Aust. J. Phys., 1978, **31**, 267–89

$^{18}O(p,\gamma)^{19}F$ and $^{18}O(p,p'\gamma)^{18}O$ Reactions below 3·50 MeV

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Abstract

The γ-ray decay schemes of resonance levels from the $^{18}O(p,\gamma)^{19}F$ reaction in the energy range E_p = 630–2260 keV and the angular distributions of the 1·98 MeV γ rays from inelastically scattered protons from ^{18}O in the energy range E_p = 3·00–3·50 MeV have been studied to obtain additional information on the properties of the resonant and bound levels of ^{19}F. Single γ-ray spectra have been measured using high resolution 40 and 120 cm^3 Ge(Li) detectors for the 10 resonances at E_p = 630, 850, 1169, 1400, 1620, 1770, 1933, 2010, 2175 and 2260 keV. A consistent decay scheme for the resonances and for the bound levels in ^{19}F has been derived. The present results lead to revised cascade branching ratios for the levels at 1·346, 1·459, 1·555, 3·908, 4·555 and 4·684 MeV. Two primary γ rays observed at the E_p = 1770 keV resonance correspond to the first two $T = 3/2$ states at 7·540 and 7·660 MeV. From the measurements of the angular distributions of the 1·98 MeV γ rays following the reaction $^{18}O(p,p'\gamma)^{19}F$, the spin and parity assignments made for the five resonances at E_p = 3·05, 3·17, 3·28, 3·39 and 3·49 MeV are respectively $5/2^+$, (5/2), $3/2^-$, $\geqslant 5/2$ and $5/2^+$.

1. Introduction

The present information available on ^{19}F levels has been obtained from studies of several different reactions. A number of authors have previously investigated proton capture with ^{18}O, although most of the measurements have been made with NaI crystals. Butler and Holmgren (1959) measured the yield from $^{18}O(p,\gamma)^{19}F$ for the proton energy range E_p = 600–1950 keV. They observed seven resonances and measured the γ-ray spectra with a 3 in. by 3 in. (7·6 cm square) NaI crystal. Nelson and Hudspeth (1962) extended the proton bombarding energy region from 2·0 to 3·0 MeV and investigated the γ-ray decay schemes to the three lowest energy levels of ^{19}F for six excited states from 8·56 to 10·10 MeV with a slow-coincidence technique. Allen *et al.* (1965) studied two resonances at 850 and 1169 keV using a gas target and a 5 in. by 5 in. (12·7 cm square) NaI spectrometer, while Wormald and Wright (1969, personal communication) reported the results of a study of three resonances at 1764, 1934 and 2260 keV with a 20 cm^3 Ge(Li) detector.

In work on other reactions, Prosser *et al.* (1967) studied $^{18}O(p,n)^{18}F$, $^{18}O(p,p'\gamma)^{18}O$ and $^{18}O(p,\alpha'\gamma)^{15}N$ from E_p = 2500 to 3000 keV by simultaneous observation of neutrons and 1·98 and 5·30 MeV γ rays; they assigned spins and parities to several resonances from measurements of the angular distributions of the 1·98 MeV γ rays. Din (1969), using a 40 cm^3 Ge(Li) detector, measured excitation functions from $^{18}O(p,p'\gamma)^{18}O$, $^{18}O(p,\alpha'\gamma)^{15}N$ and $^{18}O(p,n'\gamma)^{18}F$ by observing simultaneous yields of 0·940, 1·045, 1·080, 1·98 and 5·30 MeV γ rays from the decay of the excited states of the final nuclei as a function of proton energy from 3·0 to 7·0 MeV. The yield curves showed five resonances in the region of bombarding energy from 3·0 to 3·5 MeV. These were seen in all three channels.

Thomas *et al.* (1966) studied several excited states in ^{19}F from the reaction ^{19}F(p, p$'\gamma$)^{19}F, the γ-ray spectra being measured with a 12·7 cm by 15·2 cm NaI crystal. They reported values of branching ratios, spins and mixing ratios. Information on the ^{19}F levels was also obtained from studies of the ^{15}N(α, γ)^{19}F reaction by Aitken *et al.* (1969*a*, 1969*b*, 1970) and Rogers *et al.* (1972).

In the present study, measurements were made for 10 resonances below E_p = 2300 keV in the reaction ^{18}O(p, γ)^{19}F using higher resolution 40 and 120 cm^3 Ge(Li) detectors and an enriched ^{18}O target which was nearly contamination free. Also, from the reaction ^{18}O(p, p$'\gamma$)^{18}O angular distributions of the 1·98 MeV γ rays were measured for five resonances between E_p = 3·0 and 3·5 MeV. As the second excited state in ^{18}O is 3·5 MeV above the ground state, inelastically scattered protons below this energy can populate only the first excited state of ^{18}O.

2. Experimental Procedures

The proton beams for the study of the reaction ^{18}O(p, γ)^{19}F were obtained from the 2 MeV Van de Graaff accelerator at the Australian National University and the 3 MeV Van de Graff accelerator at the Accelerator Laboratory, University of Helsinki. A proton beam above 3 MeV for the reaction ^{18}O(p, p$'\gamma$)^{18}O was provided by the Australian National University EN tandem accelerator.

