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A Study of the ^{42}Ca(p,γ)^{43}Sc Reaction

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Abstract

The ^{42}Ca(p, γ)^{43}Sc reaction has been studied below 2·75 MeV proton bombarding energy. Approximately 100 resonances have been identified and located in the range E_p = 2·00–2·75 MeV. Nine resonances at E_p = 1045, 1201, 1299, 1319, 2038, 2471, 2523, 2643 and 2714 keV for the ^{42}Ca(p, γ)^{43}Sc reaction were investigated with either a 54 or a 120 cm^3 Ge(Li) detector. Single spectra were obtained at each of these resonances, and these were used to derive consistent γ ray decay schemes and accurate level energies for the resonant and bound levels of ^{43}Sc. Fifty-two bound levels up to an excitation energy of 4·47 MeV were observed, out of which seventeen new levels have been identified at 2·114, 2·796, 2·846, 2·860, 2·875, 3·160, 3·331, 3·374, 3·463, 3·504, 3·645, 3·734, 3·757, 3·860, 4·007, 4·038 and 4·430 MeV. In addition, new results or results differing from earlier reports have been obtained for the decay properties of levels below 4·47 MeV in ^{43}Sc. The strengths of the nine resonances were measured relative to the reported strength at E_p = 2038 keV. The resonance at E_p = 2643 keV was shown for the first time to populate levels of spin $>7/2$ via the proton capture reaction. A strong M1 (analogue to anti-analogue) transition from the resonance level to the level at 1·931 MeV ($9/2^+$) was observed. From measurements of γ ray angular distributions, the following spin and parity assignments were made: $9/2^+$ at 7·514, $7/2^+$ at 4·371, $\geqslant 7/2$ at 4·038 and 7/2 at 3·808 MeV. The resonance level at 7·514 MeV has possibly a $T = 3/2$ character. The low-lying excited states in ^{43}Sc are in reasonable agreement with the theoretical predictions of Johnstone (1968).

1. Introduction

The properties of the excited levels in ^{43}Sc have been investigated by a number of workers. The ^{42}Ca(p, γ)^{43}Sc reaction was first studied by Dubois and Broman (1963) in the energy range E_p = 780–1420 keV. They studied the capture γ ray spectra using NaI detectors. Broman and Dubois (1965) studied the same reaction using both a NaI and a 0·5 cm^3 Ge(Li) detector. Walinga *et al.* (1969) studied the reaction in the energy range E_p = 1200–2060 keV with a 40 cm^3 Ge(Li) detector. They reported 26 bound levels up to an excitation energy of 4·46 MeV in ^{43}Sc. The same work was extended by Manthuruthil *et al.* (1970) to determine the spin and multipolarity ratios of the bound levels in ^{43}Sc. The mean lifetimes of excited states of ^{43}Sc were reported by Ball *et al.* (1970) and Poirier *et al.* (1970). Additional levels in ^{43}Sc have been found by Cujec (1966), Phillips *et al.* (1967) and Schwartz *et al.* (1967) using the ^{40}Ca(α, p)^{43}Sc reaction; by Schwartz and Alford (1966), Broman (1967) and Bommer *et al.* (1971) using the ^{42}Ca(^{3}He, d)^{43}Sc reaction; by Grandy *et al.* (1968) and Bommer *et al.* (1971) using the ^{42}Ca(d, n)^{43}Sc reaction; by Plendl *et al.* (1965) using the ^{46}Ti(p, α)^{43}Sc reaction; and by Alford *et al.* (1971) using the ^{42}Ca(^{3}He, t)^{43}Sc reaction. Manthuruthil *et al.* (1974) studied proton elastic scattering in the energy regions E_p = 1230–1250, 1770–2700, 2440–2530, 2700–2800 and 3000–3250 keV. For a more complete review of previous work on ^{43}Sc, see the article by Endt and Van der Leun (1973).

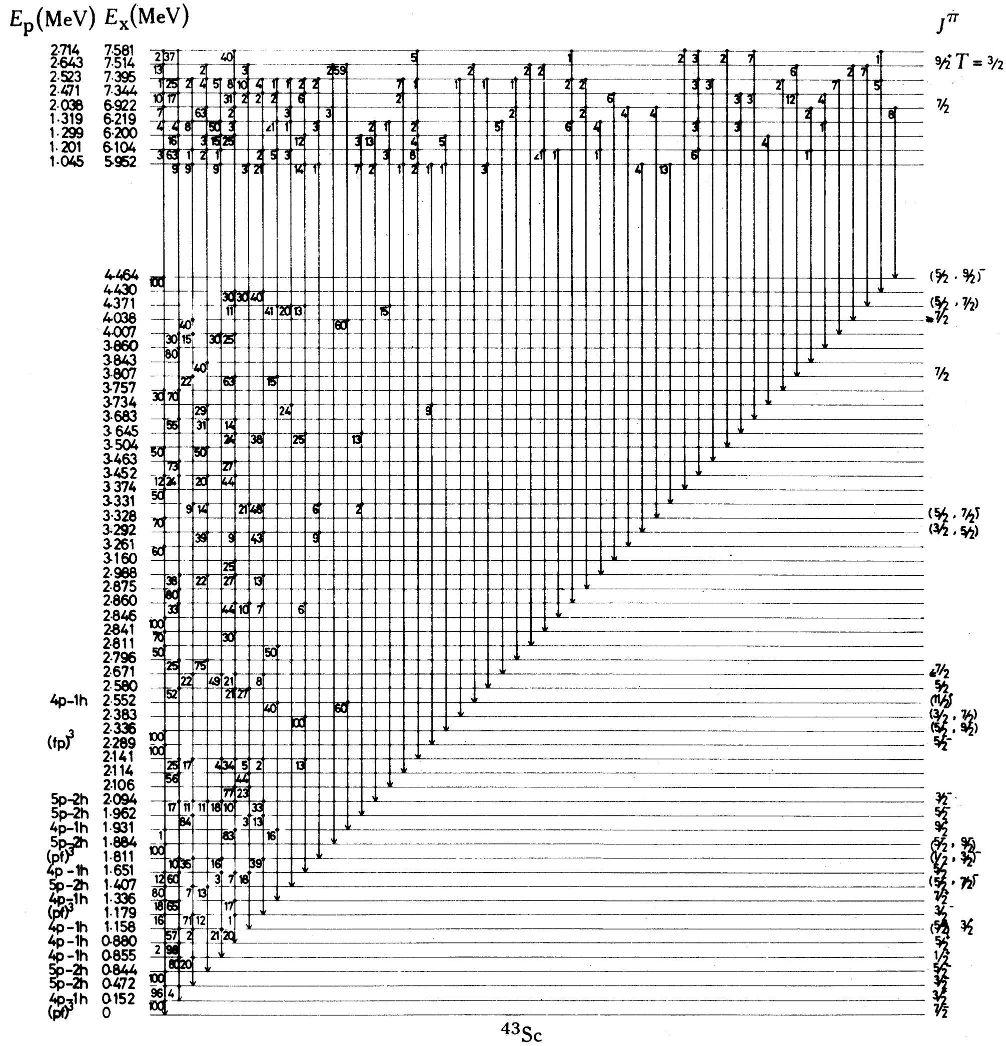


Fig. 1. Decay schemes and branching ratios (%) for 9 resonances and 52 bound states studied in the present work. The following spins and parities have been assigned: $9/2^+$ at 7·514 MeV, $7/2^+$ at 4·371 MeV, $>7/2$ at 4·038 MeV and 7/2 at 3·807 MeV. The remaining spin and parity assignments are taken from other workers.

The purpose of the present study of the ^{42}Ca(p, γ)^{43}Sc reaction was to verify the existence or otherwise of uncertain levels, to search for new levels, to derive the decay properties of the bound state and to look for resonances having a dominant γ ray de-excitation branch which could correspond to an analogue to anti-analogue M1 transition. It was noticed from the previous results that some of the bound levels in ^{43}Sc were not populated by the (p, γ) reaction, this presumably being due to the high spin values of these bound levels. It was anticipated that at higher proton bombarding energies it would be possible to form resonance levels of relatively high spin which would subsequently decay to high-spin bound levels.

In the present study, results were obtained for nine resonances at $E_p = 1045$, 1201, 1299, 1319, 2038, 2471, 2523, 2643 and 2714 keV, by means of either a 54 or a 120 cm^3 Ge(Li) detector. The resulting decay schemes and branching ratios of these resonances are summarized in Fig. 1 for convenience of reference throughout the paper.

2. Experimental Procedure

The present study of the $^{42}Ca(p, \gamma)^{43}Sc$ reaction was carried out at three different laboratories. Above 2 MeV, the proton beam was provided by the 4 and 3 MeV Van de Graaff accelerators, at the Centre de Recherches Nucléaires, Strasbourg, France, and at McMaster University, Hamilton, Canada, respectively. The proton beam below 2 MeV was obtained from the 3 MeV Van de Graaff accelerator at the Accelerator Laboratory, University of Helsinki, Finland. The analysis of the data was carried out at Strasbourg and at the Department of Physics, Kuwait University.

Tungsten and gold were chosen as target backings to minimize the contamination. Blanks of tungsten metal were heated with an induction heater to clean the surface and to remove the occluded gases. Targets were prepared using samples of $CaCO_3$ (enriched in ^{42}Ca) evaporated onto blanks. Two ^{42}Ca targets were used. One target, with a nominal thickness of 10 $\mu g\,cm^{-2}$, was employed for the measurement of γ ray spectra at 55° and of angular distributions at the $E_p = 2643$ keV resonance. The other target, with a nominal thickness of 5 $\mu g\,cm^{-2}$, was used to measure yield curves for the $^{42}Ca(p, \gamma)^{43}Sc$ and $^{42}Ca(p, p'\gamma)^{42}Ca$ reactions. The targets were water cooled. A liquid nitrogen trap was placed in front of each target to remove condensable vapours and to minimize carbon build-up. Also, a thin lead sheet was placed in front of the detector to absorb low energy radiation generated in the target backing for γ ray spectra measured above 2 MeV proton energy.

A 120 cm^3 Ge(Li) detector was used (Helsinki) to locate the resonances and to measure γ ray spectra below 2 MeV proton energy. At low bombarding energies, it was expected that the low energy γ ray peaks below 500 keV would be relatively free from γ rays arising from contamination. The 120 cm^3 Ge(Li) detector had resolutions of 1·93 keV for the 1·33 MeV γ ray; 2·64 keV for the 2·614 MeV γ ray; 4·42 keV for the 6·6 MeV γ ray; and 5·05 keV for the 7·6 MeV γ ray. It had a peak to Compton ratio of 50 to 1, and an efficiency for the 1·33 MeV γ ray of 23%. The other detector (a 54 cm^3 Ge(Li) detector) employed for the experimental data above 2 MeV at Strasbourg had a resolution of 2·8 keV for the ^{60}Co lines. The angular distributions were measured with this detector, while the data were normalized with an 86 cm^3 Ge(Li) detector.

A 65 cm^3 Ge(Li) detector placed at an angle of 55° with respect to the beam direction was used to locate the resonances. The resonance γ ray yields were measured with the discrimination level set at $E_\gamma > 0{\cdot}700$ and $> 2{\cdot}000$ MeV. For the resonance at $E_p = 2643$ keV, the output from the amplifier was fed to two single-channel analysers, one to select γ rays of energy greater than 2·6 MeV, the other to monitor the 1·524 MeV γ ray from the inelastic proton scattering of the first excited state of ^{42}Ca.

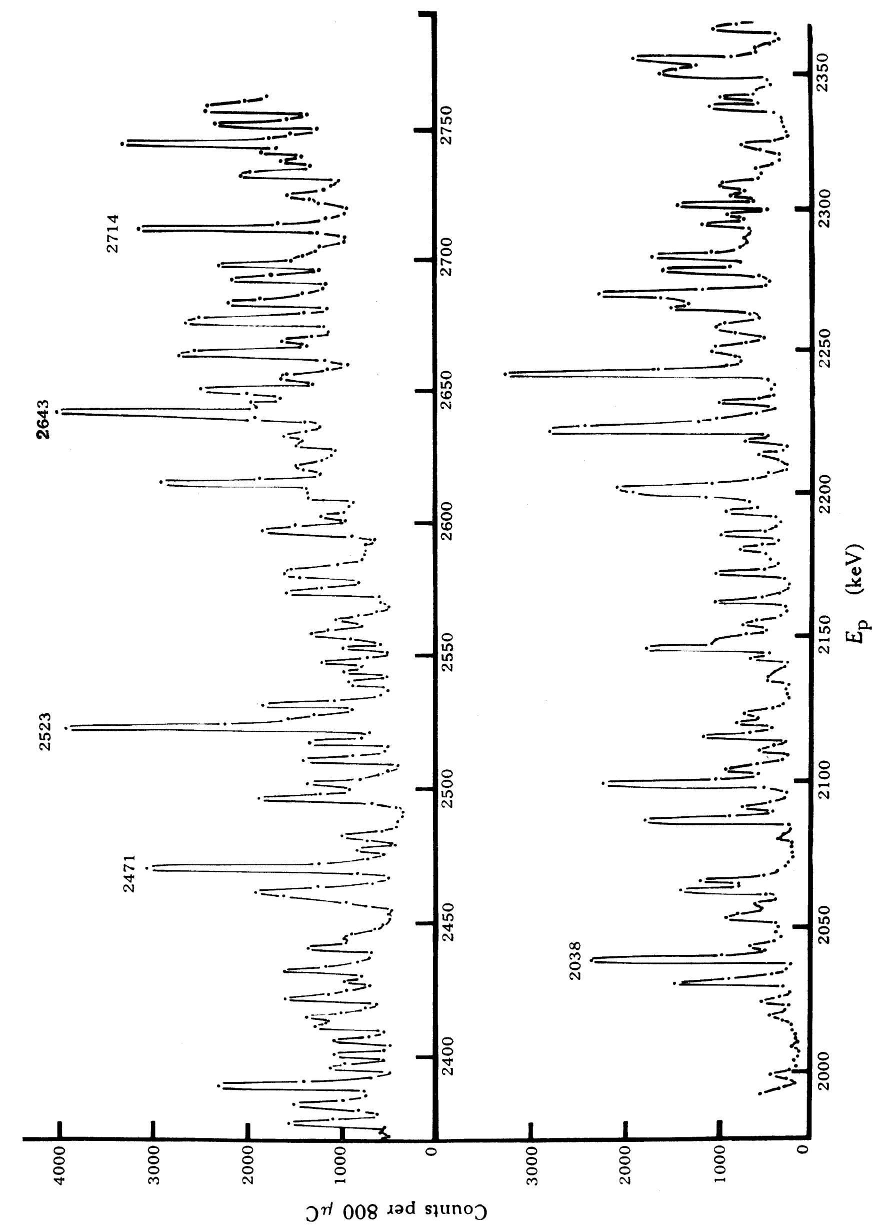


Fig. 2. Relative yield as a function of proton energy E_p in the range 2000–2750 keV. Measurements were made, using a <1 keV-thick target on tungsten backing, with a Ge(Li) detector at 55° to the beam direction.

