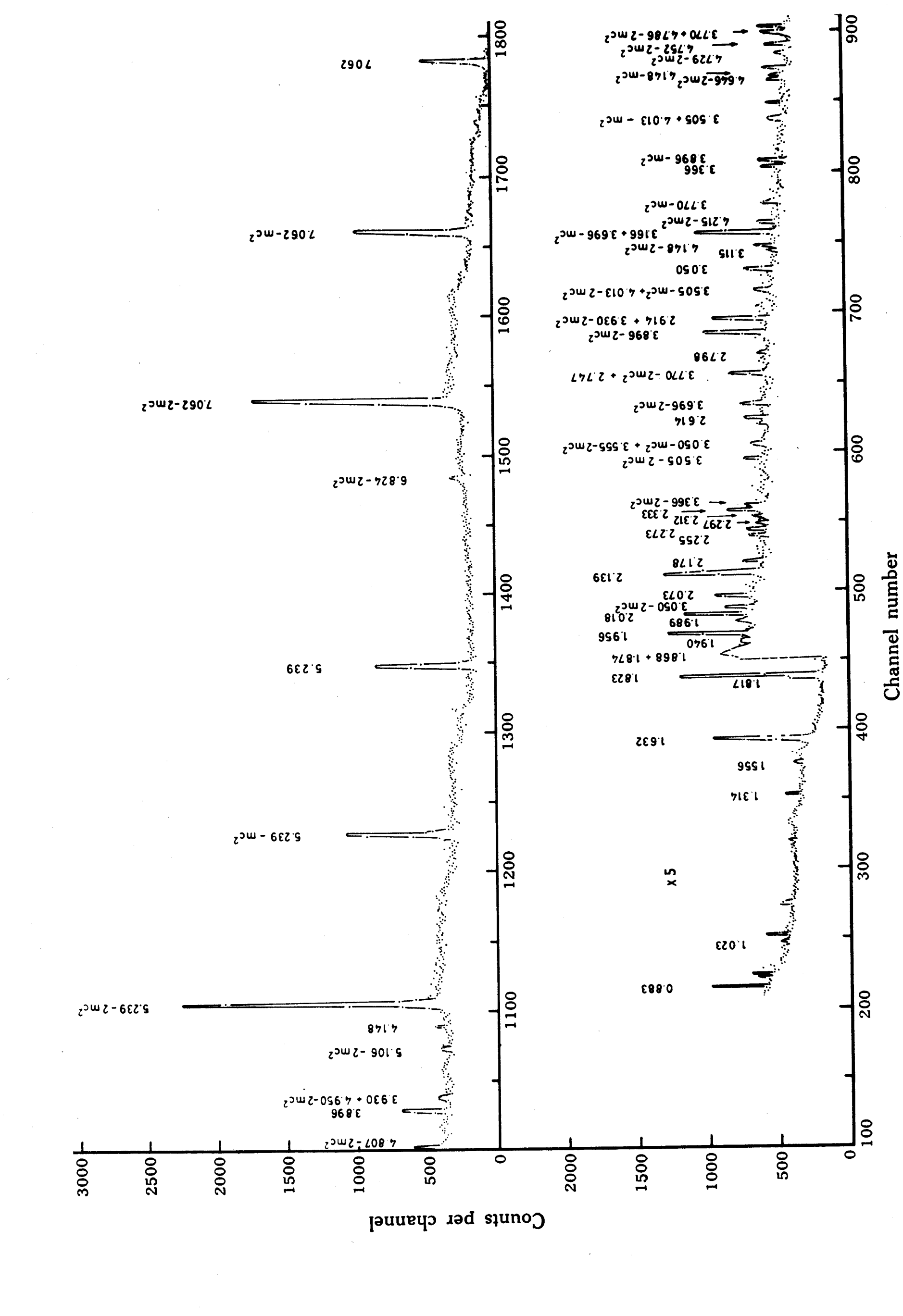

Fig. 1c. $E_p = 1830$ keV. Transitions to 20 bound levels including 4 previously unreported levels in (p, γ) reactions at 4·729, 4·925, 5·073 and 5·188 MeV were observed.