Two ^{18}O targets were used. The one for the reaction ^{18}O(p, p$'\gamma$)^{18}O was prepared by heating a tungsten disc 1·90 cm diameter by 0·05 cm thick in an induction heater in an atmosphere of oxygen enriched to 90% in ^{18}O. The other target for the ^{18}O(p, γ)^{19}F reaction was prepared by heating a tungsten metal strip 2·5 cm long, 1·3 cm wide and 0·02 cm thick in an atmosphere of oxygen enriched to 98% in ^{18}O. The thinner tungsten blank was chosen as a target backing to minimize ^{19}F and possibly other contamination. Both targets were water cooled.

The γ rays from the proton capture resonances were measured with two Ge(Li) detectors. The 40 cm^3 detector used at the ANU had a resolution of 2·4 keV for the ^{60}Co lines. The measurements of the three resonances at 1·169, 1·770 and 1·933 MeV were repeated at Helsinki with a 120 cm^3 Ge(Li) detector, which had a resolution of 1·93 keV at 1·33 MeV, 2·64 keV at 2·614 MeV, 4·42 keV at 6·6 MeV, and 5·05 keV at 7·6 MeV γ-ray energy. The peak to Compton ratio was 50 to 1 and the efficiency for the full energy peak at E_γ = 1·33 MeV was 23% relative to a 7·6 cm by 7·6 cm NaI crystal.

The γ-ray spectra at each resonance were stored in either a 2048- or 4096-channel analyser. The decay schemes of the resonances and the branching ratios were derived from γ-ray spectra measured at 55° to the beam direction. The relative intensities of the transitions were determined from the full energy and double-escape intensities in the spectrum. The efficiencies of the two detectors were determined with the ^{27}Al(p, γ)^{28}Si resonance at 992 keV as well as with a ^{56}Co radioactive source. The relative errors for the intensity calibration curves were 8% and 5% below and above 0·511 MeV respectively.

A 7·6 cm by 7·6 cm NaI crystal was used for the detection of the 1·98 MeV γ rays from the reaction ^{18}O(p, p$'\gamma$)^{18}O at five resonances. The front surface of the movable detector was placed 30 cm from the target. The target was at 45° to the beam direction. Another NaI crystal placed at the backward angle was used as a monitor to normalize the data. The spectra were analysed with a 4096-channel ADC, which was interfaced to a computer. A typical 1·98 MeV γ-ray spectrum measured at 3·49 MeV proton energy is shown in Fig. 12 below. The yield of γ rays was determined by integration of the area under the full energy peak in the spectrum after subtraction of the underlying Compton tail from high energy radiation. This was accomplished by a least-squares fit of the full energy peak to a gaussian shape. The angular distributions were measured at 15° intervals between 0° and 90°, and the measurements were repeated at 0° and 90° to check the consistency of the results. The agreement was good within statistical error.

A proton beam current of 0·1 A was employed for the measurement of the angular distributions of the 1·98 MeV γ rays from the inelastic scattering of protons from ^{18}O. For the measurement of the γ-ray spectra from the proton capture reaction, the proton beam current was kept below 10 μA to avoid deterioration of the ^{18}O target.

3. Results from Proton Capture Reaction

The γ-ray spectra from $^{18}O(p,\gamma)^{19}F$ measured at 10 resonances between $E_p = 630$ and 2260 keV are shown in Figs 1–10. Since the ^{18}O target had relatively little contamination, the intensities of the γ rays at 1·367, 1·632 and 6·129 MeV from the reactions $^{27}Al(p,\alpha\gamma)^{24}Mg$, $^{23}Na(p,\alpha'\gamma)^{20}Ne$ and $^{19}F(p,\alpha'\gamma)^{16}O$ were greatly reduced. The room background γ rays were at 1·460 MeV from ^{40}K and 2·614 MeV from ThC″.

Each γ-ray spectrum was accumulated for an average proton charge of 0·15 C, in order to obtain better statistics for the area under the peaks and to enhance the possibility of observing weak transitions. Some of the spectra were accumulated more than once with different Ge(Li) detectors as well as with different ^{18}O targets. Each time the spectrum reproduced the one measured previously. No decay schemes have been reported previously for the five resonances at $E_p = 1400$, 1620, 1770, 2010 and 2175 keV presented here. The total scheme for the 10 resonances is shown in Fig. 11.

(a) Decay Schemes of Resonances

630 keV Resonance ($E_x = 8\cdot590$ MeV)

For the resonance at $E_p = 630$ keV (Fig. 1) the primary transitions to the levels at 1·346, 1·555, 3·908 and 4·555 MeV were not observed in the previous measurements by Butler and Holmgren (1959). They reported that the γ-ray spectrum (NaI measurement) was complex but concluded that a reasonably strong γ ray of $8\cdot5 \pm 0\cdot2$ MeV represented transitions to the three lowest levels.