The γ ray spectra at each resonance were stored in either a 2048- or a 4096-channel analyser. The decay schemes of the resonances and branching ratios (%) were derived from the γ ray spectra measured at 55° to the beam direction. The relative intensities of the transitions were determined from the relative full energy and double-escape peak intensities in the spectrum. The Ge(Li) detector efficiencies were determined

Table 1. $^{42}Ca(p, \gamma)^{43}Sc$ resonance and ^{43}Sc excitation energies

E_p (MeV)	E_x (MeV)	E_p (MeV)	E_x (MeV)	E_p (MeV)	E_x (MeV)
1·999	6·883	2·264	7·142	2·540	7·412
2·019	6·902	2·269	7·147	2·543	7·415
2·024	6·907	2·277	7·155	2·547	7·418
2·030	6·913	2·282	7·160	3·552	7·423
2·038	6·922	2·294	7·171	2·559	7·430
2·043	6·926	2·297	7·174	2·563	7·434
2·053	6·936	2·300	7·177	2·573	7·444
2·062	6·945	2·304	7·181	2·580	7·451
2·065	6·948	2·307	7·184	2·596	7·466
2·079	7·961	2·322	7·199	2·602	7·472
2·086	7·968	2·336	7·212	2·611	7·481
2·090	7·972	2·339	7·215	2·614	7·484
2·098	7·980	2·348	7·224	2·622	7·492
2·103	7·986	2·353	7·229	2·629	7·499
2·110	7·991	2·365	7·240	2·632	7·501
2·115	7·996	2·375	7·250	2·643	7·512
2·119	7·000	2·389	7·264	2·645	7·514
2·123	7·004	2·395	7·270	2·650	7·519
2·135	7·016	2·401	7·276	2·654	7·523
2·142	7·023	2·406	7·281	2·663	7·532
2·145	7·026	2·411	7·285	2·668	7·537
2·153	7·033	2·414	7·288	2·676	7·544
2·162	7·042	2·421	7·295	2·683	7·551
2·171	7·051	2·428	7·302	2·692	7·560
2·179	7·059	2·432	7·306	2·697	7·565
2·184	7·064	2·440	7·314	2·714	7·581
2·193	7·073	2·471	7·344	2·725	7·592
2·201	7·080	2·477	7·350	2·734	7·601
2·212	7·091	2·482	7·355	2·737	7·604
2·217	7·096	2·494	7·367	2·741	7·608
2·221	7·100	2·501	7·373	2·745	7·612
2·230	7·105	2·510	7·382	2·752	7·619
2·240	7·118	2·517	7·389	2·758	7·625
2·249	7·127	2·523	7·395		
2·257	7·135	2·531	7·403		

from the $^{27}Al(p, \gamma)^{28}Si$ resonance at 992 keV and also by means of a ^{56}Co radioactive source. The relative errors for the intensity calibration curve were 8% and 5% below and above 0·511 MeV respectively. For the prominent γ ray peaks the relative intensity error was 8%, increasing to 15% for the smaller peaks.

The decay scheme and branching ratios have also been obtained for the bound levels fed by these resonances. This has been done by using the primary γ ray

Table 2. Branching ratios for decay of nine resonances in $^{42}Ca(p,\gamma)^{43}Sc$

E_x	Branching ratios (%) from resonances at E_p =								
(keV)	1045	1201	1299	1319	2038	2471	2523	2643	2714 keV
0		3		4	7	10	1	13	2
152	9	63	16	4		17	25		37
472	9	1		8			2		
844		2	3	50	63		4	2	
855	9	1	15				5		
880			25	3	2	31	8		40
1158	3					2	10	3	
1179	21	2				2	4		
1336		5		<1		2	1		
1407		3		1	3		1		
1651	14		12			6	2		
1811	1			3			2		
1884					3			2	
1931								59	
1962	7		3						
2094	2		13	2					
2106		3		1					
2114	1					2	7		
2141	2	8	4	2			1		5
2289	1								
2336	1		5						
2383							1		
2552								2	
2580	3						1		
2671				5					
2796					2		1		
2811								2	
2841		<1						2	
2846		1							
2860				6			2		1
2875					2		2		
2988		1		4					
3160		1				6			
3261					4				
3292	4								
3328					4				
3331	13								
3374									2
3452		6		3			3		3
3463							3		
3503									2
3645				3		3			
3683						3			7
3734			4						
3757							2		
3807						12		6	
3843		1			2				
3860				1		4			
4007								2	
4038							7		
4371								7	
4430							5		1
4464					8				

intensities, and consequently the sum of the intensities of the secondary γ rays may add up to less than 100%. The γ ray spectra were recorded at 0°, 30°, 45°, 60° and 90° for the resonance at $E_p = 2643$ keV. The γ ray angular distributions were analysed by a standard χ^2 program. Because only channel spin $s = \frac{1}{2}$ is possible, no formation parameters are involved.

3. Results

The γ ray yield from the ^{42}Ca(p, γ)^{43}Sc reaction measured at 55° to the beam direction is shown in Fig. 2. The resonance energies are listed in Table 1. Walinga *et al.* (1969) measured the resonance γ ray yield in the range $E_p = 1200$–2060 keV and, in the region of overlap with the present results, there is good agreement for the values of the resonance energies.

Gamma ray spectra were measured with the 120 cm^3 Ge(Li) detector at 55° to the beam direction for the four resonances at $E_p = 1045$, 1201, 1299 and 1319 keV. The 1201, 1299 and 1319 keV resonances have been reported previously by Walinga *et al.* (1969) who, however, did not measure the γ ray spectra. Background γ rays were found at energies of 0·440 MeV from ^{23}Na(p, p'γ)^{23}Na, at 1·632 MeV from ^{23}Na(p, $\alpha\gamma$)^{20}Ne and at 6·129 MeV from ^{19}F(p, $\alpha\gamma$)^{16}O, in addition to room background at 1·460 and 2·614 MeV from ^{40}K and ThC'' respectively.

The exceptional features of the four γ ray spectra are the strong γ ray peaks below 500 keV and the separation of the closely spaced γ rays at 0·192 and 0·197; 0·373 and 0·383; 0·703 and 0·707; 0·910 and 0·914; 1·238, 1·249 and 1·261; 1·480, 1·490 and 1·499; 2·325, 2·335 and 2·346; 2·614 and 2·620; 5·097 and 5·107; and 5·346 and 5·357 MeV. With the higher efficiency of the 120 cm^3 detector, the γ rays from the weaker transitions were also observable.

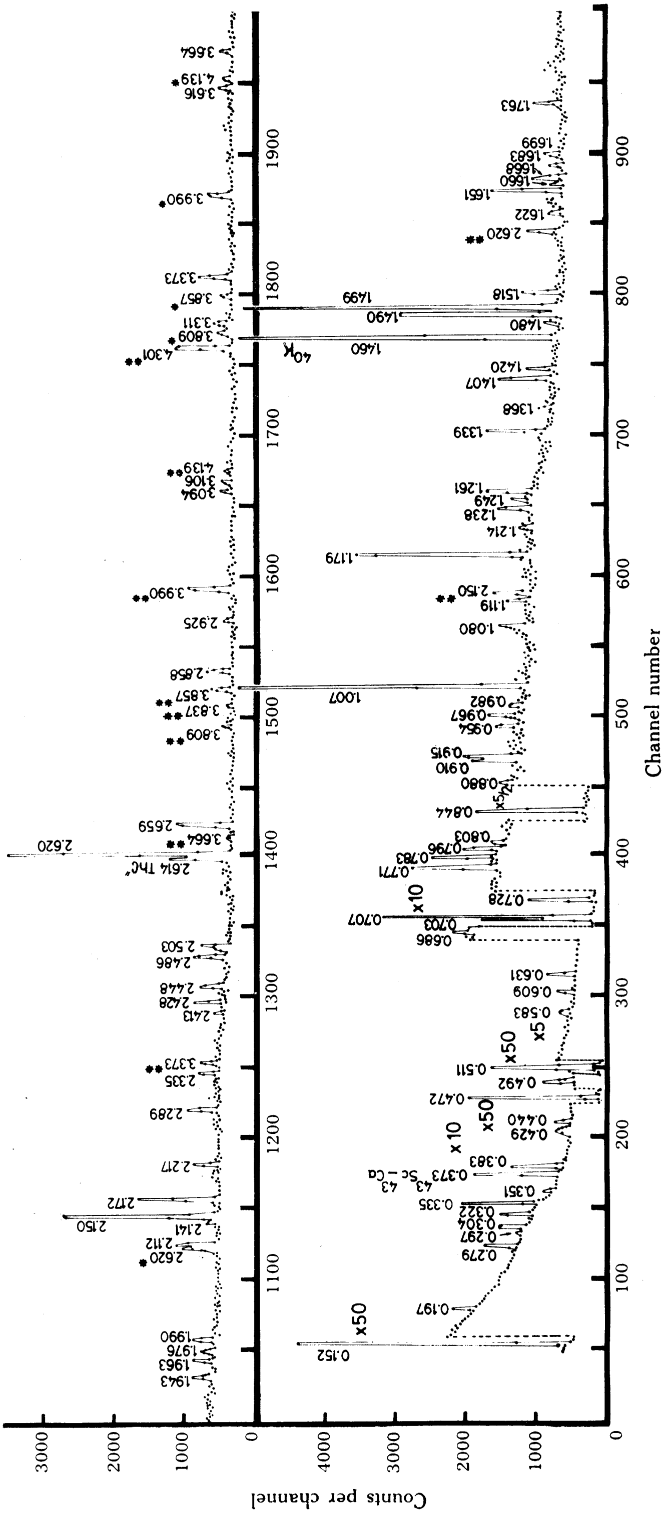
Resonance Decay Scheme

The four γ ray spectra below 2·0 MeV proton energy were stored in a 4096-channel analyser possessing a dispersion of 1·79 keV per channel. The other five γ ray spectra were stored in a 2048-channel analyser. Some of the γ ray spectra were repeated, and consistent decay schemes were obtained. The branching ratios (%) of the γ rays from each resonance to the different bound levels are given in Table 2.

1045 keV Resonance ($E_x = 5 \cdot 952$ MeV)

The γ ray spectrum measured at $E_p = 1045$ keV is shown in Fig. 3. This energy corresponds to the lowest proton bombarding energy in the present study. The decay scheme resulting from the analysis of the spectrum is included in Fig. 1, where the decay of this resonance to 16 bound levels is shown, including the 1% decay to the bound level at 2·114 MeV which has not been reported previously. The relatively stronger transitions to the levels at 1·179, 1·651 and 1·962 MeV made it possible to determine the branching ratios from the decay of these bound levels with a greater accuracy.

Figs 3–11 (pp. 424–41). Gamma ray spectra for the indicated resonances in the ^{42}Ca(p, γ)^{43}Sc reaction measured at 55° to the beam direction with a Ge(Li) detector. In Figs 3–6 the detector volume is 120 cm^3, and in Figs 7–11 the volume is 54 cm^3. Peaks are labelled with the corresponding γ ray energy, while single and double asterisks denote single- and double-escape peaks respectively.


Counts per channel
Channel number
^{40}K
^{43}Sc – ^{43}Ca
2.614 ThC″

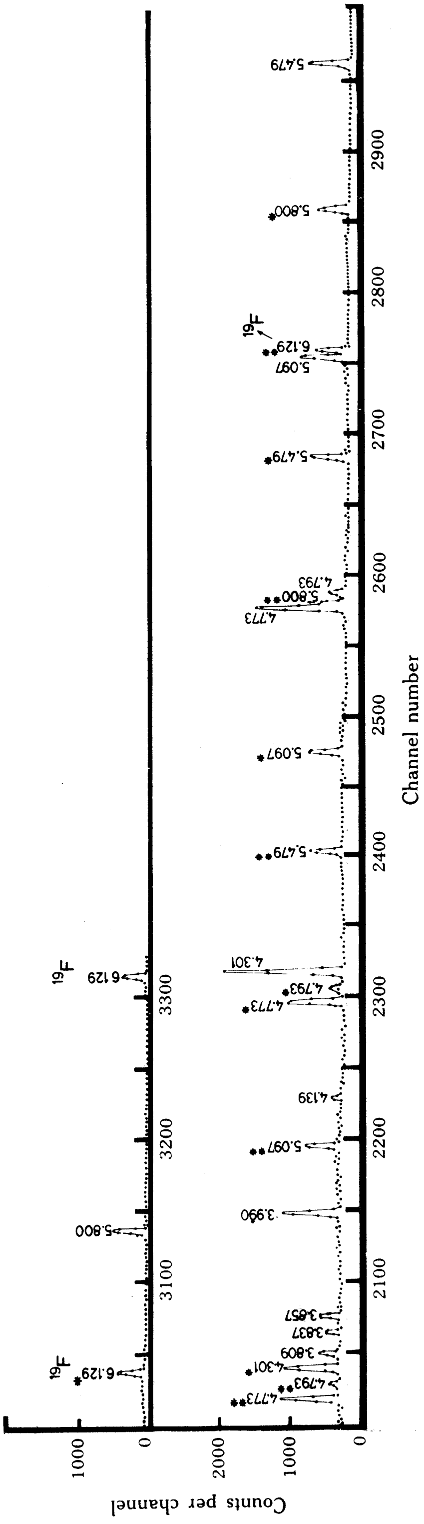
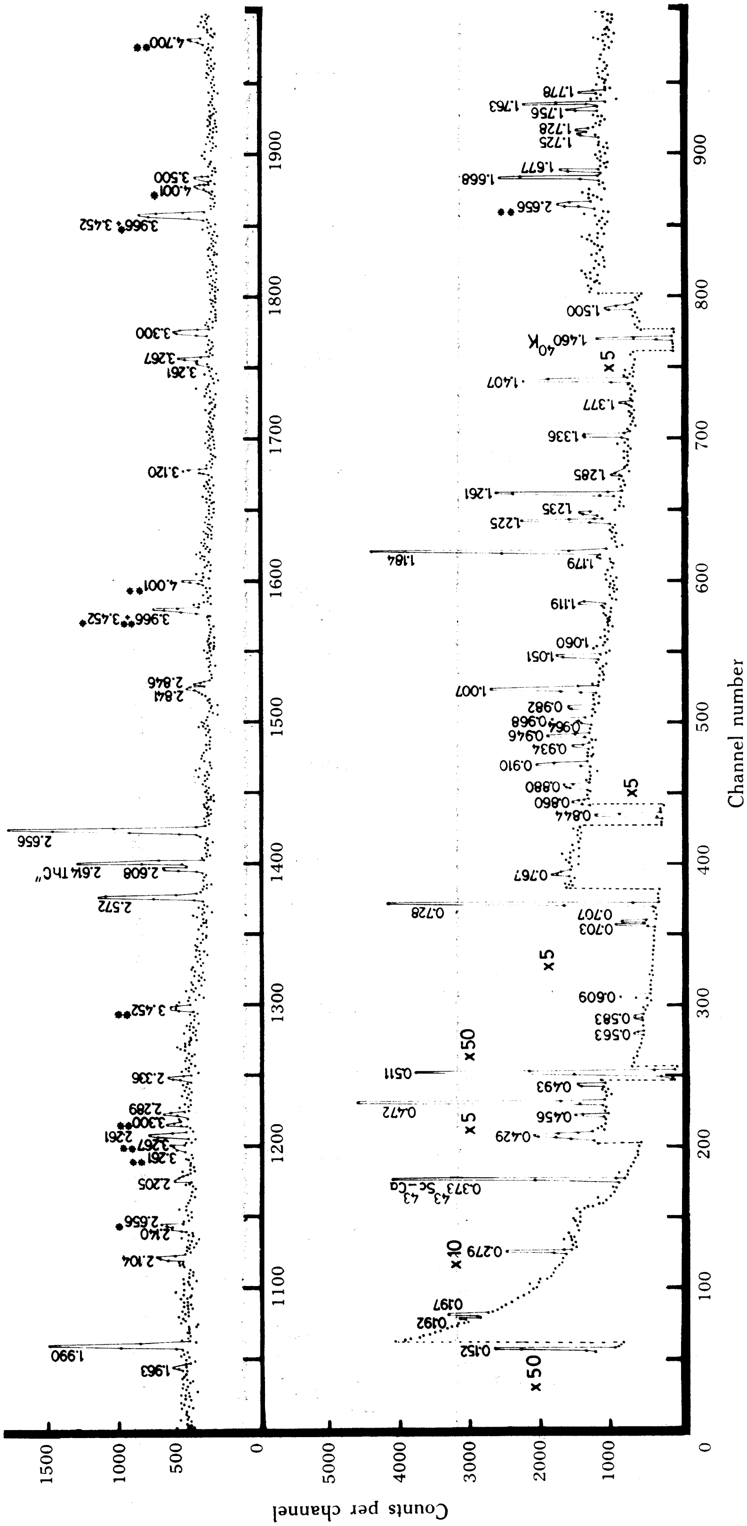