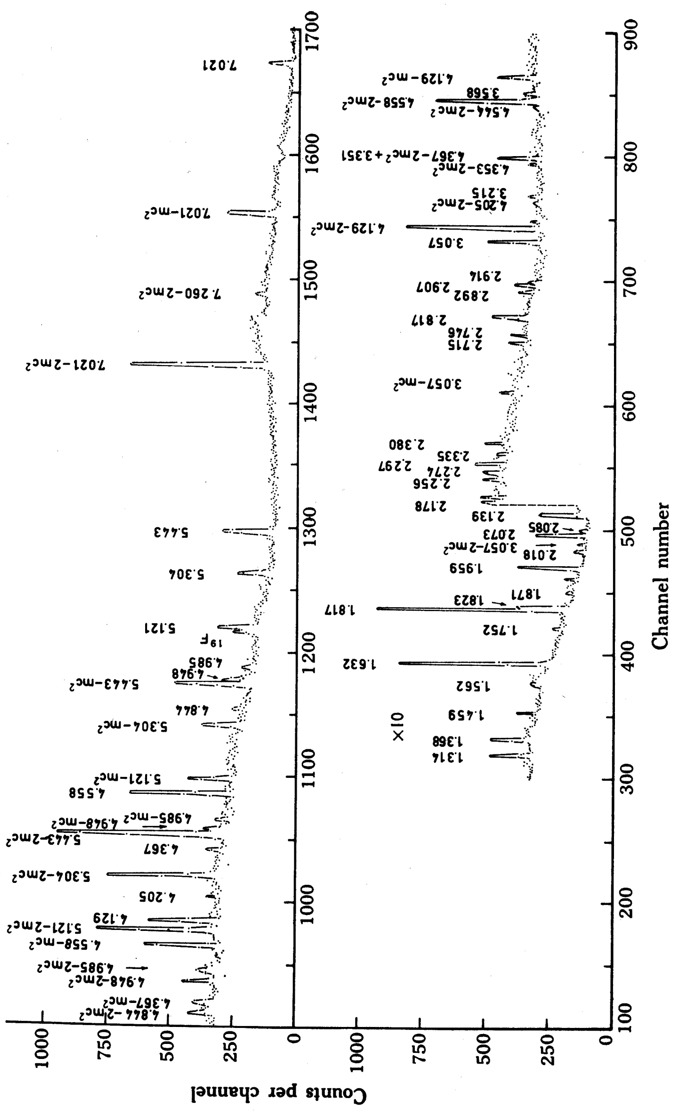

Fig. 1d. E_p = 2031 keV. Two previously unreported levels at 4·052 and 5·188 MeV were populated.

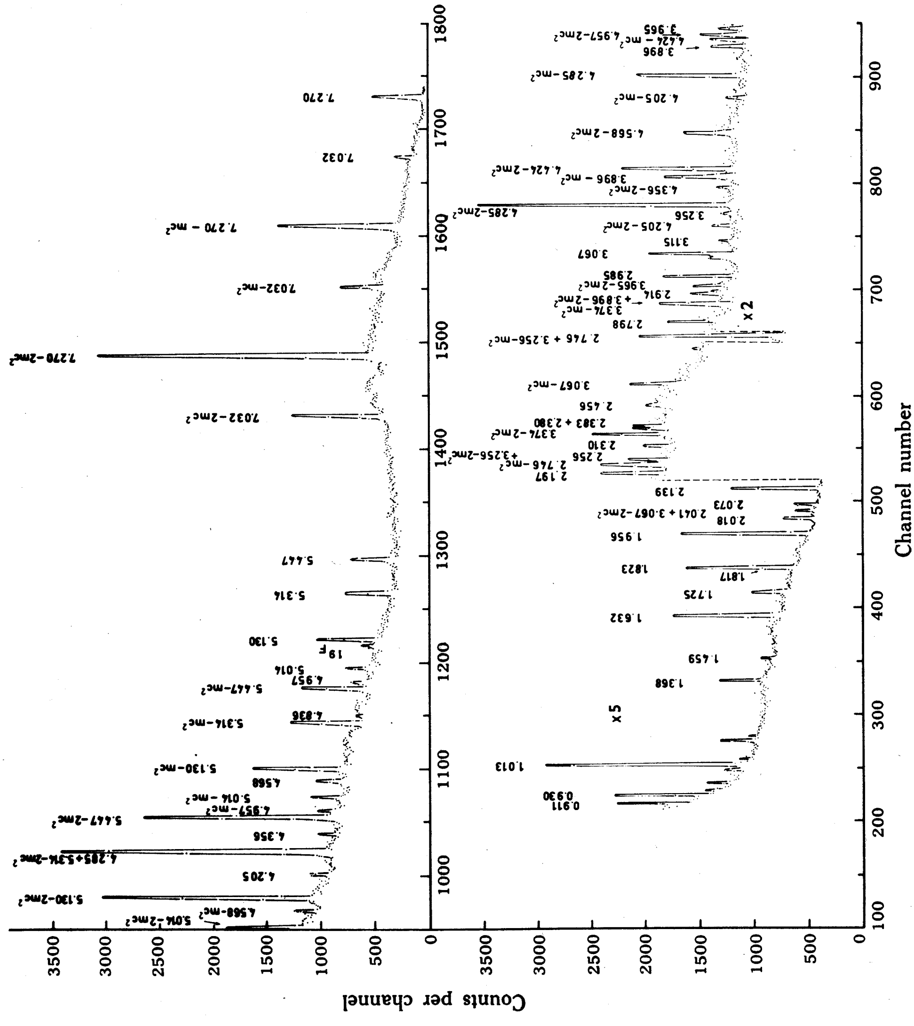

Fig. 1e. E_p = 2042 keV. Fifteen primary γ-ray transitions were observed.