850 keV Resonance ($E_x = 8\cdot795$ MeV)

The resonance at $E_p = 850$ keV was studied by Butler and Holmgren (1959) and Allen *et al.* (1965), but their system resolutions using NaI detectors were clearly inadequate to resolve the primary transitions to the members of two triplets. The resonance level decays (Fig. 2) to all three members of the first triplet and to the two members of the second triplet at 1·459 and 1·555 MeV. The rest of the decay from the resonance level (22%) goes to the bound level at 3·908 MeV. The cascade

γ rays from the two levels at 1·459 and 1·555 MeV are shown at twice the dispersion per channel in the inset to Fig. 2. The two closely spaced γ rays at 1·350 and 1·358 MeV belong to the 1·459 $\rightarrow$ 0·109 and 1·555 $\rightarrow$ 0·197 MeV transitions respectively (see subsection (*b*) below).

1169 keV Resonance ($E_x = 9\cdot100$ *MeV*)

The present findings for this resonance differ, not only in the branching ratios but also in the number of transitions, from the results reported by Butler and Holmgren (1959) and Allen *et al.* (1965). There are 13 primary transitions from the resonance level, the strongest (44%) being to the bound level at 2·779 MeV. The four γ rays of energies 3·000, 3·480, 3·570 and 3·680 MeV with intensities of 9, 3, 1 and 13 % respectively have been assigned to the primary γ rays resulting from population of the bound levels at 6·100, 5·620, 5·530 and 5·420 MeV (Ajzenberg-Selove 1972).

1770 keV Resonance ($E_x = 9\cdot670$ *MeV*)

This resonance was also studied by Butler and Holmgren (1959) and Allen *et al.* (1965) with NaI detectors, but their conclusion was that the γ spectrum was complicated and it was difficult to determine a decay scheme. Subsequently Wormald and Wright (1969) measured the spectrum and the angular distributions of some of the γ rays with a 20 cm^3 Ge(Li) detector. The present findings (Fig. 6) are in general agreement with their results except for one primary transition to the bound level at 5·620 MeV. The two primary γ rays of 2·010 and 2·130 MeV come respectively from transitions to the bound levels at 7·660 and 7·540 MeV, which were reported by Aitken *et al.* (1969*b*) as strong isolated resonances in the $^{15}N(\alpha,\gamma)^{19}F$ reaction (see subsection (*b*) below). The γ rays at 2·835, 3·025 and 3·310 MeV could not be placed.

1933 keV Resonance ($E_x = 9\cdot825$ *MeV*)

Again this resonance was studied by Butler and Holmgren (1959) and Allen *et al.* (1965) and found to have a complicated decay scheme. Wormald and Wright (1969) also measured the γ-ray spectrum with their 20 cm^3 Ge(Li) detector but did not observe the weak primary transitions reported here (Fig. 7) to the ground state, the first excited state and the level at 5·620 MeV. A stronger 4·405 MeV γ ray as a primary from the resonance level indicates population of the bound level at 5·420 MeV (see subsection (*b*)).

2010 keV Resonance ($E_x = 9\cdot897$ *MeV*)

The proton capture resonance at 2010 keV (Fig. 8) has been studied for the first time here. This is the second of only two resonances (the other being at 1169 keV) which have a transition to the bound level at 2·779 MeV. There are eight transitions in all from this resonance level.

Figs 1–10 (pp. 271–80). Gamma ray spectra from $^{18}O(p,\gamma)^{19}F$ measured with a 40 cm^3 Ge(Li) detector at 55° to the beam direction for proton bombarding energies E_p between 630 and 2260 keV. (Portions of the spectra also taken with a 120 cm^3 detector are shown in Figs 3, 6 and 7.) Peaks are labelled by the corresponding γ-ray energies (in MeV), with asterisks and double asterisks indicating single-escape and double-escape peaks respectively.