Fig. 3. E_p = 1045 keV. The level at 2·114 MeV is found to be populated for the first time.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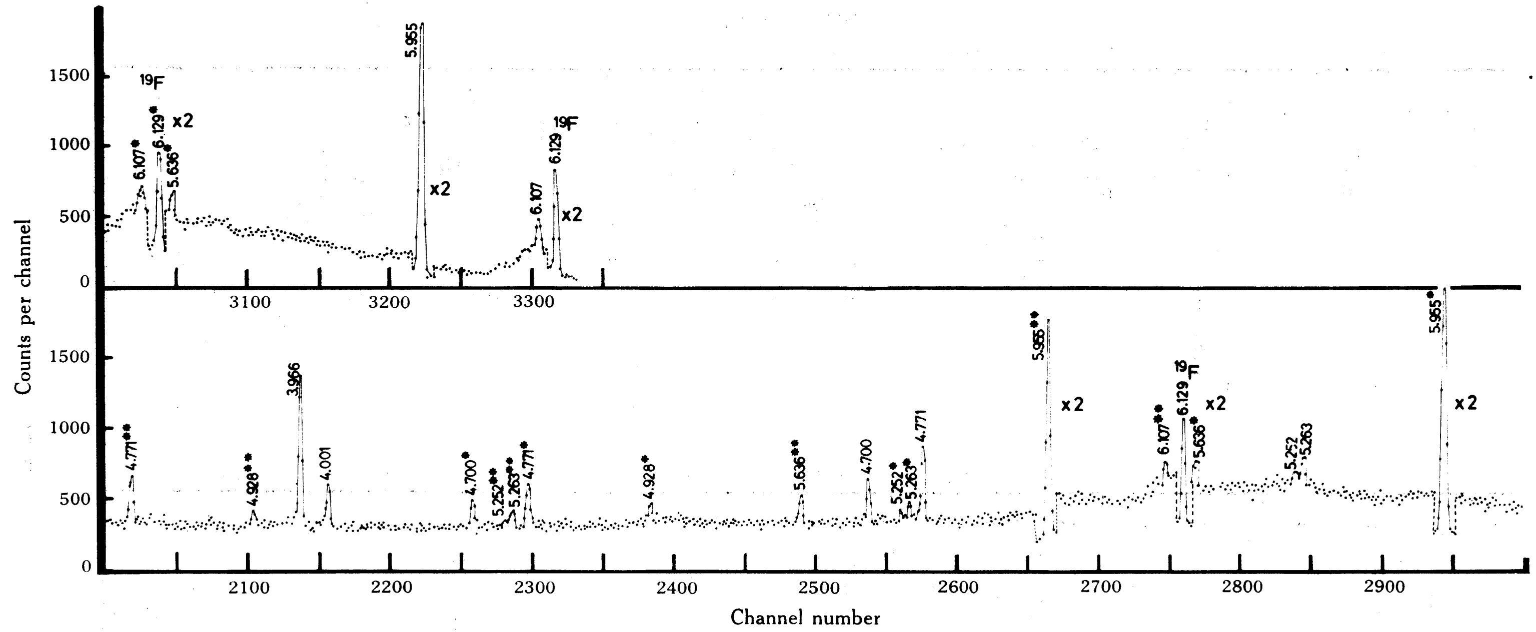
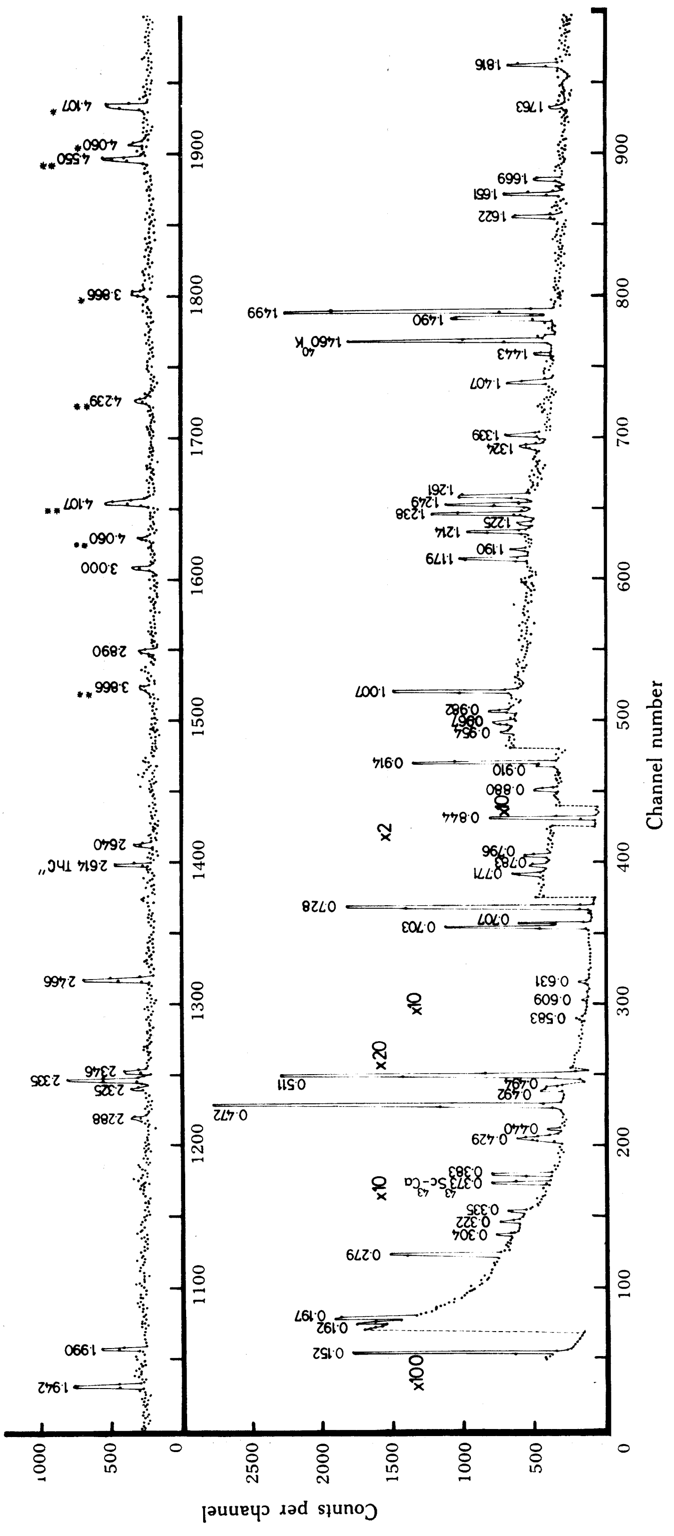


Fig. 4. $E_p = 1201$ keV. The two closely spaced levels at 2·841 and 2·846 MeV are populated, and the γ rays of these energies arising from transitions to the ground state are well separated.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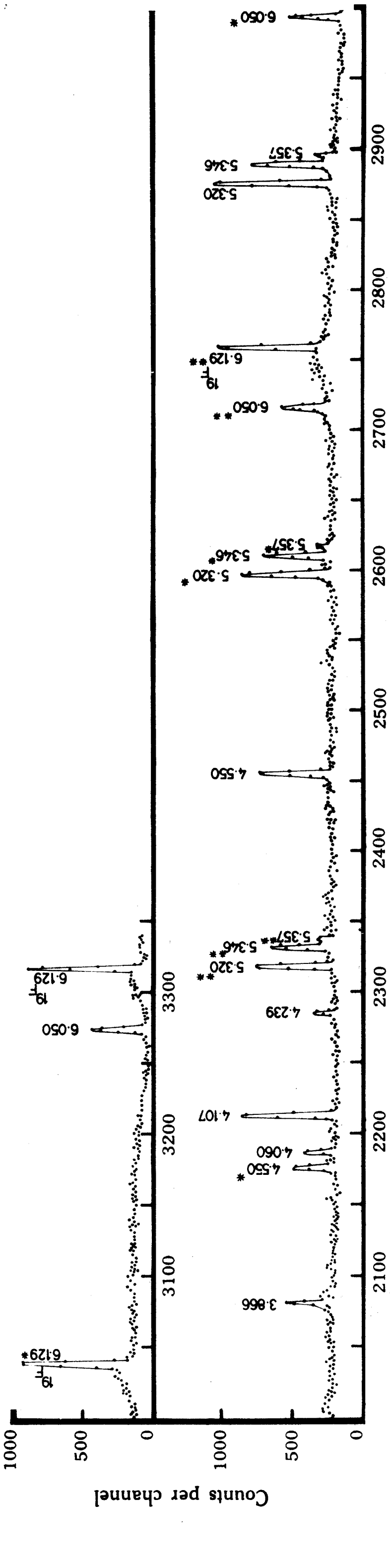
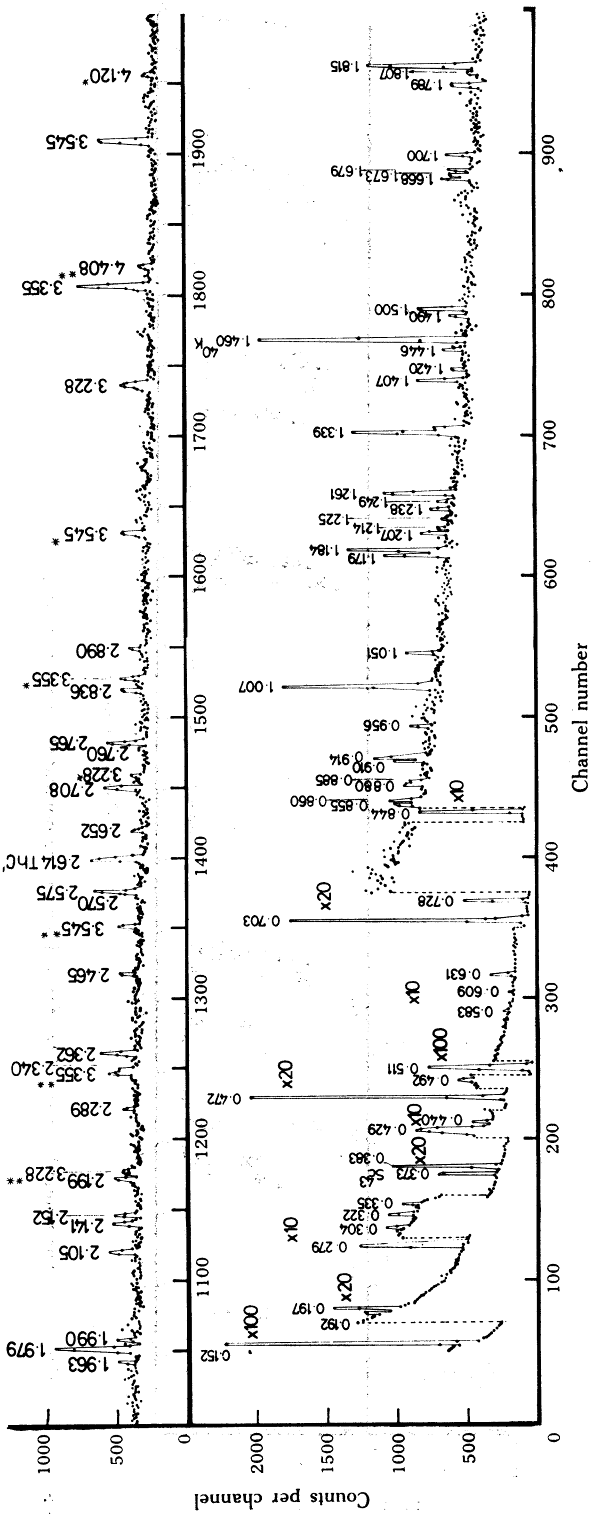