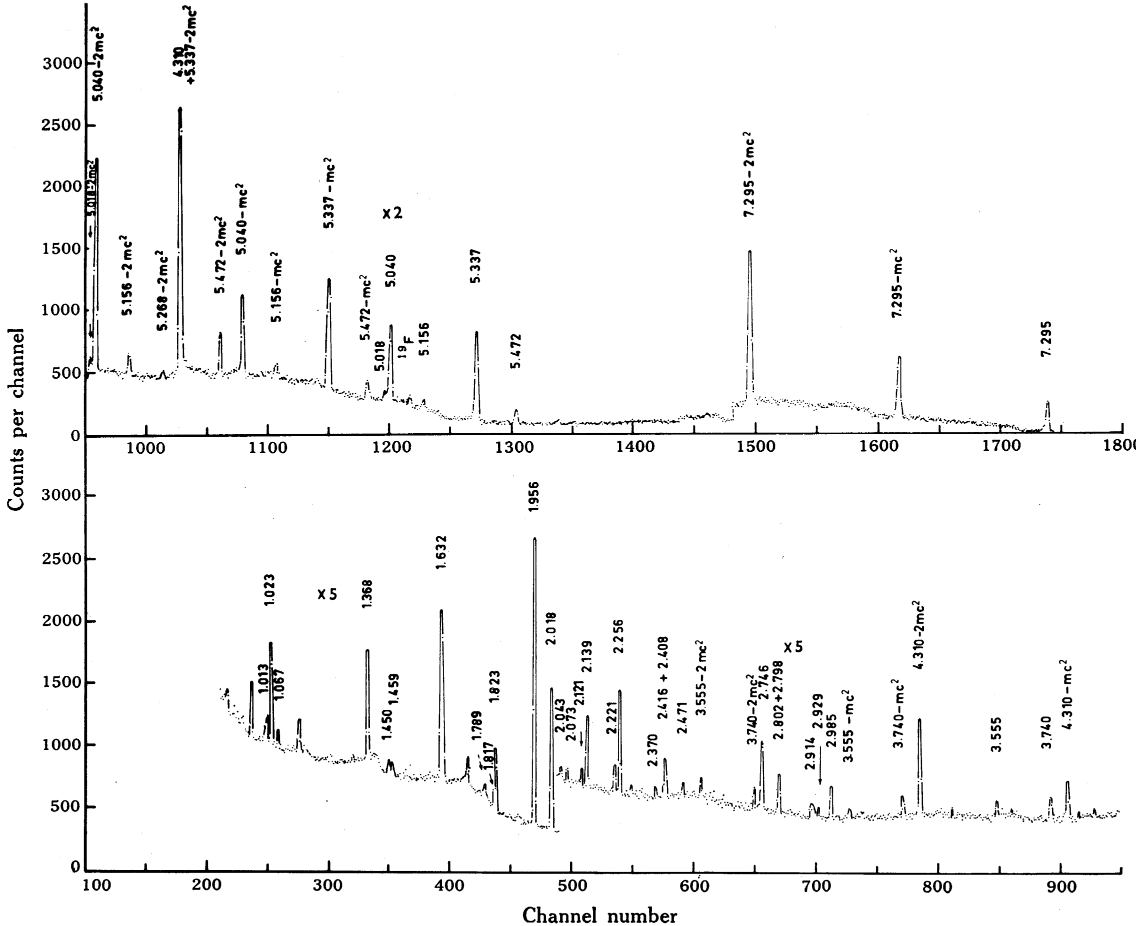

Fig. 1*f*. $E_p = 2067$ keV. A level at 5·506 MeV, previously unreported in (p, γ) reactions, decays to the first excited state and the level at 4·052 MeV with γ-rays of 5·268 and 1·450 MeV respectively.

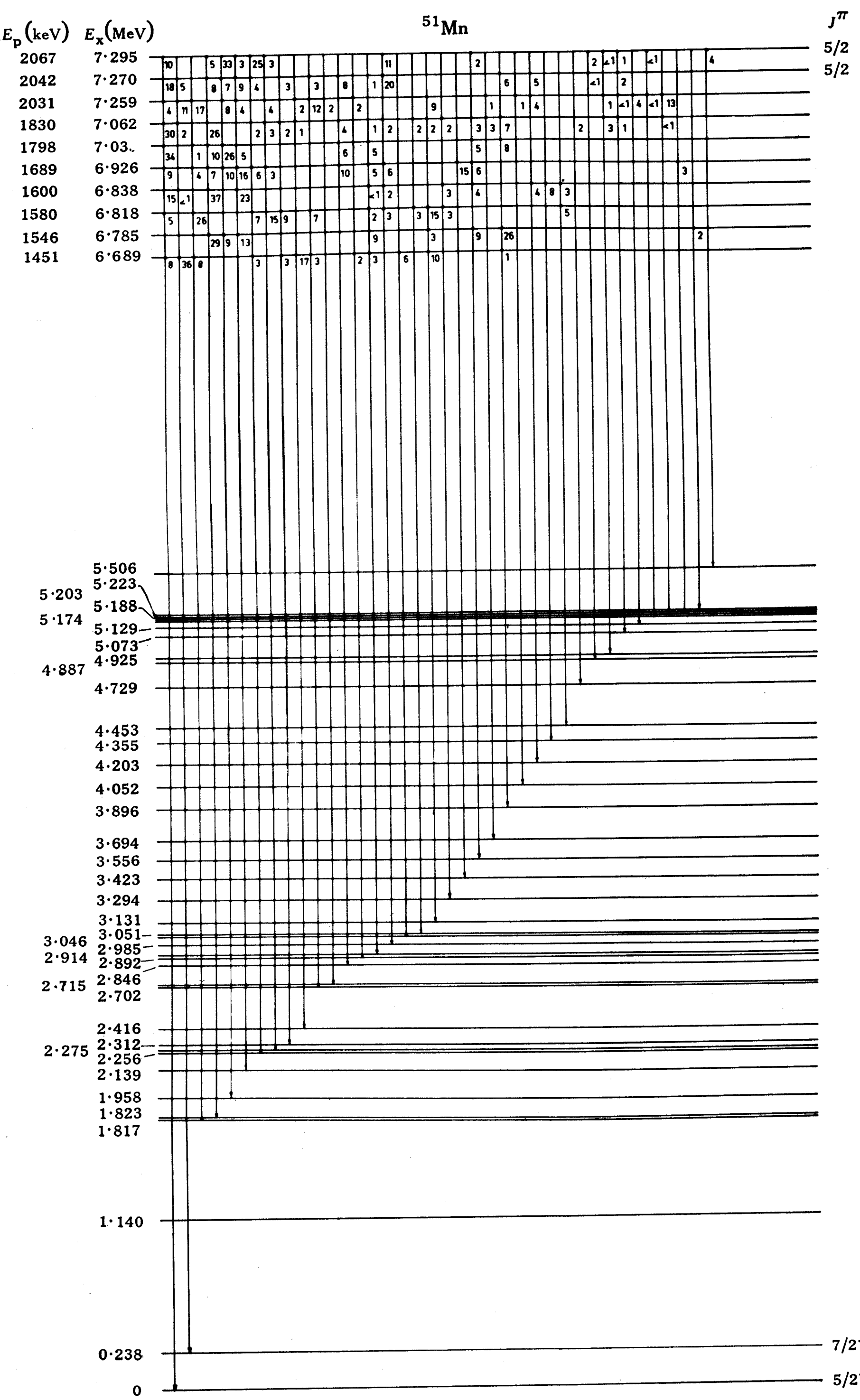

Fig. 2. Decay schemes of 10 resonance states (E_p = 1451–2067 keV) to bound levels in ^{51}Mn.