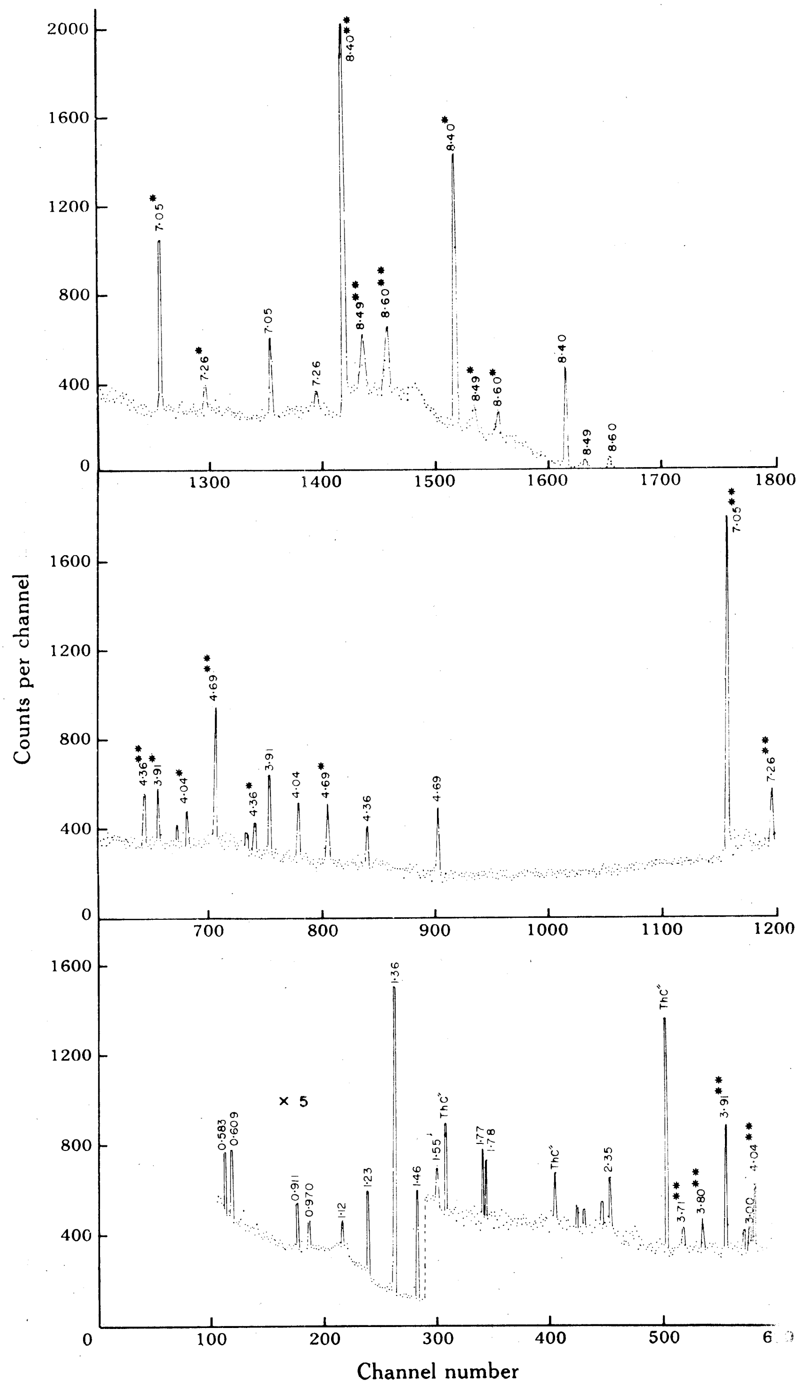

Fig. 1. $E_p = 630$ keV.

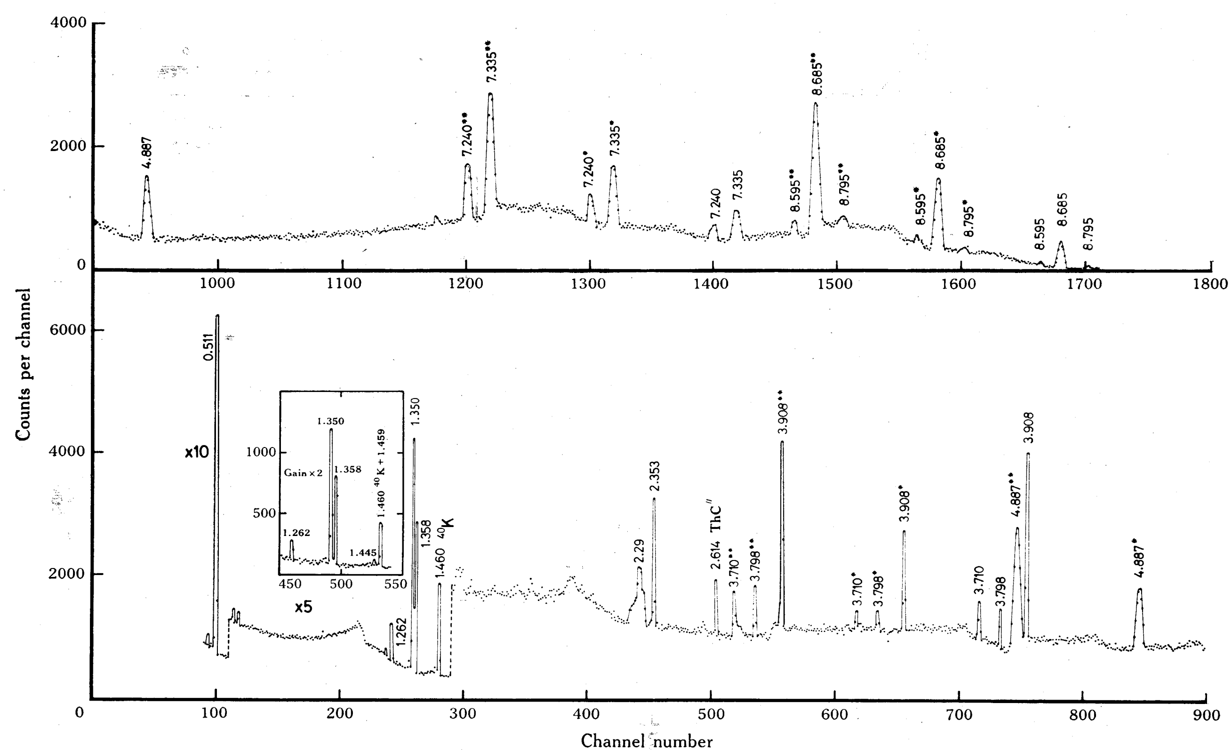

Fig. 2. $E_p = 850$ keV. The inset shows a low energy portion of the spectrum at double the amplifier gain to separate the decays of the $1 \cdot 459$ and $1 \cdot 555$ MeV levels.