Fig. 5. E_p = 1299 keV. The bound level at 3·734 MeV is found to be populated for the first time.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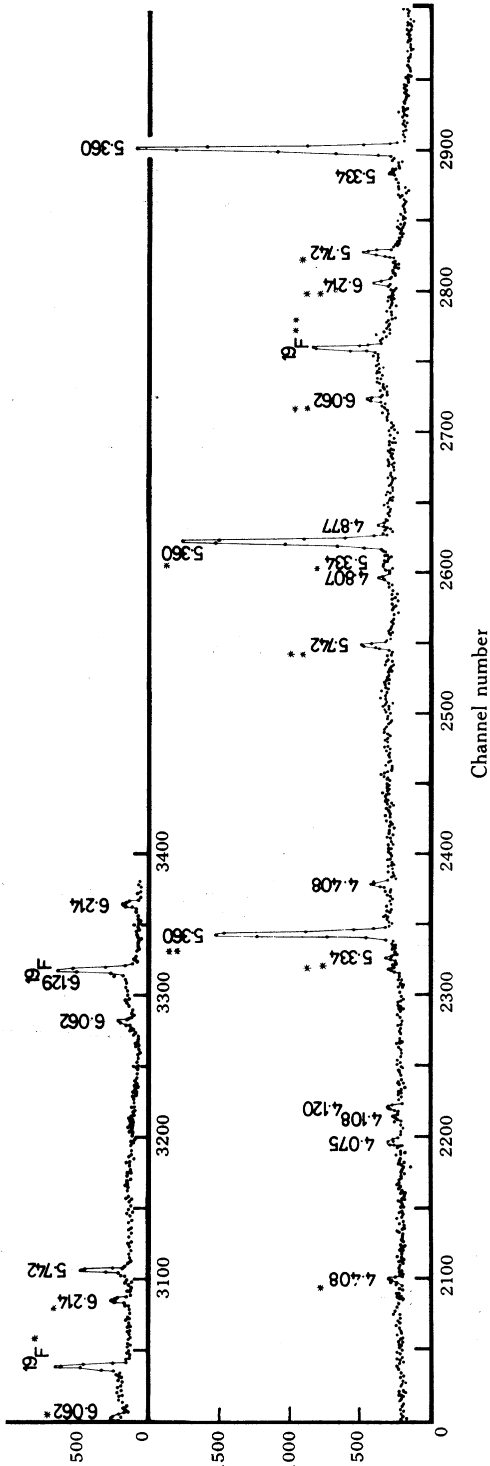
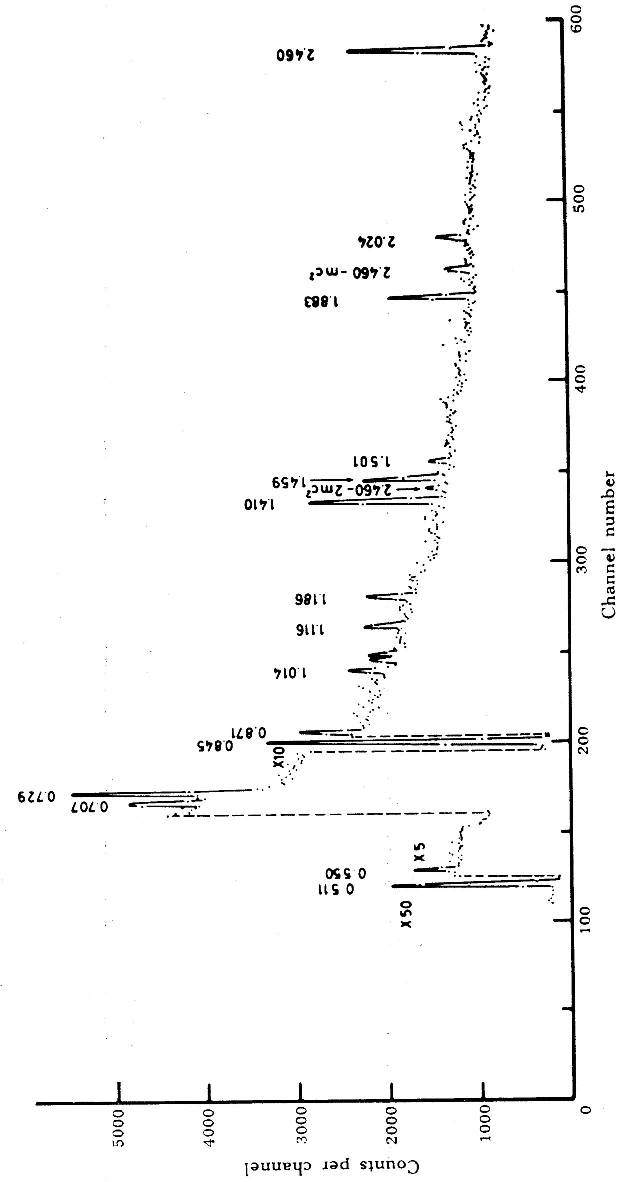
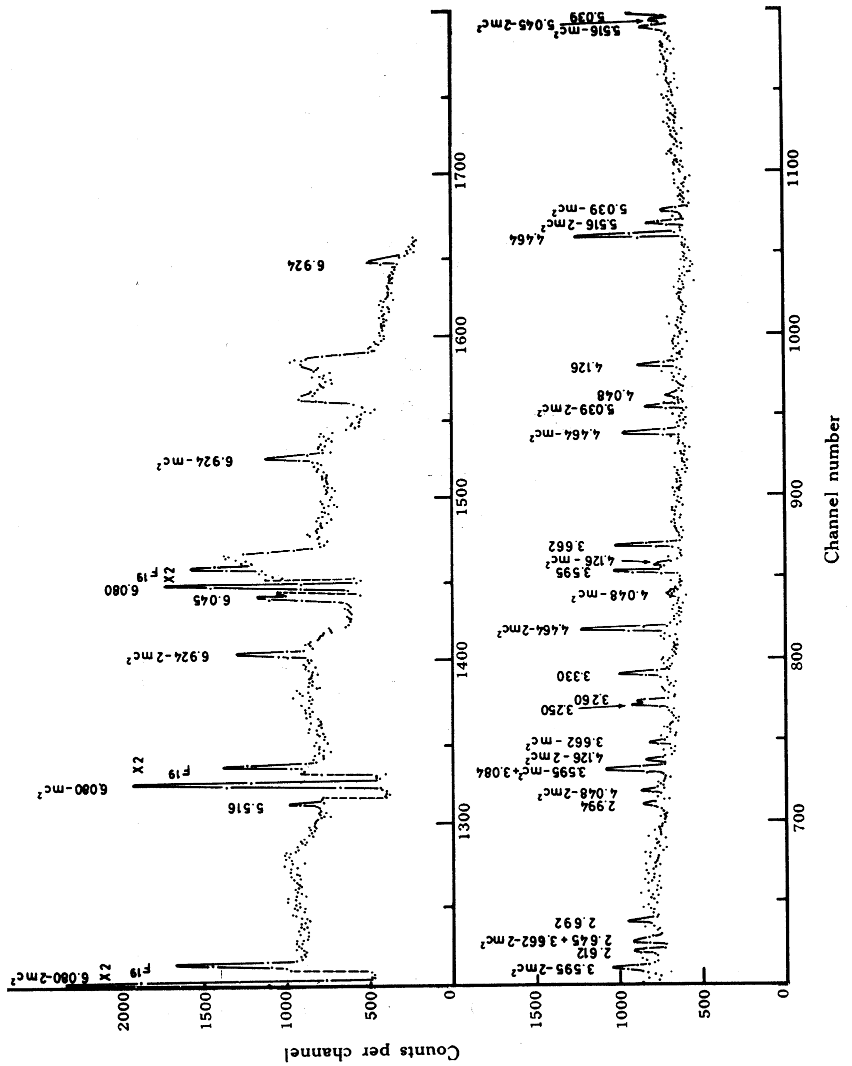


Fig. 6. E_p = 1319 keV. Three bound levels at 2·860, 3·645 and 3·860 MeV are found to be populated for the first item.

Fig. 7. $E_p = 2038$ keV. This is the only resonance previously studied. In general there is good agreement with the results of Walinga *et al.* (1969).

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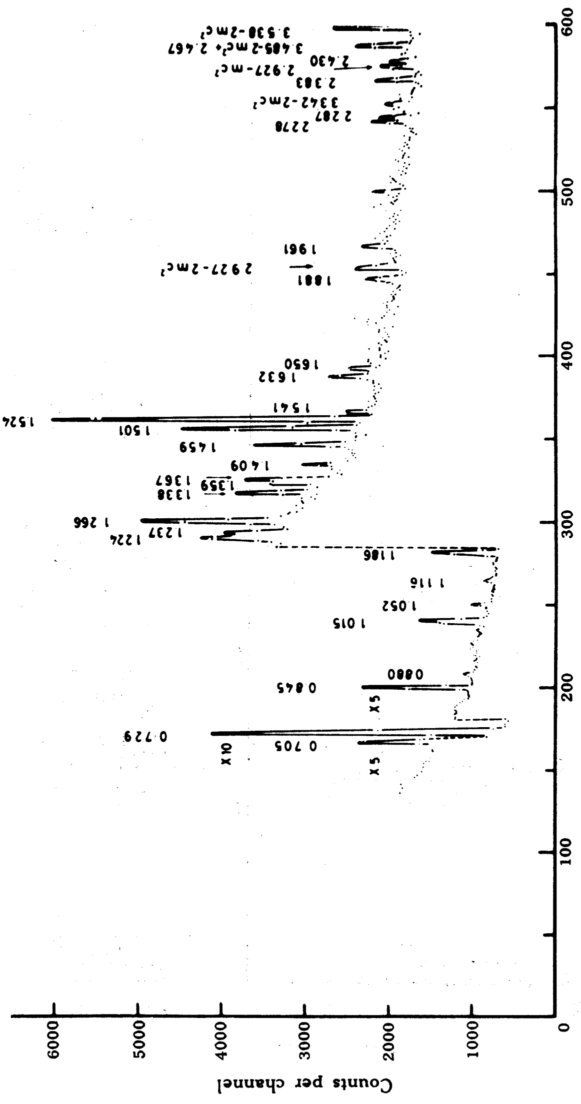


Fig. 8. E_p = 2471 keV. Three bound levels at 2·796, 3·645 and 3·860 MeV are found to be populated for the first time.

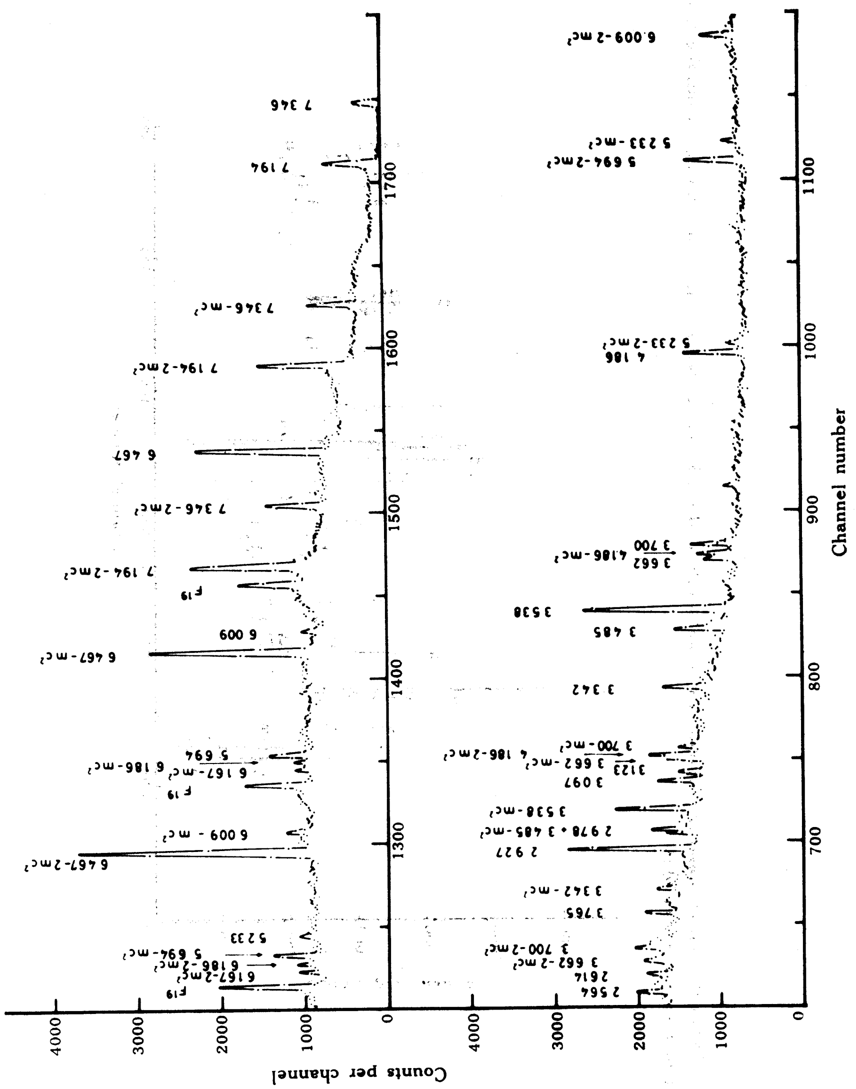
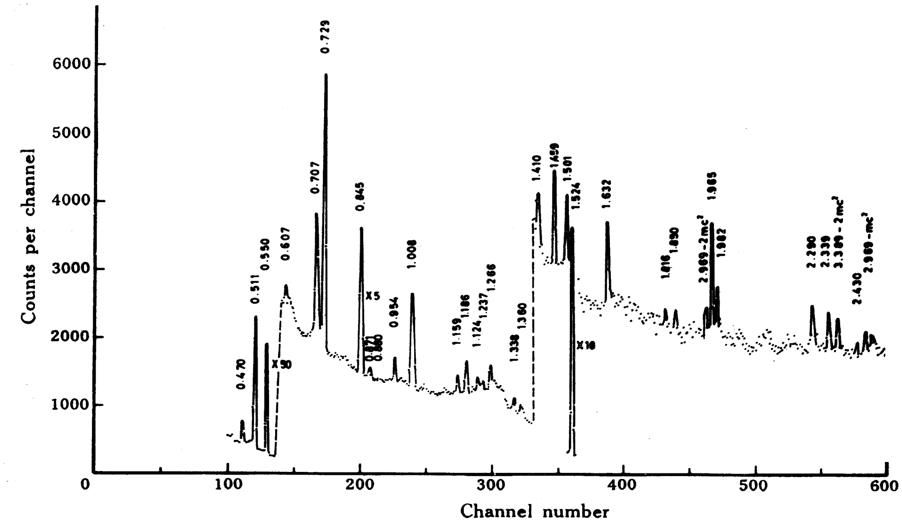

Counts per channel
Channel number

Fig. 9. E_p = 2523 keV. This resonance populates 24 bound levels, and the 12 successive primary transitions are from the ground state up to the excited level at 1·811 MeV.