Resonance decay schemes

The resonances at $E_p = 1451$, 1546, 1580, 1600, 1798 and 1830 keV have already been investigated by previous workers, but several revisions in the decay schemes are found to be necessary. The resonances at $E_p = 1689$, 2031, 2042 and 2067 keV have not been studied earlier. The decay of the resonance states is summarized in Table 1, while the branching ratios for the transitions in the decay of the bound states and the γ-ray energies are given in Table 2.

1451 keV Resonance ($E_x = 6 \cdot 689$ *MeV*)

The decay scheme found for this resonance is in agreement with the results of Forsblom *et al.* (1972), though the branching ratios differ for certain transitions. The weak transition to the level at 3·896 MeV was not reported by them.

1546 keV Resonance ($E_x = 6 \cdot 785$ *MeV*)

Again the decay scheme of this resonance agrees in general with the results reported by Forsblom *et al.* (1972). However, their reported 2% transition to the ground state and 1% transition to the bound level at 5·585 MeV were not detected in our study. The 3% transition to the level at 3·131 MeV observed here was not reported by them.

1580 keV Resonance ($E_x = 6 \cdot 818$ *MeV*)

The transitions observed from this resonance level to the bound levels at 2·985, 3·051 and 3·294 MeV were not reported by Forsblom *et al.* (1972), while transitions noted by them to the levels at 2·841 and 3·422 MeV were not seen in our γ-ray spectra. The rest of the decay scheme is in agreement.

1600 keV Resonance ($E_x = 6 \cdot 838$ *MeV*)

The decay scheme of this resonance is in general agreement with the results of Wall and Erlandsson (1967) and Forsblom *et al.* (1972). Those authors did not record, however, the transitions from the resonance to the first excited state and to the level at 4·453 MeV. Their reported transitions to 2·276, 2·488 and 3·058 MeV levels were not observed in the present investigation. The population of the level at 4·453 MeV from the two resonances at 1580 and 1600 keV confirms its existence.

1689 keV Resonance ($E_x = 6 \cdot 926$ *MeV*)

The resonance at 1689 keV was reported by Wall and Erlandsson (1967) and Forsblom *et al.* (1972), but decay schemes were not determined by them. The γ-ray spectrum from the present work is shown in Fig. 1*a*. The resonance decays to a number of bound levels as shown in the decay scheme (Fig. 2). The population of the bound level at 5·203 MeV was observed for the first time in the proton capture reaction.

1798 keV Resonance ($E_x = 7 \cdot 032$ *MeV*)

The results for the decay of the 1798 keV resonance (Fig. 1*b*) agree in general with those of Wall and Erlandsson (1967). However, it is found that the resonance has a 6% decay to the 2·846 MeV level which was not reported in the previous work.

1830 keV Resonance ($E_x = 7 \cdot 062$ *MeV*)

The γ-ray spectrum measured at this resonance is shown in Fig. 1*c*; the decay scheme resulting from the analysis of the spectrum is presented in Fig. 2. The results obtained by Wall and Erlandsson (1967) are considerably different from the present findings. Here transitions were detected from the resonance to the first excited state and to the levels at 2·275, 2·416, 2·846, 2·985, 3·051, 3·556, 4·729, 4·925, 5·073 and 5·188 MeV, all of which were not found in the previous work. A transition from the resonance to the level at 4·017 MeV as reported by Wall and Erlandsson was not observed in the present study. The resonance branching ratios given here (Fig. 2) are also different from their values. The levels at 4·729, 4·925, 5·073 and 5·188 MeV have been observed to be populated in the proton capture reaction for the first time.

2031 keV Resonance ($E_x = 7 \cdot 259$ MeV)

The γ-ray spectrum for this resonance, which has not been previously investigated, is shown in Fig. 1*d*, the decay scheme resulting from the analysis of the spectrum being incorporated in Fig. 2. The resonance level decays to a number of bound levels, with relatively stronger (10%) transitions to the levels at 0·238, 1·817, 2·702 and 5·188 MeV. The population of the levels at 4·925, 5·073 and 5·188 MeV confirms their existence, as these levels were also observed at the $E_p = 1830$ keV resonance. The bound levels at 4·052, 5·129 and 5·174 MeV have been observed to be populated for the first time in the proton capture reaction.

2042 keV Resonance ($E_x = 7 \cdot 270$ MeV)

The γ-ray spectrum obtained at $E_p = 2042$ keV is shown in Fig. 1*e* and the resulting decay scheme is included in Fig. 2. This resonance has not been investigated previously. The resonance state decays to 15 bound levels including the ground state. The strongest transitions with 20% and 18% branches are to the bound level at 2·985 MeV and the ground state respectively.