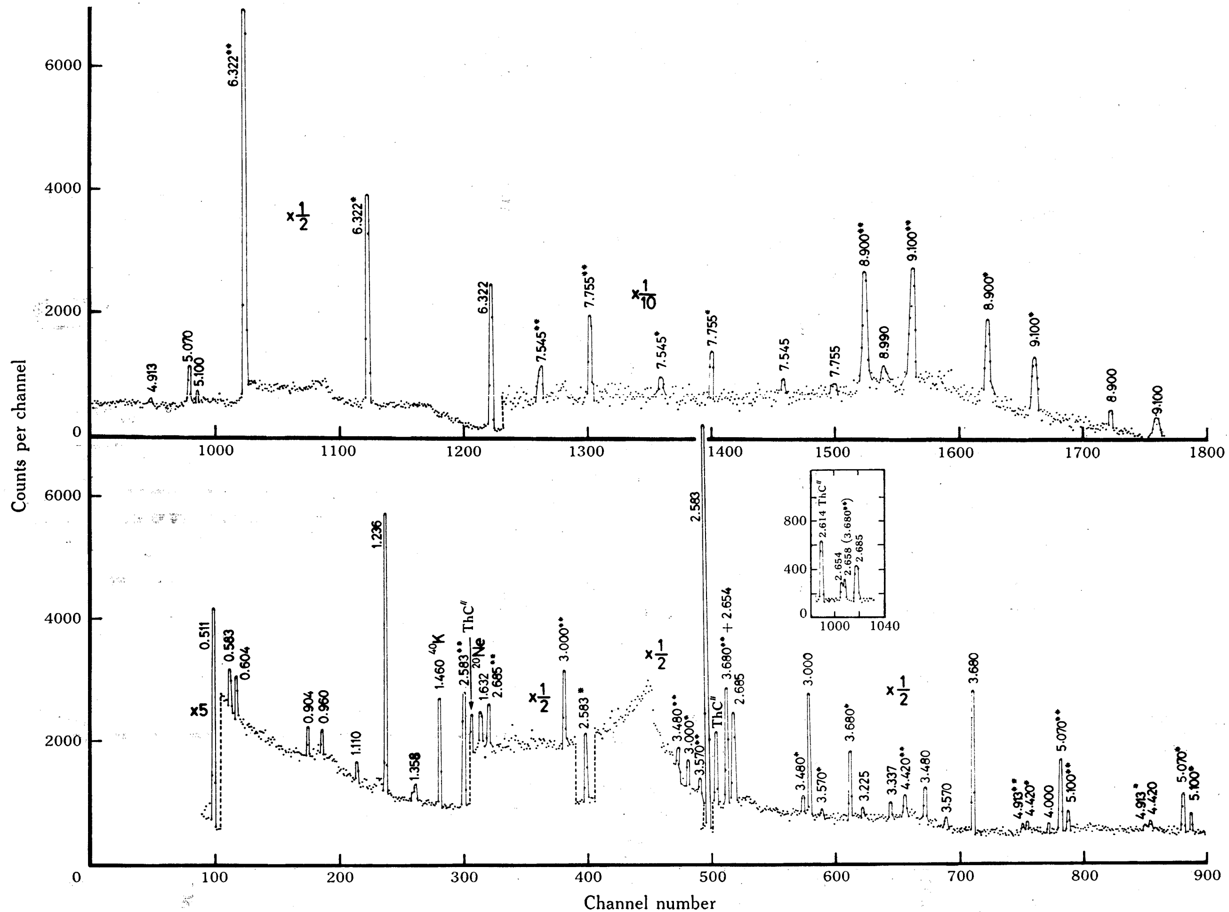

Fig. 3. E_p = 1169 keV. The inset shows a portion of the spectrum measured with a 120 cm^3 Ge(Li) detector to separate the 2·654 MeV γ ray from the 4·000→1·346 MeV decay and the 2·658 MeV double-escape peak of E_γ = 3·680 MeV.