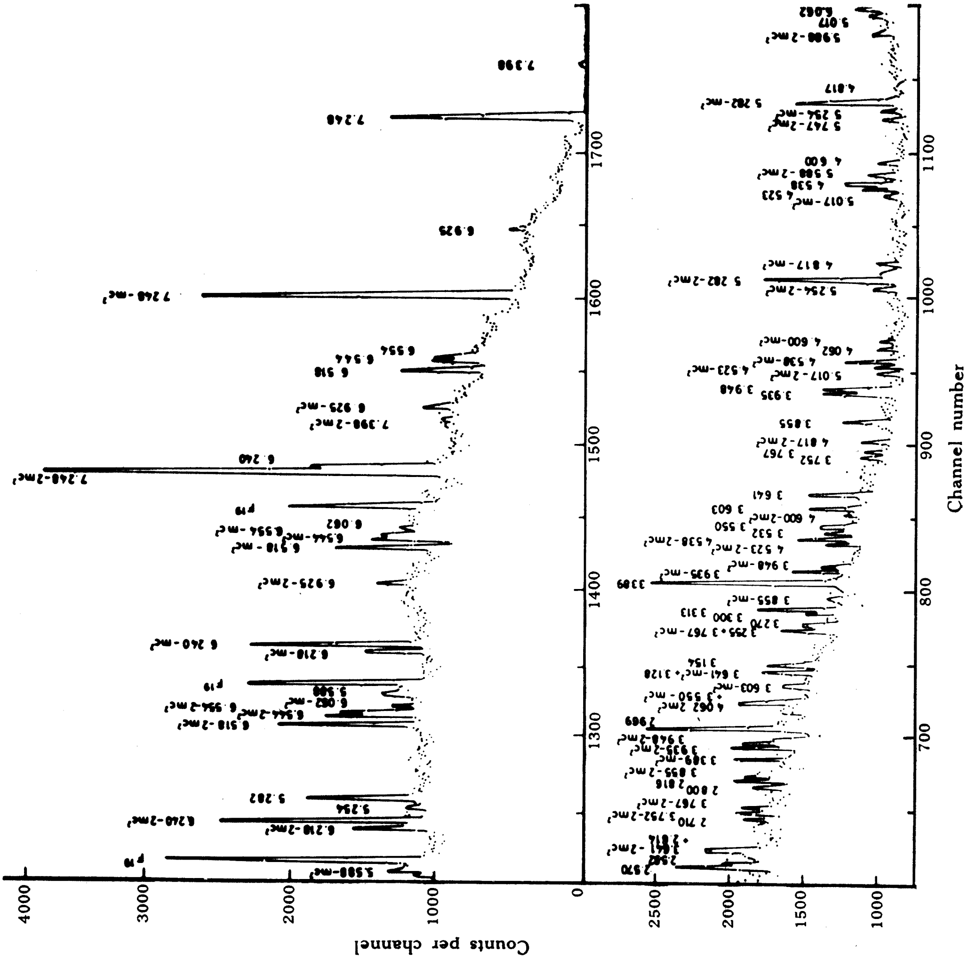
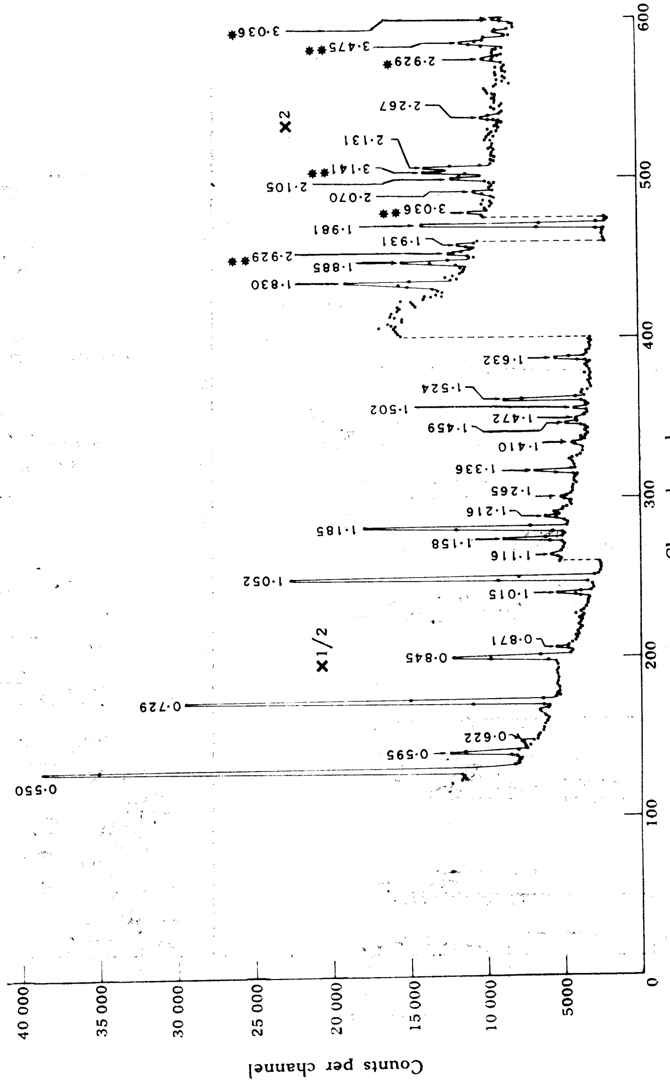
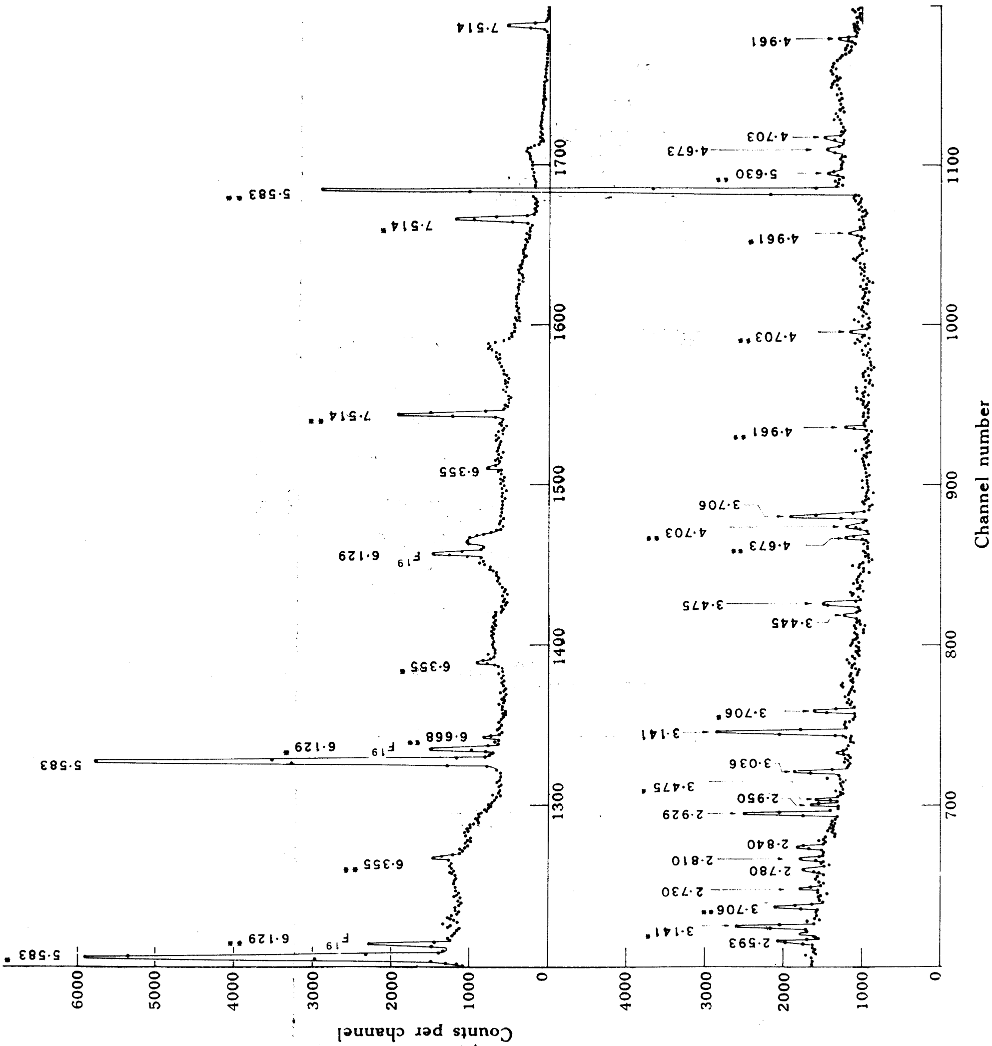

Counts per channel
Channel number

Fig. 10. $E_p = 2643$ keV. The strong transition ($5 \cdot 583$ MeV γ ray) is to the level at $1 \cdot 931$ MeV ($9/2^+$), which is found to be populated via proton capture for the first time.




Counts per channel
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2·730
2·593

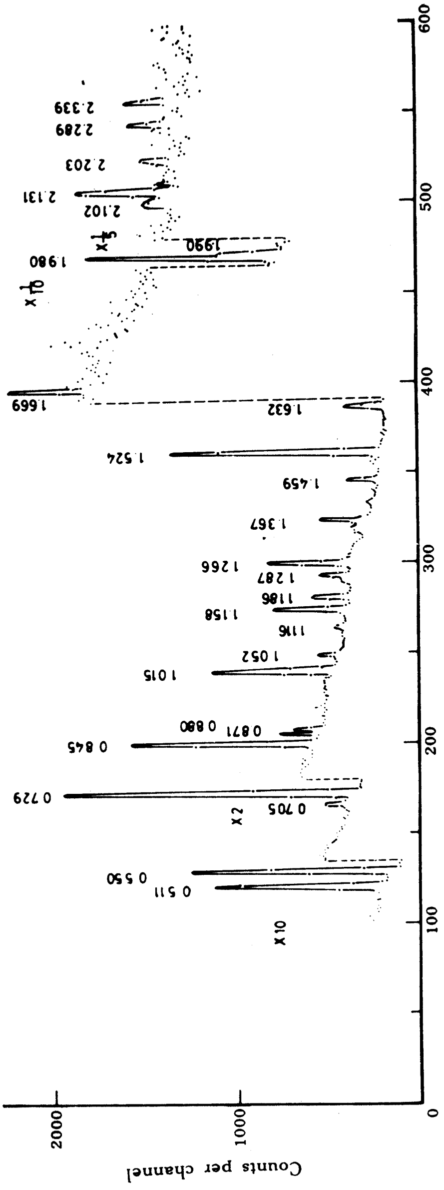
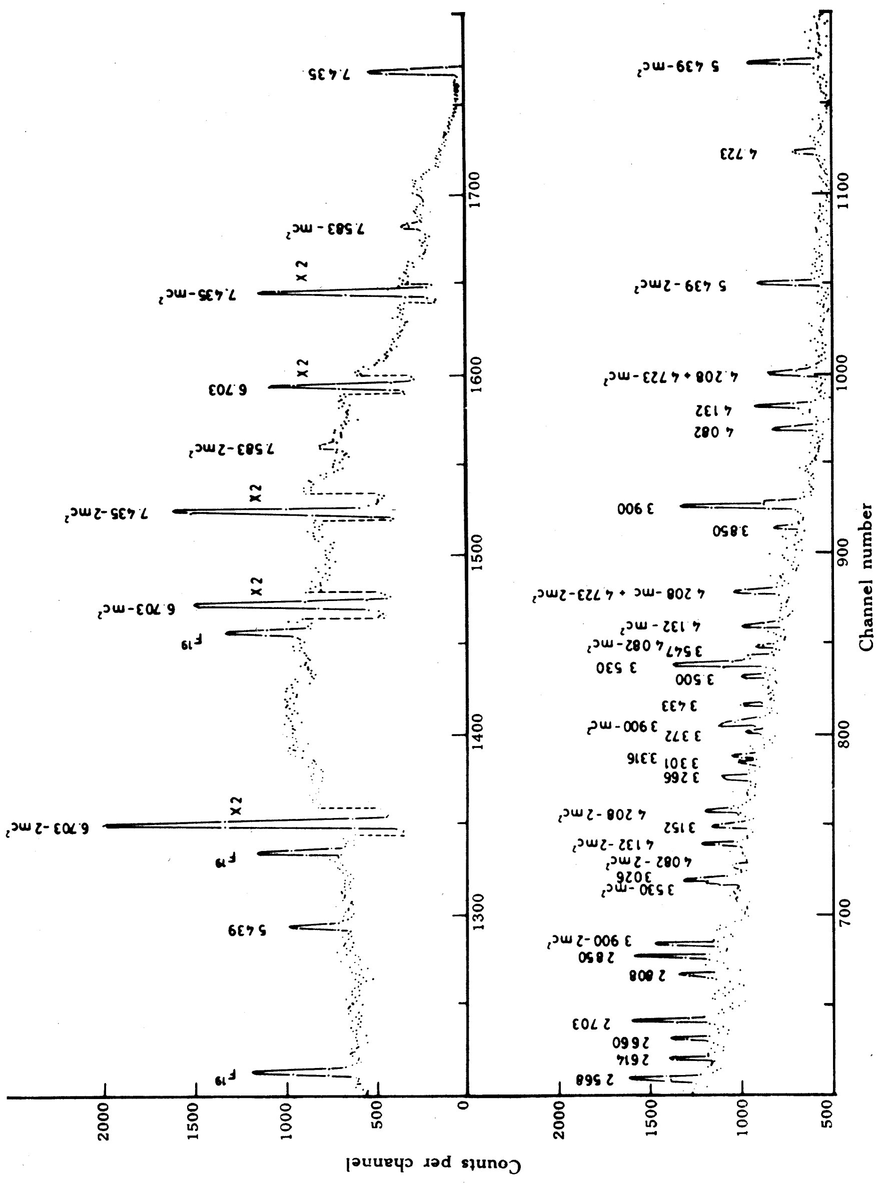


Fig. 11. E_p = 2714 keV.


Counts per channel
Channel number

1201 keV Resonance ($E_x = 6 \cdot 104$ *MeV*)

The γ ray spectrum for the resonance at $E_p = 1201$ keV is shown in Fig. 4 and the corresponding decay scheme is included in Fig. 1. There are 15 transitions from the resonance level to the excited levels in ^{43}Sc below 3·85 MeV, but the level decays primarily (63%) to the first excited state. The closely spaced doublet at 2·841 and 2·846 MeV is populated at this resonance, thus confirming the existence of the doublet. The decay properties of the bound levels at 2·141 and 3·452 MeV were determined from the relatively stronger transitions at this resonance, although the results were confirmed from the population of these levels at other resonances.

1299 keV Resonance ($E_x = 6 \cdot 200$ *MeV*)

The resonance at 1299 keV (Fig. 5) populates 10 bound levels (see Fig. 1) of which the bound level at 3·734 MeV has not been reported previously. The relatively stronger intensities for the primary γ rays leading to the bound levels at 0·855, 0·880, 1·651, 2·094 and 2·336 MeV improved the accuracy of the branching ratios of these levels. Some of these results differ from those previously reported, and these are discussed in the Section 4.

1319 keV Resonance ($E_x = 6 \cdot 219$ *MeV*)

Fig. 6 shows the γ ray spectrum measured at $E_p = 1319$ keV, while the decay scheme for this resonance (derived from the analysis of the spectrum) is included in Fig. 1. This resonance decays to 17 bound levels, and 50% of the decay from the resonance level goes to the bound level at 0·855 MeV. Three bound levels at 2·860, 3·645 and 3·860 MeV are populated, and these have not been reported previously. Branching ratios from a number of bound levels were established with greater accuracy.

2038 keV Resonance ($E_x = 6 \cdot 922$ *MeV*)

This is the only resonance of those considered in the present work which was previously studied by Walinga *et al.* (1969). The γ ray spectrum for the resonance is shown in Fig. 7. The primary decay (63%) from the resonance is to the bound level at 0·844 MeV. For the stronger primary transitions, there is good agreement with the measurements of Walinga *et al.* (1969). However, the reported decays from the resonance to the bound levels at 0·472, 2·580 and 4·272 MeV were not confirmed, although four additional primary transitions were found to the bound levels at 2·796, 2·875, 3·261 and 3·843 MeV. The decay properties of a number of bound levels were determined for which no previous information was available.

2471 keV Resonance ($E_x = 7 \cdot 344$ *MeV*)

Analysis of the γ ray spectrum (Fig. 8) measured at the $E_p = 2471$ keV resonance leads to the decay scheme for it included in Fig. 1. The resonance level populated 13 bound levels out of which the two levels at 3·645 and 3·860 MeV have not been reported previously. The relatively stronger transitions to the bound levels at 0·880, 1·651 and 3·807 MeV were used either to confirm the decay schemes of these levels which were derived from the other resonances as well, or to obtain the decay schemes of those bound levels which were not populated by other resonances.

2523 keV Resonance (E_x = 7·395 MeV)

The γ ray spectra measured at the 2523 keV resonance (Fig. 9) shows an interesting decay scheme (see Fig. 1). The resonance level populates 24 bound levels, and there are 12 successive primary transitions from the ground state up to an excited level at 1·811 MeV. The following two bound levels at 3·757 and 4·430 MeV have not been reported previously. The closely spaced bound levels at 3·452 and 3·453 which are populated from the same resonance have their existence confirmed. The decay properties of a number of bound levels were determined at this resonance.