2067 keV Resonance ($E_x = 7 \cdot 295$ MeV)

The γ-ray spectrum obtained at the 2067 keV resonance is shown in Fig. 1*f* and the resulting decay scheme is included in Fig. 2. This resonance has not been investigated previously. The strong transitions exhibited by the resonance are 11%, 25%, 33% and 10% to the bound levels at 2·985, 2·256, 1·958 MeV and the ground state respectively. There are, however, weaker transitions to a number of bound levels at 4·887, 5·073 and 5·506 MeV among others.

Properties of bound levels

The decay schemes of the bound levels as obtained from the study of the resonances are given in Fig. 3. In the following, some comments are made for either those levels where the decay schemes differ from earlier reports or the levels which have been observed for the first time in the proton capture reaction.

1·140 MeV Level

The level at 1·140 MeV was not populated directly from any of the resonances. Its existence is based only on the decays of the bound levels at 2·416, 2·702 and 2·892 MeV. The level decays 10% to the ground state and 90% to the first excited state, which is in agreement with the results of Forsblom *et al.* (1972).

Doublet Levels at 1·817 and 1·823 MeV

Both of these levels decay completely to the ground state. Their existence is confirmed by the presence of the primary γ-rays from different resonances. The strongest transitions (26% and 17%) to the level at 1·817 MeV are from the resonances at 1580 and 2031 keV, whereas 29% and 26% decays to the level at 1·823 MeV come from two resonances at 1546 and 1830 keV.

2·702 and 2·715 MeV Levels

The decay schemes of both these levels were derived from the resonance at 2031 keV, from which the 2·702 MeV level was populated relatively strongly compared with other resonances. This level has 2%, 21%, 26% and 37% decays to the levels at 1·140, 1·817, 1·958 and 2·312 MeV respectively. The results disagree with those of Forsblom *et al.* (1972), who reported the decays only to the levels at 1·958 and 2·312 MeV. The bound level at 2·715 MeV decays completely to the ground state, rather than to the level at 1·817 MeV as reported by Wall and Erlandsson (1967).

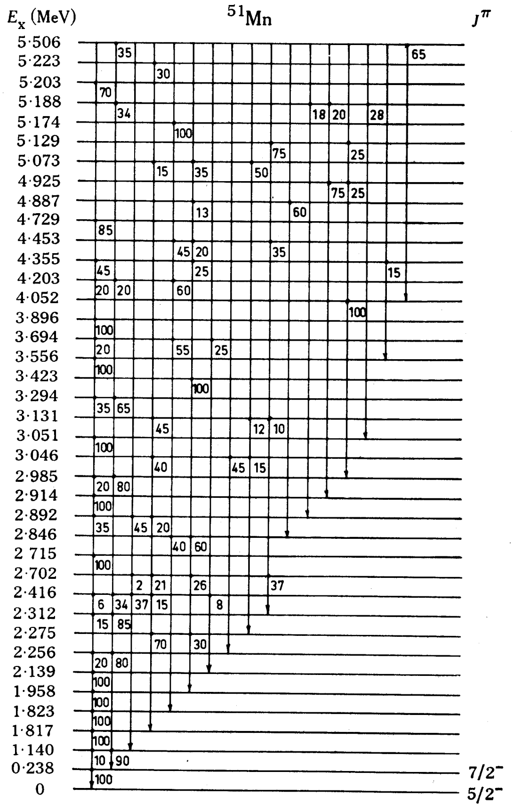

Fig. 3. Decay schemes of low lying bound levels of ^{51}Mn up to an excitation energy of 5·51 MeV, as determined in the present investigation.

2·846 MeV Level

The transition ratios of 40% and 60% from the bound level at 2·846 MeV to the levels at 1·823 and 1·958 MeV are in disagreement with the findings of Forsblom *et al.* (1972), who reported 25% and 75% transitions respectively.

3·046 MeV Level

This bound level showed three transitions, 40%, 45% and 15% leading to the levels at 1·817, 2·256 and 2·275 MeV respectively. The transition to the first excited state reported by Forsblom *et al.* (1972) was not observed.

3·294 MeV Level

The bound level at 3·294 MeV has only two transitions: 35% to the ground state and 65% to the first excited state. These values are to be compared with 25% and 75% as reported by Forsblom *et al.* (1972).

3·694 MeV Level

The bound level at 3·694 MeV was populated in the 1830 keV resonance. It decays 20%, 55% and 25% to the ground state and the levels at 1·823 and 2·139 MeV respectively. The 10% decay to the level at 2·914 MeV reported by Forsblom *et al.* (1972) was not observed.

3·896 MeV Level

The strong transition (26%) to the bound level at 3·896 MeV was observed in the 1546 keV resonance. The level decays 100% to the ground state. The transition to the level at 2·846 MeV as reported by Forsblom *et al.* (1972) was not observed.

4·052 MeV Level

The bound level at 4·052 MeV was populated (weakly) at one resonance, namely $E_p = 2031$ keV. The level has not been reported earlier and it decays 100% to the level at 2·985 MeV.

4·453 MeV Level

This level was excited at two resonances, 1580 and 1600 keV. It decays 45%, 20% and 35% to the levels at 1·823, 1·958 and 2·312 MeV; Forsblom *et al.* (1972) only reported a 46% decay to the level at 1·823 MeV. The bound level at 4·453 MeV has been identified as an isobaric analogue associated with the ground state of ^{51}Cr by Rapaport *et al.* (1967).

4·729 and 4·925 MeV Levels

These levels are excited at the 1830 keV resonance. They were observed to be populated for the first time in the proton capture reaction, though they were reported in (^{3}He, d) studies by Rapaport *et al.* (1967). Only 85% of the decay from the level at 4·729 MeV to the ground state is accounted for by the present results. The level at 4·925 MeV decays 75% and 25% to the levels at 2·914 and 2·985 MeV respectively.