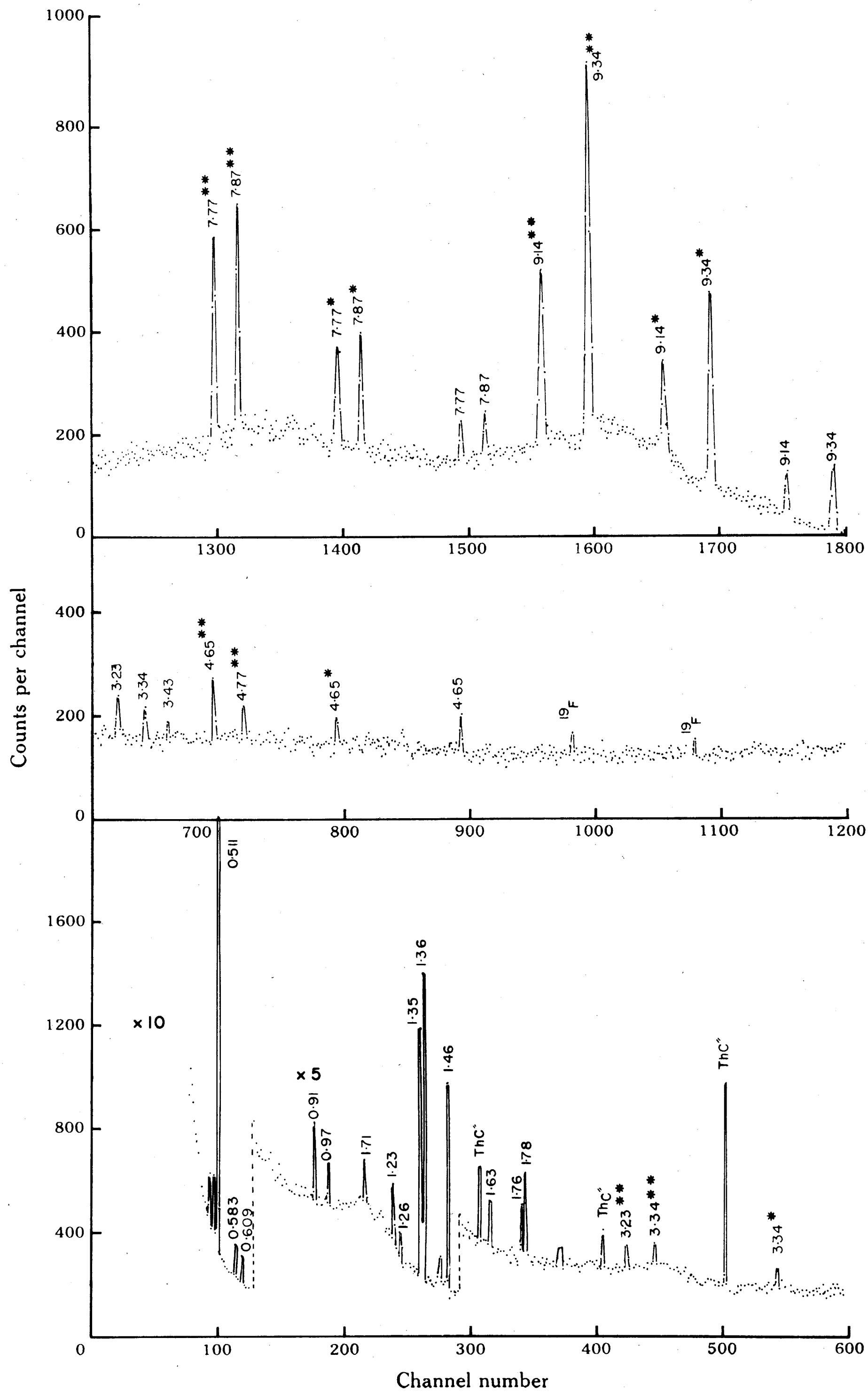

Fig. 4. $E_p = 1400$ keV.