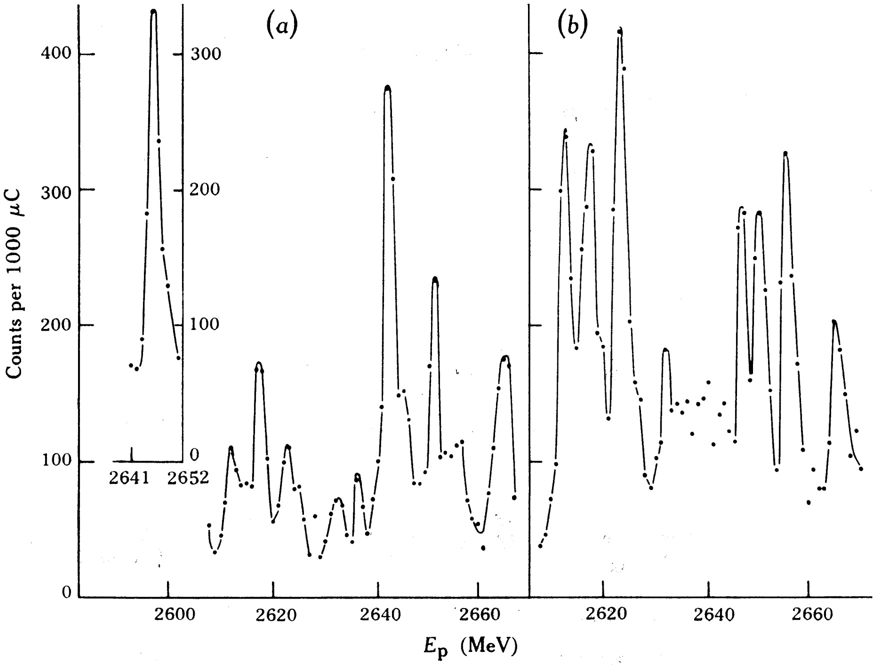


Fig. 12. Relative yields for (*a*) the $^{42}Ca(p, \gamma)^{43}Sc$ and (*b*) the $^{42}Ca(p, p'\gamma)^{43}Sc$ reactions as functions of proton energy E_p in the range 2600–2670 keV. The inset in (*a*) shows the 5·580 MeV γ ray peak.

2643 keV Resonance (E_x = 7·514 MeV)

The γ ray yields from the $^{42}Ca(p, \gamma)^{43}Sc$ and $^{42}Ca(p, p'\gamma)^{42}Ca$ reactions are shown in Figs 12*a* and 12*b* respectively for the range E_p = 2600–2670 keV. The strongest peak in the (p, γ) yield curve is at E_p = 2643 keV; this peak is reproduced in the inset of Fig. 12*a*, with a window set on the 5·583 MeV γ ray which corresponds to the transition from the resonance level to the bound level at 1·931 MeV. A number of peaks in the (p, p'γ) yield curve are observed but there is no peak at 2643 keV proton energy.

The γ ray spectrum measured at E_p = 2643 keV resonance is shown in Fig. 10, while the corresponding decay scheme is shown in Fig. 13. This resonance exhibits a strong transition (59%) to the bound level at 1·931 MeV and a 7% transition to the level at 4·371 MeV. These levels have been found to be populated in the proton capture reaction for the first time. The branching ratios of some of the bound levels presented in Fig. 13 were obtained from the other resonances if the primary transitions

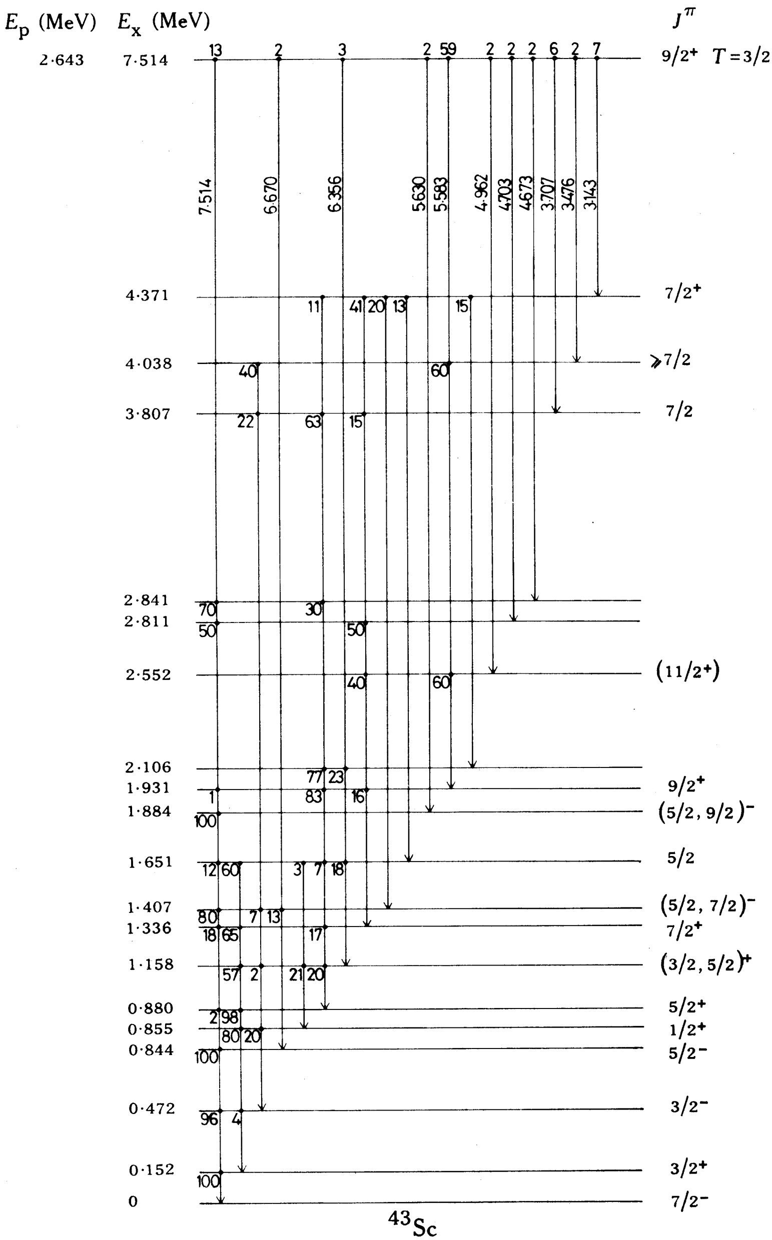


Fig. 13. Decay scheme of the resonance at E_p = 2643 keV. The γ ray energies and the branching ratios (%) are indicated. The spin and parity assignments for the level at 7·514 MeV is $9/2^+$, at 4·371 MeV is $7/2^+$, at 4·038 MeV is 7/2 and at 3·807 MeV is 7/2. These have been assigned from the γ ray angular distributions. The 59% transition from 7·514 → 1·931 MeV is a $9/2^+ \rightarrow 9/2^+$, analogue to anti-analogue transition. The population of the levels at 1·931, 2·552, 4·038 and 4·371 MeV has been found for the first time via the proton capture reaction.

were of greater intensity than the transitions to these bound levels. Most of the primary transitions are to the positive parity states.

2714 keV Resonance (E_x = 7·581 MeV)

Fig. 11 shows the γ ray spectrum measured at E_p = 2714 keV, while the decay scheme resulting from the analysis of the spectrum is included in Fig. 1. Two primary transitions (37% and 40%) occur to the first excited state and the level at 0·880 MeV. There are, however, eight other weaker transitions from the resonance to the excited levels below an excitation energy of 4·430 MeV. The level at 4·430 MeV was observed to be populated once more (it was formerly observed at the E_p = 2643 keV resonance).

Table 3. Absolute strengths of resonances in ^{42}Ca(p, γ)^{43}Sc

Absolute strengths $S = (2J+1)\Gamma_\gamma \Gamma_p/\Gamma$ are normalized to that given by Walinga *et al.* (1969) for the E_p = 2038 keV resonance

E_p (keV)	E_x (MeV)	S (eV)	E_p (keV)	E_x (MeV)	S (eV)
1045	5·952	0·67	2471	7·344	3·59
1201	6·104	0·68	2523	7·395	2·28
1299	6·200	0·74	2643	7·514	4·20
1319	6·219	0·73	2714	7·581	2·93
2038	6·922	3·01			

Resonance strengths

The resonance γ ray yields were measured with the Ge(Li) detectors placed at an angle of 55° with respect to the beam direction. The relative intensities of the resonances were determined by measuring the area under the yield curve. The resonance strengths

$$S = (2J+1)\Gamma_\gamma \Gamma_p/\Gamma$$

reported here were determined from the decay schemes and relative intensities. The absolute strengths were obtained by normalizing the absolute strength given by Walinga *et al.* (1969) for the E_p = 2038 keV resonance. Table 3 lists the resonance energies, excitation energies and the absolute strengths.

Energy of excited levels

The precise values of the energies of the bound levels of ^{43}Sc were obtained by a 120 cm^3 high resolution and high efficiency Ge(Li) detector. In many cases the energy of the given level could be determined in several ways because the level was involved in several different cascades. In addition, many levels were populated by more than one resonance, which allowed us to make several independent measurements of the level energy. The final energy values, after appropriate averaging (with a few exceptions), are presented in Table 4 where they are compared with previously reported results. The agreement with the values obtained by other authors is good. However, a number of levels have not been observed previously in proton capture, (α, pγ), (^{3}He, d), (d, n) and (^{3}He, t) reactions.

Table 4. Comparison of excitation energies for ^{43}Sc

Excitation energy (keV) from							
Present* (p, γ)	Walinga* (p, γ)	Ball* (α, pγ)	Broman* (^{3}He, d)	Schwartz* (^{3}He, d)	Bommer* (^{3}He, d)	Grandy* (d, n)	Alford* (^{3}He, t)
152·2±0·3	150·9±0·7	151±2	152	152±8	154	152±11	
472·3±0·4	472·3±0·6	472±2	473	475±6	470	475±11	
844·4±0·5	845·7±0·5	844·9±0·5	846				
855·3±0·4	855·6±1·0	855·2±0·4	857	856±10	851	860±10	
880·4±0·5	880·5±0·4	880·1±0·6	876				
1158·3±0·6	1158·3±0·4	1159·1±0·5					
1179·4±0·8	1178·9±0·5	1179·5±0·6	1186	1180±7	1179	1177±9	1178±4
1336·2±0·5	1136·4±0·5	1336·5±0·6					
1406·7±0·4	1410·0±0·8	1407·6				1395±13	1402±4
1650·8±0·6	1652·0±0·9	1650·9±0·6	1655				
1810·6±0·7	1809·7±1·0	1811·5±0·8	1819	1812±6	1809	1817±9	
1883·6±0·9	1885·0±0·6	1883·1±0·5					1881±4
1931·2±0·6		1931·4±0·6					
1962·2±0·5	1962·7±0·5	1962·5±1·5	1965	1962±6	1958	1947±13	
2094·2±0·6	2094·3±0·3	2094·0±1·0					
2106·4±0·7		2106·1±0·7	2103	2100±9	2097	2117±9	
2114·3±0·9			(2120)				
2140·6±0·5	2143·2±0·5	2142·5±1·5					
2289·3±0·8		2288·7±1·0	2296	2294±5	2291	2310±10	2284±4
2335·8±0·9		2336·5±1·1	2339				
2383±1·5	2382·8±0·5		(2395)				
2552±1·5		2552·3±0·7					
2580·4±0·8	2580·4±1·0	2579±2					
2670·6±0·6	2669·6±				2657		
2796±2							

Table 4 (*Continued*)

Present* (p, γ)	Walinga* (p, γ)	Ball* (α, pγ)	Excitation energy (keV) from Broman* (^{3}He, d)	Schwartz* (^{3}He, d)	Bommer* (^{3}He, d)	Grandy* (d, n)	Alford* (^{3}He, t)
2811·2±1·0		2810·4±0·9					
2840·5±1·5		(2839±2)					
2846·2±1·5							
2859·7±1·6							
2875±2			2890				
2988·4±1·5	2985·8±1·1	2987±2	3000	2992±15	2978	2977±11	2983±4
3160±2		3141±2					
3261±2							3254±4
3291·6±1·6	3288·8±1·6		3273				
3328±2	3326·7±1·5						3324±4
3331·4±1·7			3337	3337±15	3330		
3374±2							
3451·8±1·8	3451·7±1·0						
3463±2							
3503±2							
3645·4±1·8							
3683±2	3676·9±0·5		3682	3673±15	3673	3683±9	3667±8
3733·8±1·8							
3757±2							
3807±2	3806·6±0·7						
3843±2							3843±8
3860±2							
4007±2				3992±10	3985	4011±12	
4038±2							
4371±2			4376	4380±10	4363	4379±9	4371
4430±2							
4464±2	4454·7±2·8						

* Data are from the present work, Walinga *et al.* (1969), Ball *et al.* (1970), Broman (1967), Schwartz and Alford (1966), Bommer *et al.* (1971), Grandy *et al.* (1968) and Alford *et al.* (1971).

Table 5. Branching ratios in ^{43}Sc

Initial level (keV)	Branching ratio (%) for transition to final level at 0	152	472	844	855	880	1158	1179	1336	1407	1651	1811	1931	1962	2106	2289 keV
152	100															
472	96±2	4±1														
844	100															
855		80±4	20±2													
880	2±1	98±2														
1158		57±2	2±1		21±3	20±3										
1179	16±2		71±6	12±2		1										
1336	18±3	65±2				17±2										
1407	80±3		7±2	13±2												
1651	12±2	60±3			3±1	7±2	18±2									
1811		10±3	35±4		16±4			39±5								
1884	100															
1931	1					83±3			16±2							
1962			84±2				3±1	13±2								
2094		17±3	11±3	11±2	18±2	10±2		33±3								
2106						77±5	23±3									
2114		56±7					44±5									
2141		25±2	17±2		4±2	34±3	5±2	2±1			13±2					
2289	100															
2336	100															
2383											100					
2552									40±4				60±5			
2580		52±7				21±4	27±5									
2671			22±3		49±2	21±4		8±2								
2796		25±4		75±7												

Table 5 (*Continued*)

Initial level (keV)	Branching ratio (%) for transition to final level at 0	152	472	844	855	880	1158	1179	1336	1407	1651	1811	1931	1962	2106	2289 keV
2811	50±5								50±5							
2841	70±5					30±6										
2846	100															
2860		33±3				44±2	10±3	7±2			6±2					
2875		80														
2988		38±3		22±3		27±2		13±3								
3160						25										
3261	60															
3292				39±4		9±3		43±5				9±2				
3328	70															
3331			9±2	14±3			21±2	48±2				6±2		2±1		
3374	50															
3452	12±4	24±3		20±3		44±3										
3463		73±5				27±3										
3503	50±5			50±5												
3645						24±5		38±6			25±5			13±4		
3683		55±6		31±3		14±2										
3734				29						24						9
3757	30±5	70±7														
3807			22±5			63±3			15±4							
3843				40												
3860		80														
4007		30±5	15±4		30±6	25±6										
4038			40±9										60±8			
4371						11±3			41±4	20±5	13±4				15±3	
4430						30±4	30±5	40±6								
4464	100															

4. Decay Schemes of Bound Levels

In the present investigation most of the bound levels were populated at more than one resonance with different intensities (see Table 2). This made it possible to determine with improved accuracy the γ ray branching ratio of a bound level by considering the resonances which populated it with relatively stronger intensity. The decay schemes of the bound levels were found to be consistent from one resonance to another and are shown in Fig. 1, while the γ ray branching ratios of all observed bound levels are listed in Table 5. Most values for branching ratios are averages of results obtained at several different resonances. The results obtained for the bound levels are discussed briefly below.