4·887 MeV Level

This level was excited at two resonances, 2042 and 2067 keV. It decays 60% to the level at 2·846 MeV and 13% to the level at 1·958 MeV. The remaining 27% of its decay could not be determined from the γ-ray spectra.

5·073 MeV Level

This level was reported by Rapaport *et al.* (1967) from the (^{3}He, d) reaction, but it has been observed to be populated in the proton capure reaction here for the first time. The level decays to the 2·275, 1·958 and 1·817 MeV levels with branching ratios of 50%, 35% and 15% respectively.

5·129 MeV Level

This level was also seen to be excited for the first time in the proton capture reaction, though it was observed in the (^{3}He, d) reaction by Rapaport *et al.* (1967). It decays 75% to the level at 2·312 MeV and 25% to the level at 2·985 MeV.

5·174 MeV Level

Again this level was seen to be excited for the first time in the proton capture reaction, though it was reported in the (^{3}He, d) reaction by Rapaport *et al.* (1967). It decays 100% to the level at 1·823 MeV with a γ-ray of energy 3·35 MeV.

5·188 MeV Level

This level decays to the first excited state with the emission of a 4·95 MeV γ-ray (34%), to the 2·892 MeV level with a 2·297 MeV γ-ray (18%), to the 2·914 MeV level with a 2·274 MeV γ-ray (20%) and to the 3·051 MeV level with a 2·137 MeV γ-ray (28%). The level has not been observed in charged particle reactions.

5·203 MeV Level

This level was only excited at E_p = 1689 keV. A 70% decay goes to the ground state.

5·506 MeV Level

This level was reported by Rapaport *et al.* (1967), but again it is observed in the proton capture reaction for the first time here. Its decay is to two levels: 35% to the first excited state and 65% to the level at 4·052 MeV.

Table 3. γ-ray angular distribution measurements at two resonances in ^{51}Mn

The results summarized are the Legendre coefficients $A_2 = a_2/a_0$ and $A_4 = a_4/a_0$ from

$$W(\theta) = a_0 + a_2 P_2(\theta) + a_4 P_4(\theta),$$

the values of χ^2_{min} and the mixing ratios δ for the primary γ-rays emitted in the transitions from the resonances to the final states E_f

Final state E_f (MeV)	J_f	Experimental A_2	Experimental A_4	Theoretical A_2	Theoretical A_4	χ^2_{min}	δ
E_p = 2042 keV (E_x = 7·270 MeV, J = 5/2)							
0	5/2	−0·20±0·04	−0·11±0·04	−0·19	−0·12	0·43	0·60±0·02
0·238	7/2	−0·02±0·05	−0·16±0·05	−0·02	−0·16	11·8	−0·18±0·08
						8·90	$5·67^{+8·6}_{-2·2}$
1·823	3/2	0·15±0·05	0·13±0·06	0·16	0·13	3·30	−0·29±0·05
2·139	3/2	0·03±0·06	−0·11±0·06	0·04	−0·12	2·86	−0·30±0·07
2·985	5/2	−0·02±0·05	−0·21±0·05	−0·02	−0·21	2·80	0·49±0·11
						0·28	−6·30±2·3
E_p = 2067 keV (E_x = 7·295 MeV, J = 5/2)							
0	5/2	0·44±0·06	−0·13±0·06	0·45	−0·13	1·22	−1·43±0·36
1·958	3/2	−0·18±0·03	−0·10±0·03	−0·18	−0·10	3·31	0·27±0·05
						2·44	4·33±0·03
2·256	7/2	−0·02±0·04	−0·10±0·04	−0·03	−0·10	3·90	−0·10±0·19
						1·86	$5·14^{+4·36}_{-2·54}$
2·985	5/2	−0·06±0·03	−0·20±0·03	−0·06	−0·20	2·20	$-8·14^{+2·54}_{-6·16}$
						9·00	0·53±0·03

Spins of resonance levels

The results of the angular distribution measurements for the resonances at E_p = 2042 and 2067 keV are summarized in Table 3, which gives the Legendre coefficients, the transition mixing ratios for the primary γ-rays from ^{51}Mn resonances and the values of χ^2_{min}.

2042 keV Resonance ($E_x = 7\cdot270$ MeV)

Since the measured distributions of the five transitions from the resonance level at $E_x = 7\cdot270$ MeV all show clear anisotropy, a spin of 1/2 can be excluded. The data and the chi-squared projection curves are shown in Fig. 4. It is clear from the figure that a spin of 5/2 for the resonance state has the minimum χ^2 value. The choice of 5/2 is also consistent with the transitions to the bound levels at $0\cdot238$ MeV (7/2), $1\cdot823$ MeV (3/2), $2\cdot139$ MeV (3/2) and $2\cdot985$ MeV (5/2). The χ^2_{min} values are all below the $0\cdot1\%$ limit except for the transition to the first excited state.