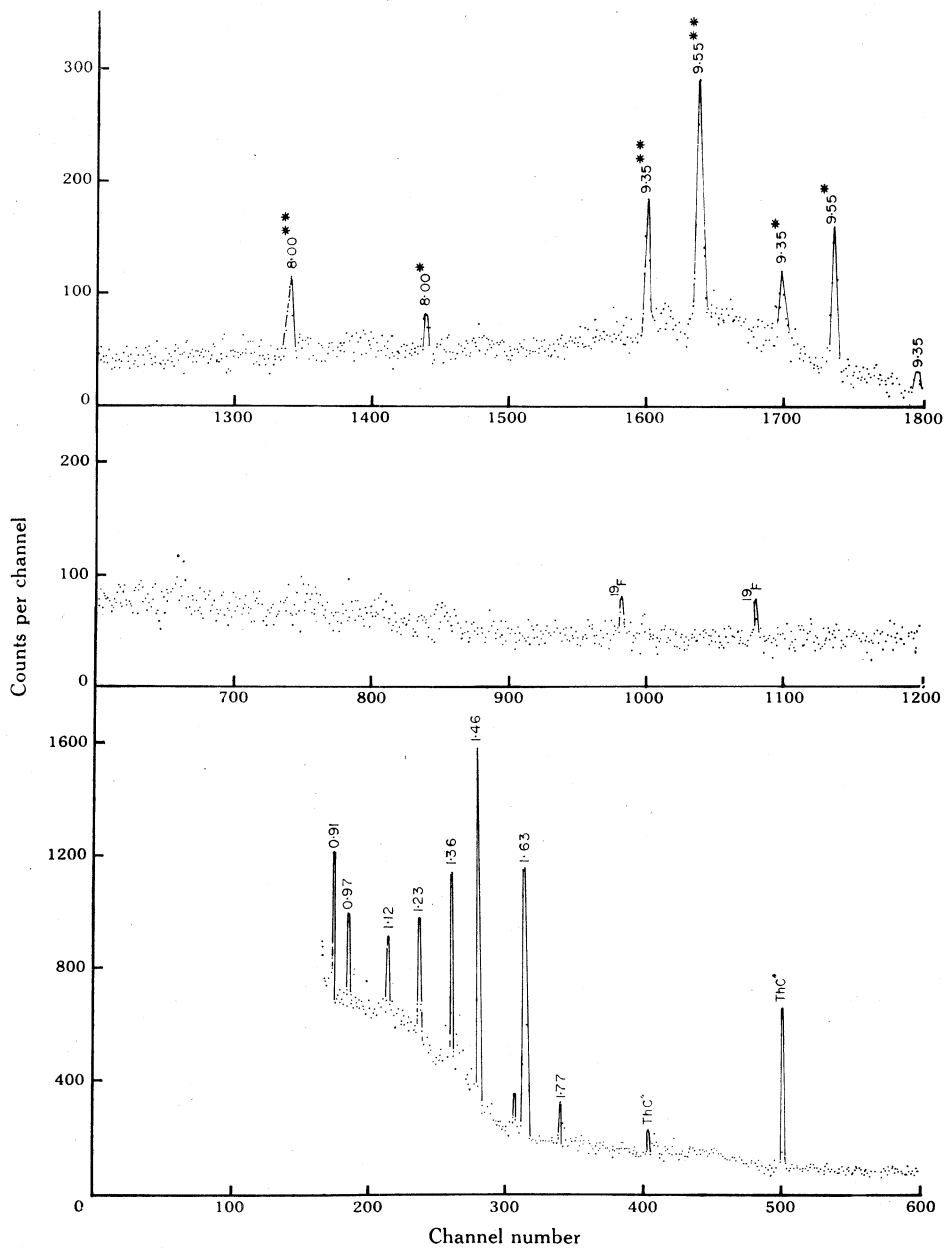

Fig. 5. $E_p = 1620$ keV.