0·472 MeV Level

The 0·472 MeV level decays primarily to the ground state (96%). Only a 4% decay to the first excited state (0·320 MeV γ ray) is found, which is in agreement with the γ ray transition observed by Ball *et al.* (1972).

0·844 MeV Level

Two resonances at $E_p = 1319$ and 2038 keV populate (50% and 63% respectively) the level at 0·844 MeV. The level decays completely to the ground state, which is in agreement with previously reported results. The upper limit of $<4\%$ for the $844 \rightarrow 152$ keV transition obtained by Ball *et al.* (1972) does not agree with the present results. The 0·372 MeV γ ray for this transition (shown in the spectra) belongs to the decay of the first excited state of ^{43}Ca.

0·855 MeV Level

The transition from the 0·855 MeV level to the ground state is not observed. The 0·703 and 0·383 MeV γ rays shown in the γ ray spectrum (Fig. 5) correspond to transitions to the first excited state and the level at 0·472 MeV. The high resolution of the Ge(Li) detector separates the 0·703 MeV γ ray from the 0·707 MeV γ ray, which is from the $1 \cdot 179 \rightarrow 0 \cdot 472$ MeV transition. The branching ratios are 80% to the 0·152 and 20% to the 0·472 MeV levels. This agrees with the results of Walinga *et al.* (1969) but not with those of Ball *et al.* (1970).

0·880 MeV Level

The 0·880 MeV level decays 2% to the ground state and 98% to the first excited state. The transition to the ground state reported by Ball *et al.* (1972) is confirmed.

1·158 MeV Level

The 1·007, 0·687, 0·304 and 0·279 MeV γ rays (Fig. 3) arise from the four transitions, $1 \cdot 158 \rightarrow 0 \cdot 152$, 0·472, 0·855 and 0·880 MeV. The branching ratios to these levels are 57%, 2%, 21% and 20% respectively. These results differ from previously reported ones with regard to the number of transitions as well as to the branching ratios.

1·179 MeV Level

The strongest (21%) primary transition to the bound level at 1·179 MeV is found at the $E_p = 1045$ keV resonance. The four γ rays of 1·179, 0·707, 0·335 and

0·299 MeV (Fig. 3) are for the transitions from the level at 1·179 to the 0, 0·472, 0·844 and 0·880 MeV levels. The branching ratios to these levels are 16%, 71%, 12% and 1% respectively. The 0·707 MeV γ ray is well separated from the γ ray at 0·703 MeV, which is for the 0·855 → 0·152 MeV transition. The 1% transition to the level at 0·880 MeV has not been reported previously. The other three branching ratios differ from the results of Walinga *et al.* (1969) and Ball *et al.* (1970).

1·336 MeV Level

The strongest primary transition to the bound level at 1·336 MeV is found at the $E_p = 1201$ keV resonance, and the strongest cascade feed to this level is from the level at 1·931 MeV, which is populated at $E_p = 2643$ keV (Fig. 10). The three γ rays of 1·336, 1·184 and 0·456 MeV (Figs 1 and 13) are for the three transitions 1·336 → 0, 0·152 and 0·880 MeV. The branching ratios to these levels are 18%, 65% and 17% respectively. These findings are different from the results of Walinga *et al.* (1969) who reported only two transitions, and also from the branching ratios reported by Ball *et al.* (1970).

1·407 MeV Level

The three γ rays of 1·407, 0·935 and 0·563 MeV (Fig. 4) correspond to three transitions from the level at 1·407 MeV to the levels at 0, 0·472 and 0·844 MeV. The branching ratios to these levels are 80%, 7% and 13% respectively. The 7% decay to the 0·472 MeV level was not observed either by Walinga *et al.* (1969) or by Ball *et al.* (1970).

1·651 MeV Level

The 1·651 MeV level is found to decay to five levels at 0, 0·152, 0·855, 0·880 and 1·158 MeV with 1·651, 1·499, 0·796, 0·771 and 0·493 MeV γ rays. The branching ratios to these levels are 12%, 60%, 3%, 7% and 18% respectively. It was possible only by means of a high resolution and high efficiency Ge(Li) detector to observe the weaker transitions and the well-separated 1·499 MeV γ ray from the γ ray at 1·490 MeV (Fig. 3), the latter γ ray being for the 1·962 → 0·472 MeV transition. These results are in serious disagreement with the results of Walinga *et al.* (1969). Ball *et al.* (1972) did not report the 7% decay to the level at 0·880 MeV.

1·811 MeV Level

The 1·811 MeV level decays to four levels at 0·152, 0·472, 0·855 and 1·179 MeV, and the branching ratios are 10%, 35%, 16% and 39% respectively. These results are in disagreement with the previously reported two transitions to levels at 0·472 and 1·179 MeV and with the branching ratios as well.

1·884 MeV Level

The 1·884 level decays completely to the ground state, which is in agreement with the results of Ball *et al.* (1970) but in disagreement with those of Walinga *et al.* (1969) who reported decays of 40% and 60% to the levels at 0·472 and 1·179 MeV respectively.

1·931 MeV Level

The 1·931 MeV level is populated (59%) from only one resonance, that at $E_p = 2643$ keV. The three γ rays at 1·931, 1·052 and 0·595 MeV (Fig. 10) are for the three transitions from the 1·931 MeV level to the ground state and the levels at 0·880 and 1·336 MeV (Fig. 13). The branching ratios to the three levels are 1%, 83% and 16% respectively. These results are different from those of Ball *et al.* (1970) who reported 69% and 31% decays to the levels at 0·880 and 1·336 MeV respectively.

1·962 MeV Level

This level is found to decay primarily (84%) to the level at 0·472 MeV and 13% to the level at 1·179 MeV, while a 3% decay to the level at 1·158 MeV is observed which had not been reported previously. The three γ rays of 0·783, 0·804 and 1·490 MeV (Fig. 3) for the three transitions are well separated from the closely spaced γ rays in the γ ray spectra, and the γ ray for the weaker transition is clearly observable. This has been achieved by means of the high resolution and high efficiency detector.

2·094 MeV Level

The 2·094 MeV level decays to six levels at 0·152, 0·472, 0·844, 0·855, 0·880 and 1·179 MeV with branching ratios of 17%, 11%, 11%, 18%, 10% and 33% respectively. The γ rays for the six transitions (Fig. 5) are 1·942, 1·622, 1·249, 1·238, 1·214 and 0·914 MeV respectively. These γ rays, especially those of 1·214, 1·238 and 1·249 MeV, are well separated from the group of closely spaced γ rays. The present results differ from previous measurements in respect of the number of transitions as well as the branching ratios.

2·106 MeV Level

The 2·106 MeV level is found to decay 77% to the level at 0·880 MeV and 23% to the level at 1·158 MeV. These branching ratios are different from those reported by Ball *et al.* (1970).

2·114 MeV Level

The 2·114 MeV level has not been reported previously. The level decays 56% to the level at 0·152 MeV and 44% to the level at 1·158 MeV.

2·141 MeV Level

Though populated at a number of resonances, the 2·141 MeV level is populated relatively strongest at $E_p = 1201$ keV. The level cascades to seven levels at 0·152, 0·472, 0·855, 0·880, 1·158, 1·179 and 1·651 MeV with branching ratios of 25%, 17%, 34%, 5%, 2%, 13% and 4% respectively. These results are different from those of Walinga *et al.* (1969) and Ball *et al.* (1970, 1972).

2·289, 2·336 and 2·383 MeV Levels

The two levels at 2·289 and 2·336 MeV decay completely to the ground, while the third level at 2·383 MeV decays completely to the level at 1·651 MeV. These results are in agreement with previous measurements.

2·552 MeV Level

The level at 2·552 MeV is populated only from the resonance at $E_p = 2643$ keV. The level decays 40% to the level at 1·336 MeV and 60% to the level at 1·931 MeV (Fig. 13). This agrees with the results of Ball *et al.* (1970).

2·580 MeV Level

The 2·580 MeV level cascades to three levels at 0·152, 0·880 and 1·158 MeV with branching ratios of 52%, 21% and 27% respectively. These results are completely different from the previous measurements.

2·671 MeV Level

The 2·671 MeV level is found to have four transitions to the levels at 0·472, 0·855, 0·880 and 1·179 MeV with branching ratios of 22%, 49%, 21% and 8% respectively, as compared with the previously reported results of two transitions of 75% and 25% to the levels at 1·179 and 1·407 MeV (Walinga *et al.* 1969).

2·796 MeV Level

The 2·796 MeV level has not been reported previously. It is populated from two resonances at $E_p = 2038$ and 2523 keV. The level decays 25% to the level at 0·152 MeV and 75% to the level at 0·844 MeV.

2·811 MeV Level

The 2·811 MeV level is populated from only one resonance at $E_p = 2643$ keV. It decays (Fig. 13) to the ground state as well as to the 1·336 MeV level with equal intensity. These results are in disagreement with those of Ball *et al.* (1970).

2·84 MeV Doublet

The two closely spaced levels at 2·841 and 2·846 MeV are populated from the resonance at $E_p = 1201$ keV, though the former level is also populated from the resonance at $E_p = 2643$ keV. The 3·261 and 3·267 MeV γ ray energies are well separated (Fig. 3). These γ rays arise from primary transitions from the resonance level to the levels at 2·841 and 2·846 MeV. The two levels of this doublet have different decay schemes, the transition to the ground state being common to both though with different branching ratios. The 2·841 and 2·846 MeV γ rays are also well separated in the γ ray spectra. The 2·841 MeV level (Figs 1 and 13) decays 70% to the ground state and 30% to the 0·880 MeV level, whereas the 2·846 MeV level goes completely to the ground state. The present results show for the first time the existence of the doublet.

2·860 MeV Level

The 2·860 MeV level has not been reported previously and is populated at three resonances in the present study. It decays to five levels at 0·152, 0·880, 1·158, 1·179 and 1·651 MeV with branching ratios of 33%, 44%, 10%. 7% and 6% respectively.

2·875 MeV Level

The 2·875 MeV level is populated from two resonances at $E_p = 2038$ and 2523 keV. The level is reported for the first time. Only 80% decay to the first excited state could be placed in the decay scheme.

2·988 MeV Level

The 2·988 MeV level is also reported here for the first time and is populated from two resonances at $E_p = 1201$ and 1319 keV. The level decays 38% to the 0·152, 22% to the 0·844, 27% to the 0·880 and 13% to the 1·179 MeV level.

3·160 and 3·261 MeV Levels

The 3·160 MeV level is populated from two resonances at $E_p = 1201$ and 2471 keV, while the 3·261 MeV level is populated from one resonance at $E_p = 2038$ keV. Only a part of the decay of these levels could be placed.

3·292 MeV Level

The 3·292 MeV is populated level from the resonance at $E_p = 1045$ keV only. The level decays 39% to the 0·844, 9% to the 0·880, 43% to the 1·179 and 9% to the 1·811 MeV level. This is completely different from the previously reported 100% transition to the ground state (Walinga *et al.* 1969).

3·33 MeV Doublet

The level at 3·328 MeV is populated from the 2038 keV resonance, while the 3·331 MeV level is populated from the 1045 keV resonance. The decay schemes of the two levels are different. The 3·328 MeV level decays 70% to the ground state, while 30% of the decay could not be placed. The 2·859, 2·487, 2·173, 2·151, 1·520 and 1·369 MeV γ rays are the results of six transitions from the level at 3·331 MeV. The branching ratios are 9% to the 0·472, 14% to the 0·844, 21% to the 1·158, 48% to the 1·179, 6% to the 1·811 and 2% to the 1·962 MeV level. A level at 3·327 MeV was, however, reported by Walinga *et al.* (1969) but no decay scheme was given.

3·374 MeV Level

The 3·374 MeV level, not reported previously, is populated from only one resonance at $E_p = 2714$ keV; 50% of the decay from the level goes to the ground state and the other 50% of the decay could not be determined.

3·45 MeV Doublet

The 3·452 MeV level is populated from four resonances, while the level at 3·463 MeV is populated from the resonance at $E_p = 2523$ keV only. The 3·452, 3·300, 2·608 and 2·572 MeV γ rays are for the four transitions from the decay of the 3·452 MeV level to the levels at 0, 0·152, 0·844 and 0·880 MeV. The respective branching ratios are 12%, 24%, 20% and 44%. The high resolution γ ray spectrum (Fig. 3) separates very well two closely spaced γ rays of 2·608 and 2·614 MeV, the latter γ ray being from the ThC″ activity. These results are in serious disagreement with the previous measurement (Walinga *et al.* 1969) who reported a 100% decay to the ground state. The other level of the doublet at 3·463 MeV has not been reported previously. It decays 73% to the first excited state and 27% to the 0·880 MeV state.

3·504 MeV Level

The 3·504 MeV level, not reported previously, is excited only at the $E_p = 2714$ keV resonance. The level decays with equal intensity to the ground state and the level at 0·844 MeV.

3·645 MeV Level

Two resonances at $E_p = 1319$ and 2471 keV populate the level at 3·645 MeV. Four γ rays, 2·765, 2·466, 1·991 and 1·683 MeV belong to the decay of the level to the four levels at 0·880, 1·179, 1·651 and 1·962 MeV. The respective branching ratios are 24%, 38%, 25% and 13% to the four levels. The level is reported for the first time.

3·683 MeV Level

The 3·683 MeV level is populated at two resonances and it decays 55% to the 0·152, 31% to the 0·844 and 14% to the 0·880 MeV level.

3·734 MeV Level

Only the resonance at $E_p = 1299$ keV populates the bound level at 3·734 MeV. The level decays 29% to the 0·844, 24% to the 1·407 and 9% to the 2·289 MeV level, while 38% of the decay from the level could not be discovered. The level has not been previously reported.

3·757 MeV Level

The resonance at $E_p = 2523$ keV excites the level at 3·757 MeV. The level decays 30% to the ground state and 70% to the first excited state. The level is reported here for the first time.

3·807 MeV Level

Two resonances at $E_p = 2471$ and 2643 keV populate the level at 3·807 MeV. The level decays (Fig. 13) 22% to the 0·472, 63% to the 0·880 and 15% to the 1·336 MeV level. These results are completely different from the reported 100% transition to the ground state (Walinga *et al.* 1969).

3·843 and 3·860 MeV Levels

The level at 3·843 MeV is populated from two resonances at $E_p = 1201$ and 2038 keV, and the level at 3·860 MeV is also populated from two resonances at $E_p = 1319$ and 2471 keV. Not all of the transitions from the two bound levels could be determined. Only a 40% transition from the level at 3·843 MeV to that at 0·844 MeV was found. The 3·860 MeV level decays 80% to the first excited state. The remaining 20% of the decay could not be established. The 3·860 MeV level has not been reported previously.

4·007 MeV Level

Only one resonance, that at $E_p = 2471$ keV, populates the level at 4·007 MeV. The level decays to four bound levels at 0·152, 0·472, 0·855 and 0·880 MeV with branching ratios of 30%, 15%, 30% and 25% respectively. The level has not been reported previously.