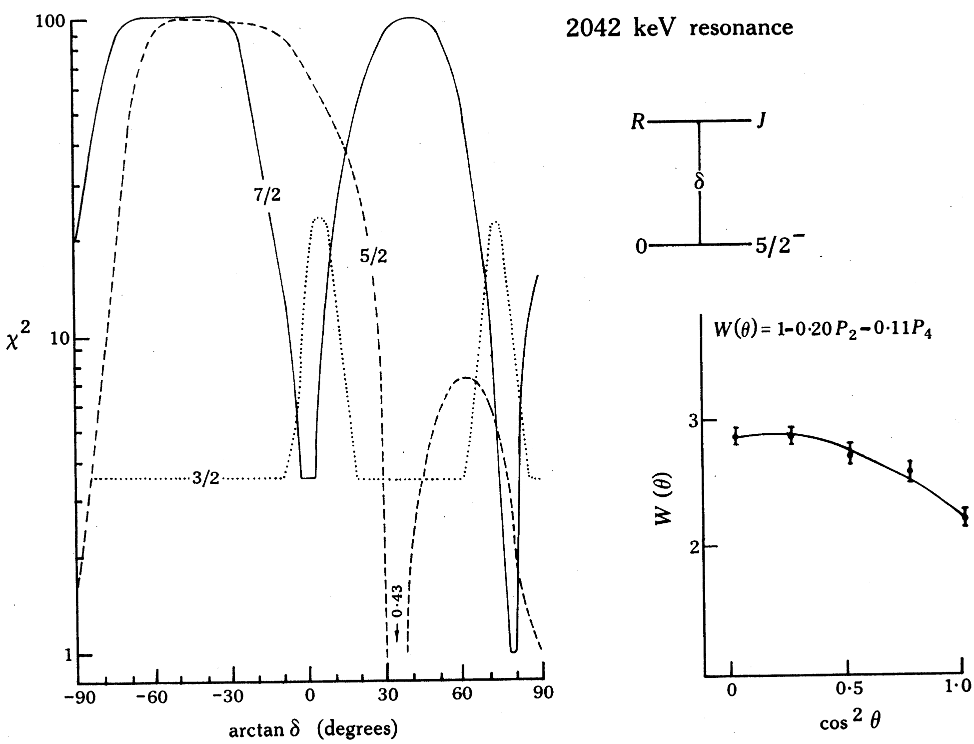

Fig. 4. Results of the analysis of the angular distributions measured for the γ-ray transition from the $E_p = 2042$ keV resonance to the ground state.

2067 keV Resonance ($E_x = 7\cdot295$ MeV)

As before, the measured distributions of the four transitions from the resonance level at $E_x = 7\cdot295$ MeV show clear anisotropy, and a spin of 1/2 is thus excluded. The χ^2_{min} value for the transition to the ground state is within the $0\cdot1\%$ acceptance limit if the spin of the resonance state is 5/2. For the other three transitions to the levels at $1\cdot958$ MeV (3/2), $2\cdot256$ MeV (7/2) and $2\cdot985$ MeV (5/2), the χ^2_{min} is again within the limit for the same spin assignment. Therefore, a spin of 5/2 for the resonance at $E_p = 2067$ keV is favoured (Fig. 5).

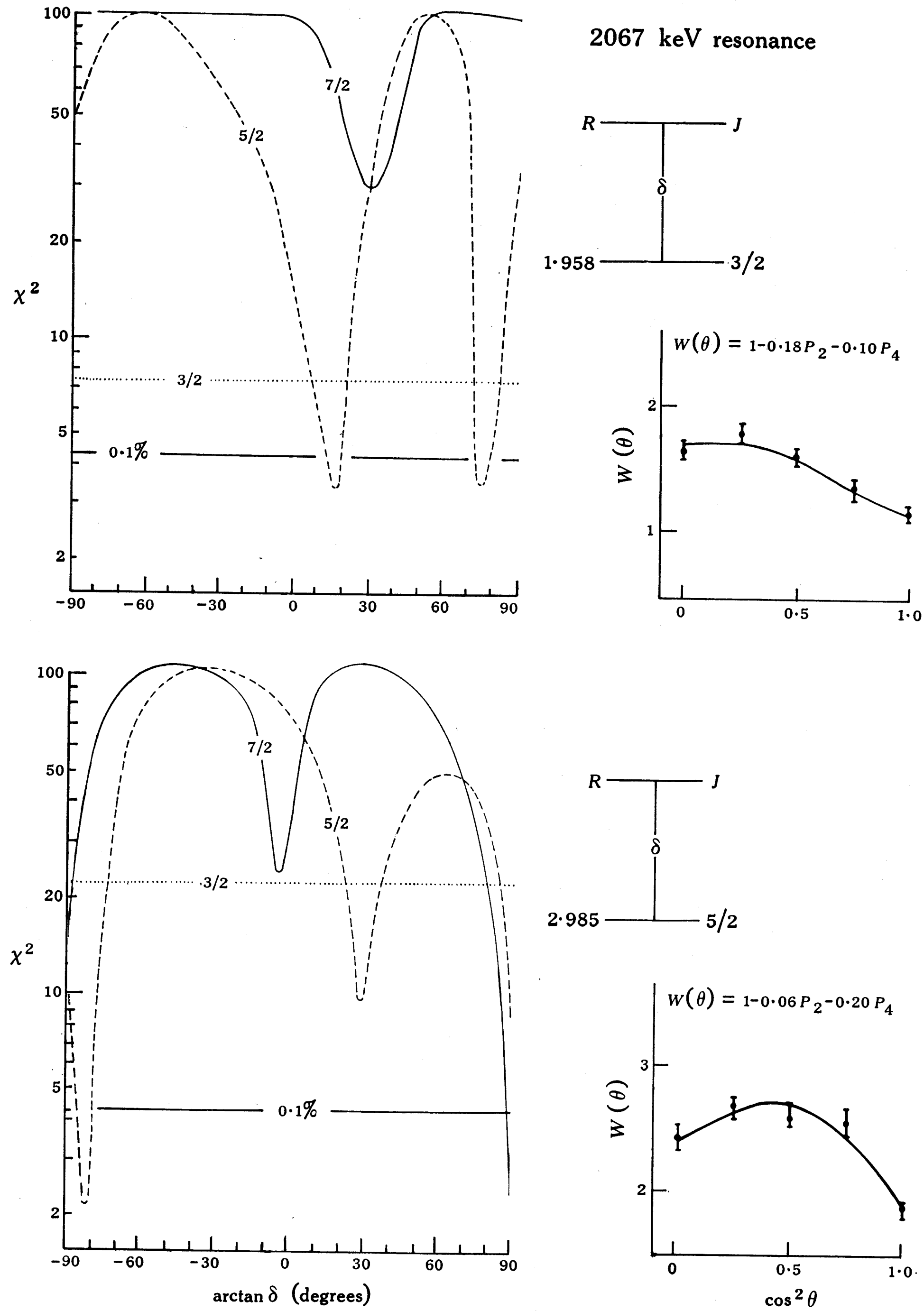

Fig. 5. Results of the analyses of the angular distributions measured for the γ-ray transitions from the E_p = 2067 keV resonance to the two bound levels at 1·958 and 2·985 MeV.

Discussion

The study of 10 resonances for the reaction ^{50}Cr(p, γ)^{51}Mn has provided extensive information on the energy levels, the spins of two of the resonance states and the decay properties of the bound levels in ^{51}Mn. Table 4 compares the excitation energies of ^{51}Mn as found from investigations of (p, γ) and (^{3}He, d) reactions, including the present study. There are 38 bound levels up to an excitation of 5·506 MeV which have been populated from the 10 resonances. The two resonances at 1830 and 2031 keV alone populated 20 and 19 bound levels respectively. Nine bound levels at 4·052, 4·729, 4·925, 5·073, 5·129, 5·174, 5·188, 5·203 and 5·506 MeV have been observed for the first time in the proton capture reaction, including the three levels at 4·052, 5·188 and 5·203 MeV which have not been detected in charged particle reactions either. The previously unknown decay properties of the bound levels at 4·729, 4·925, 5·073, 5·129, 5·174, 5·188 and 5·506 MeV have been determined, while revisions in the decay schemes have been found to be necessary for the levels at 2·416, 2·702, 2·715, 3·046, 3·294, 3·423, 3·694, 3·896, 4·355, 4·453 and 5·223 MeV. The derived values of level energies generally differ from

Table 4. Excitation energies of ^{51}Mn bound levels up to 5·506 MeV

The present results from the ^{50}Cr(p, γ)^{51}Mn reaction are compared with those of (F) Forsblom *et al.* (1972) and (W) Wall and Erlandsson (1967) from the same reaction and with those of (R) Rapaport *et al.* (1967) from the ^{50}Cr(^{3}He, d)^{51}Mn reaction

Present (p, γ) (MeV)	F (p, γ) (MeV)	W (p, γ) (MeV)	R (^{3}He, d) (MeV)	Present (p, γ) (MeV)	F (p, γ) (MeV)	W (p, γ) (MeV)	R (^{3}He, d) (MeV)
0·238	0·238	0·240	0·240	3·423	3·423	3·422	3·427
1·140	1·140		1·160	3·556	3·553	3·549	3·555
			1·500	3·694	3·694	3·690	3·698
1·817	1·817	1·817		3·896	3·894	3·897	3·900
1·823	1·825	1·826	1·830			4·017	4·017
1·958	1·959	1·958	1·962	4·052			
2·139	2·140	2·142	2·147		4·091		4·099
2·256	2·256	2·257		4·203	4·206		
2·275	2·276	2·276	2·284	4·355	4·352		4·367
2·312	2·310	2·311		4·453	4·451		4·446
2·416	2·416		2·426		4·488		4·497
		2·488			4·540		4·533
		2·660		4·729			4·730
2·702	2·702	2·702		4·887	4·883		
2·715		2·717		4·925			4·925
		2·808		5·073			5·074
2·846	2·841		2·844	5·129			5·128
2·892	2·893			5·174			5·176
2·914	2·914	2·914	2·919	5·188			
2·985	2·985	2·981	2·985	5·203			
3·046	3·049				5·212		
3·051	3·058		3·058	5·223	5·223		5·225
	3·091	3·094					5·444
3·131	3·130	3·128	3·135	5·506			5·508
3·294	3·292	3·285	3·300				

one reaction to another, possibly due to the differences in energy resolution of the particular detecting systems. A Q value to the ground state of $5\cdot269 \pm 0\cdot002$ MeV for the reaction $^{50}Cr(p, \gamma)^{51}Mn$ has been derived from the known proton bombarding energies and the energies of the strong direct ground-state transitions from the resonance levels, as determined from the γ-ray spectra observed with the Ge(Li) detector.

The interesting point in the present data is that the second excited state at 1·140 MeV was not populated directly in any of the resonances studied. The same is true in the results of Wall and Erlandsson (1967) and Forsblom *et al.* (1972). The level was only populated through the cascades from the bound levels at 2·416, 2·702 and 2·892 MeV. One of the reasons for this could be that the level has a spin of $\geqslant 9/2$, and resonances studied below 2 MeV proton bombarding energies are less likely to have higher spin values because of penetrability considerations. At higher proton energies it might be possible to form resonances of higher spins which would populate the level at 1·140 MeV and other high spin bound levels as well. There have been theoretical predictions of states with spin 9/2 and 11/2 below 3 MeV excitation energies in ^{51}Mn by Malik and Scholz (1966) and McCullen *et al.* (1964). The probable values of the bound levels (not shown in Figs 2 and 3) as reported by Forsblom *et al.* (1972) indicate only one 9/2 spin, for the level at 1·140 MeV. This is an added indication that higher spin resonances are needed to populate bound levels with spin $\geqslant 9/2$. Further work at higher proton bombarding energies might help to check the theoretical predictions.

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