4·038 MeV Level

Two resonances at $E_p = 2523$ and 2643 keV populate the level at 4·038 MeV, which has not been reported previously. It decays (Fig. 13) 40% to the 0·472 and 60% to the 1·931 MeV level.

4·371 MeV Level

The 4·371 MeV level is populated from one resonance only, that at $E_p = 2643$ keV. It has five transitions (Fig. 1) of 11%, 41%, 20%, 13% and 15% to the levels at 0·880, 1·336, 1·407, 1·651 and 2·106 MeV respectively. The level was found to be populated for the first time via the proton capture reaction.

4·430 MeV Level

The 4·430 MeV level, which has not been reported previously, is populated from two resonances at $E_p = 2523$ and 2714 keV. It decays 30% to the 0·880, 30% to the 1·158 and 40% to the 1·179 MeV level respectively.

Table 6. Angular distribution data

Energies are in keV

Initial state Energy	Initial state Spin	Final state Energy	Final state Spin	A_2	A_4	δ (E2/M1)
7514	9/2	1931	9/2	$0·38 \pm 0·04$	$-0·14 \pm 0·04$	$-0·87 \pm 0·12$[A] $0·19 \pm 0·05$[A]
1931	9/2	880	5/2	$0·38 \pm 0·06$	$-0·30 \pm 0·06$	pure E2
7514	9/2	1931	9/2	$0·38 \pm 0·04$	$-0·14 \pm 0·04$	$-0·90 \pm 0·14$[B] $0·20 \pm 0·07$[B]
1931	9/2	1336	7/2	$-0·63 \pm 0·11$	$-0·01 \pm 0·12$	$0·14 \pm 0·06$[C]
7514	9/2	0	7/2	$-0·20 \pm 0·09$	$0·01 \pm 0·09$	$-0·05 \pm 0·07$
7514	9/2	4371	7/2	$0·28 \pm 0·05$	$-0·02 \pm 0·05$	$-0·31 \pm 0·06$
7514	9/2	3807	7/2	$-0·31 \pm 0·10$	$-0·18 \pm 0·10$	$0·05 \pm 0·06$
3807	7/2	880	5/2	$-0·36 \pm 0·09$	$0·11 \pm 0·10$	$0·00 \pm 0·10$[D]
7514	9/2	4038	7/2 9/2 11/2	$-0·22 \pm 0·12$	$0·04 \pm 0·13$	$-0·05 \pm 0·08$ $0·70 \pm 0·22$ $-0·02 \pm 0·11$

[A] Values obtained by simultaneously considering in the χ^2 analysis, the pure E2 transition 1931 → 880 keV (9/2 → 5/2).
[B] Same as remark A, but taking into account the 1931 → 1336 keV transition (9/2 → 7/2) with $\delta = 0·14$.
[C] Value taken from Ball *et al.* (1970).
[D] Same as remark A, but taking into account the 7514 → 3807 keV transition (9/2 → 7/2) with $\delta = 0·05$.

4·464 MeV Level

The resonance at $E_p = 2038$ keV populates the level at 4·464 MeV and it decays completely to the ground state. This agrees with the results of Walinga *et al.* (1969) except for the excitation energy.

5. Angular Distribution Measurements

The angular distributions have been measured at the $E_p = 2643$ keV resonance. Table 6 lists the corresponding A_2 and A_4 coefficients. A standard χ^2 program was used in the analysis of the angular distributions, together with the sign convention of Rose and Brink (1967) for the mixing ratio δ. Because only channel spin $s = \frac{1}{2}$ is possible, no formation parameters are involved. The 0·1% probability limit has been adopted to accept or reject a given solution.

If we consider the χ^2 analysis for the $7 \cdot 514 \rightarrow 1 \cdot 931$ and $7 \cdot 514 \rightarrow 0$ MeV transitions independently then the spin of the resonance can only be limited to the range from $J = 3/2$ to $9/2$. However, if we consider also the cascade $7 \cdot 514 \rightarrow 1 \cdot 931$ $(9/2^+) \rightarrow 0 \cdot 880$ $(5/2^+)$ MeV, it is possible to assign a $J = 9/2$ value to the $7 \cdot 514$ MeV level (Fig. 14). This has been done knowing that the $1 \cdot 931 \rightarrow 0 \cdot 880$ MeV is a pure E2 transition and neglecting, after estimation, the very small contribution in the corresponding angular distribution of the third γ ray of the cascades via the $2 \cdot 552$ and $4 \cdot 038$ MeV levels (Fig. 13). Two mixing ratio values are possible for the $7 \cdot 514 \rightarrow 1 \cdot 931$ MeV transition, as indicated in Table 6. It has been verified that the same δ values are obtained by considering the $7 \cdot 514 \rightarrow 1 \cdot 931 \rightarrow 1 \cdot 336$ MeV cascade, using $\delta = +0 \cdot 14$ for the $1 \cdot 931 \rightarrow 1 \cdot 336$ MeV transition as measured by Ball *et al.* (1970) (see Table 5).

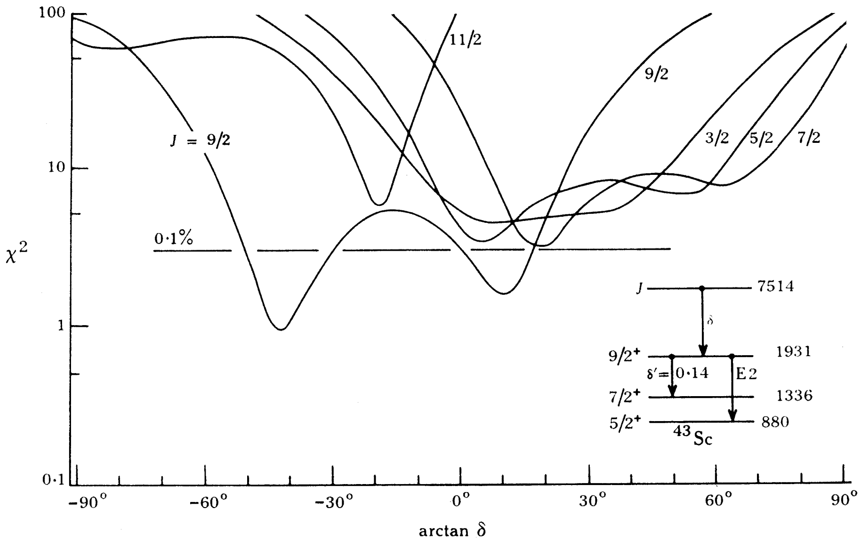


Fig. 14. Simultaneous χ^2 analysis of the $7 \cdot 514 \rightarrow 1 \cdot 931$ and $1 \cdot 931 \rightarrow 0 \cdot 880$ MeV cascade transitions, which correspond to the main γ ray decay of the $7 \cdot 514$ MeV level of ^{43}Sc. The curves obtained by considering the cascade $7 \cdot 514 \rightarrow 1 \cdot 931 \rightarrow 1 \cdot 336$ MeV are very similar. The $0 \cdot 1\%$ probability limit is indicated by the dashed line.

By taking then the spin value $J = 9/2$ for the $7 \cdot 514$ MeV level, it is possible to assign the spin values of the $4 \cdot 371$ and $3 \cdot 807$ MeV levels as $J = 7/2$, and to assign that for the $4 \cdot 038$ MeV level as $J \geqslant 7/2$. The corresponding mixing ratio values are indicated in Table 6.

6. Discussion

From the study of nine resonances, new information has been obtained on the energy levels and decay properties of the bound levels of ^{43}Sc. A summary of all results achieved in the present work is found in Tables 1–6, while the energies of excited levels in ^{43}Sc and the γ ray branching of all levels observed in the present investigation are presented in Fig. 1. All 52 bound levels up to an excitation energy of $4 \cdot 47$ MeV are populated from the nine resonances; 17 of these levels have been identified for the first time, namely those at $2 \cdot 114$, $2 \cdot 796$, $2 \cdot 846$, $2 \cdot 860$, $2 \cdot 875$, 3·160, 3·331, 3·374, 3·463, 3·503, 3·645, 3·734, 3·757, 3·860, 4·007, 4·038 and 4·430 MeV. Only two levels in the vicinity of 2·8 MeV have been reported previously, whereas in the present study four more excited levels have been established at 2·796, 2·846, 2·860 and 2·875 MeV. The level at 2·84 MeV was found to consist of two levels at 2·841 and 2·846 MeV when measured with better resolution. Similarly the closely spaced doublets at 3·328 and 3·331 MeV, and at 3·452 and 3·463 MeV have been determined.

The decay properties of most of the bound levels have been revised, either for the percentage branching ratios of transitions or for the number of transitions from the level. In some cases, both the number of transitions as well as the branching ratios have been revised. For the excited states above 2·8 MeV, the decay properties of most of the levels have been presented for the first time, except for a few levels whose previously reported decay properties have been subjected to revision. The significant changes in the decay schemes of most of the levels have been made possible by means of the 120 cm^3 Ge(Li) detector which had both high resolution and high efficiency. Also, the selection of the resonances which populated the levels with greater intensity, either from the primary or the primary and the cascades, contributed to the greater accuracy.

The measurement of the γ ray yield from the $^{42}Ca(p,\gamma)^{43}Sc$ reaction has been extended to 2·75 MeV from the previously reported range of 800–2060 keV. The present results were obtained with a ^{42}Ca target which was less than 1 keV thick. The excitation curve presented was from measurements repeated three times, each time the resonance peaks being reproduced at the same proton energy. Out of over 100 resonances, the stronger ones are well separated.

The experimental data in the case of eight resonances have shown that the bound levels populated from these resonances all have spin values of $<9/2$. It is only the resonance at 2643 keV which populates bound levels of spin from 5/2 to (11/2). The analysis from the angular distribution data leads to a $J = 9/2$ assignment for the 7·514 MeV level. The spin of the 1·158 MeV level was proposed as 3/2 or 5/2 by Ball *et al.* (1970). However, if we look at the 3% branch 7·514 → 1·158 MeV (Fig. 13), we see that an assignment of 5/2 for the 1·158 MeV level is more probable, as spin 3/2 corresponds to an octopole transition. For the two bound levels at 2·811 and 2·841 MeV, whose spin could not be determined because of poor intensities of the primary γ rays from the resonance, their spins can be limited to $>5/2$.

For the 7·514 MeV level, parity assignment can be made by considering the measured mixing ratio (Table 6). The value of $\delta \approx 0{\cdot}2$, obtained for the transition to the positive parity level at 1·931 MeV, and the value of $\delta \approx 0$, obtained for the transition to the negative parity ground state, strongly indicate a positive parity assignment for the resonance state. Consequently, the 4·371 MeV level will have positive parity and the 3·807 MeV level could have negative parity, even if the two corresponding mixing ratios (nearly zero, see Table 6) in the 7·514 → 3·807 → 0·880 MeV cascade do not allow us to reject a pure M1 transition.

The 59% branch 7·514 → 1·931 MeV (between these two levels we have $9/2^+ \rightarrow 9/2^+$) is most likely an analogue to anti-analogue transition. The $T = 3/2$ assumption for this resonance is supported by the fact that the decay scheme is quite simple (Fig. 13). The 7·514 MeV level should be the analogue of the ^{43}Ca level at 3·280 MeV based on Coulomb energy considerations. A state at 3·916 MeV in ^{43}Ca is assigned $l = 4$ and $J^\pi = 9/2^+$ from (d, p) work by Dorenbusch *et al.* (1966).

Manthuruthil *et al.* (1974), from proton elastic scattering data, found a resonance at $E_p = 3220$ keV which had $l = 4$, and they identified this resonance as the IAS of the 3·916 MeV state in ^{43}Ca. On the other hand, the same authors did not survey the proton bombarding the energy region from 2·52 to 2·70 MeV for the (p, p) reaction to verify if another resonance at $E_p = 2643$ keV had $l = 4$. In the present investigation for the (p, γ) reaction, it is possible that the resonance at $E_p = 2643$ keV may be the split analogue of the resonance at 3220 keV found by Manthuruthil *et al.* (1974). It will be of interest to measure the decay scheme and the angular distributions of the (p, γ) resonance at $E_p = 3220$ keV to compare the results with the resonance at $E_p = 2643$ keV. It has been observed in the ^{58}Ni(p, γ)^{59}Cu reaction that two resonances at $E_p = 2840$ and 3556 keV are possibly the split analogue (paper to be published).

The lowest mixing ratio value for the 7·514 → 1·931 MeV transition reported in Table 6, that is, $\delta = 0{\cdot}19 \pm 0{\cdot}05$, can be considered as the most probable solution, and is consistent with a strong M1 transition of the order of one Weisskopf unit. Johnstone (1968) and Johnstone and Payne (1969) explained the large δ values also observed, especially for the 0·880 → 0·151 and 1·158 → 0·151 MeV transitions, mainly in terms of M1 retardations rather than by E2 enhancement.

A summary of spin–parity assignments, the electromagnetic decay properties of all bound levels in ^{43}Sc, and the rotational band classification (if available) is presented in Fig. 1. The summary contains all results obtained in the present investigation as well as results for the spin–orbit assignments made by other investigators.

A large number of theoretical calculations with varying degrees of sophistication have attempted to describe the properties of the low-lying excited levels in ^{43}Sc. The spherical shell model calculations based on a closed ^{40}Ca core made by McCullen *et al.* (1964) allow particles only in the $f_{7/2}$ shell. Dieperink and Brussaard (1967) extended their calculations to include positive parity states by including a $1d_{3/2}$ hole state. Malik and Scholz (1966, 1967) and Scholz and Malik (1967) used a strong-coupling symmetric rotator model which included Coriolis coupling between bands. However, the most successful calculations are those of Johnstone (1968) and Johnstone and Payne (1969), which assumed that the low-lying negative parity levels arise from mixing pure (pf)^3 states with a $5p$–$2h$, $K^\pi = 3/2^-$ rotational band, and that the positive parity levels result from two $2p$–$1h$, $K^\pi = 1/2^+$ and $3/2^+$ bands.

Manthuruthil *et al.* (1970) made a detailed comparison of the theoretical predictions for all models with the experimental data available at that time. The pure (pf)^3 states and the members of the unperturbed $5p$–$2h$, $K^\pi = 3/2^-$ rotational band predicted from the calculations by Johnstone (1968) are in reasonable agreement with the experimental results for the low-energy excited states in ^{43}Sc. In order to account for the measured positive parity spectrum, however, it is necessary to reduce the theoretical gap between the $K^\pi = 3/2^+$ and $K^\pi = 1/2^+$ bands by decreasing the $d_{3/2}$–$s_{1/2}$ single-hole gap by approximately 1 MeV less than half the value deduced from the experimental ^{39}K and ^{39}Ca spectra.

Although most of the low-lying levels observed in ^{43}Sc can be associated with a given theoretical level, it is important to notice that a number of the levels observed above 2 MeV excitation (primarily with spin $\leqslant 7/2$) may result from core excitation configurations which are not included in Johnstone's (1968) calculations. The additional information obtained in the present study on the number of levels, the revised and new electromagnetic decay properties and the analogue to anti-analogue transition found at the $E_p = 2643$ keV resonance may stimulate additional theoretical calculations so as to completely determine the nature of these states.

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