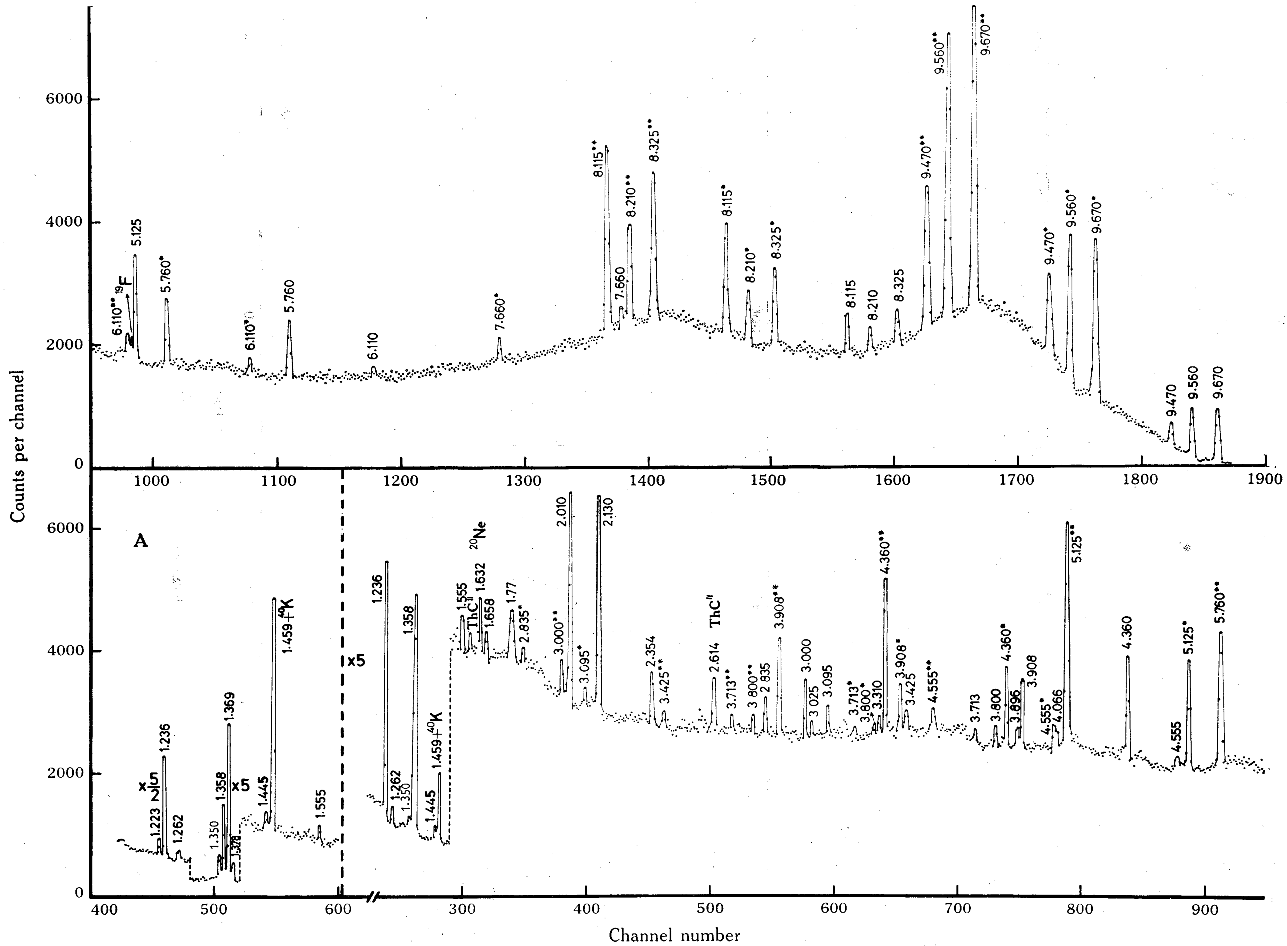

Fig. 6. $E_p = 1770$ keV. The portion A of the low energy spectrum was measured with a 120 cm³ Ge(Li) detector.

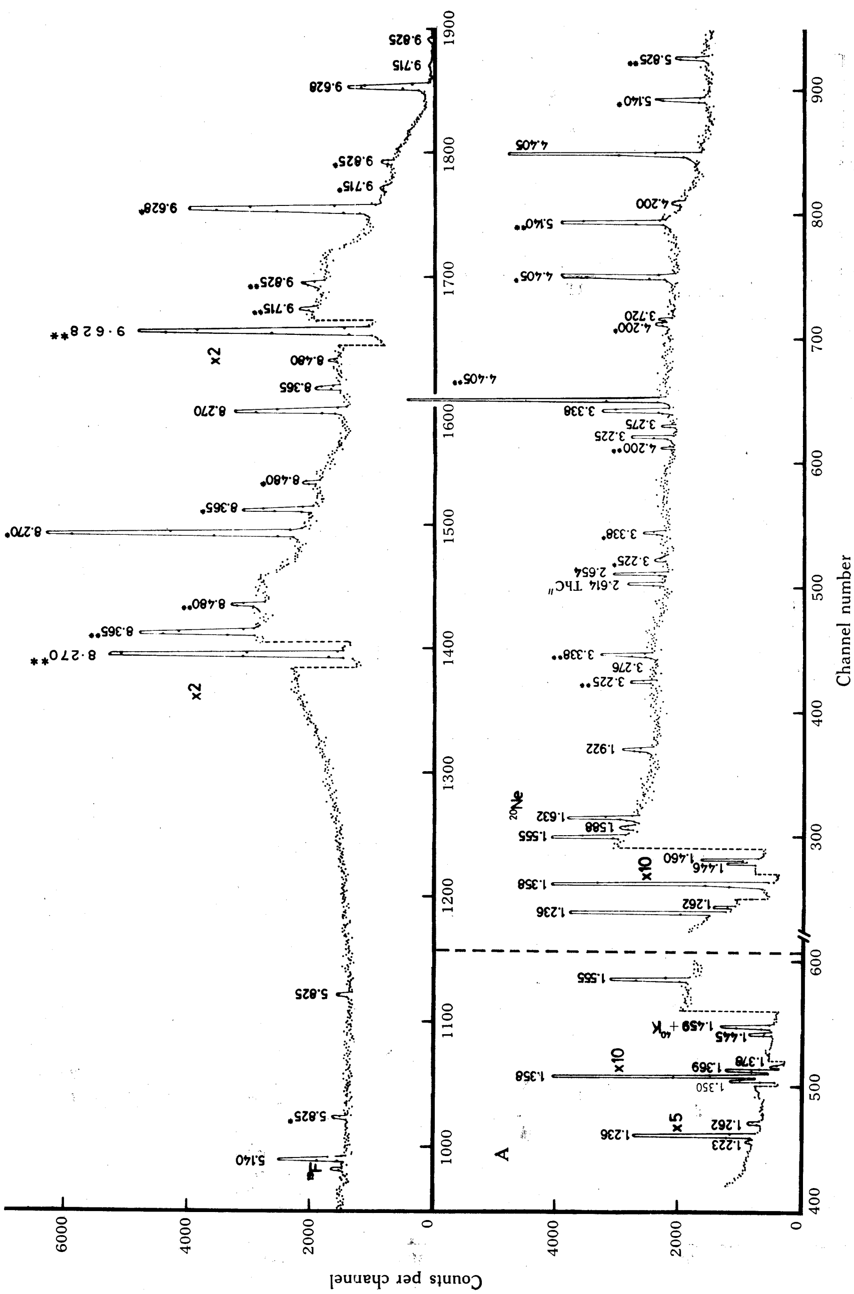

Fig. 7. $E_p = 1933$ keV. The portion A of the low energy spectrum was measured with a 120 cm^3 Ge(Li) detector.

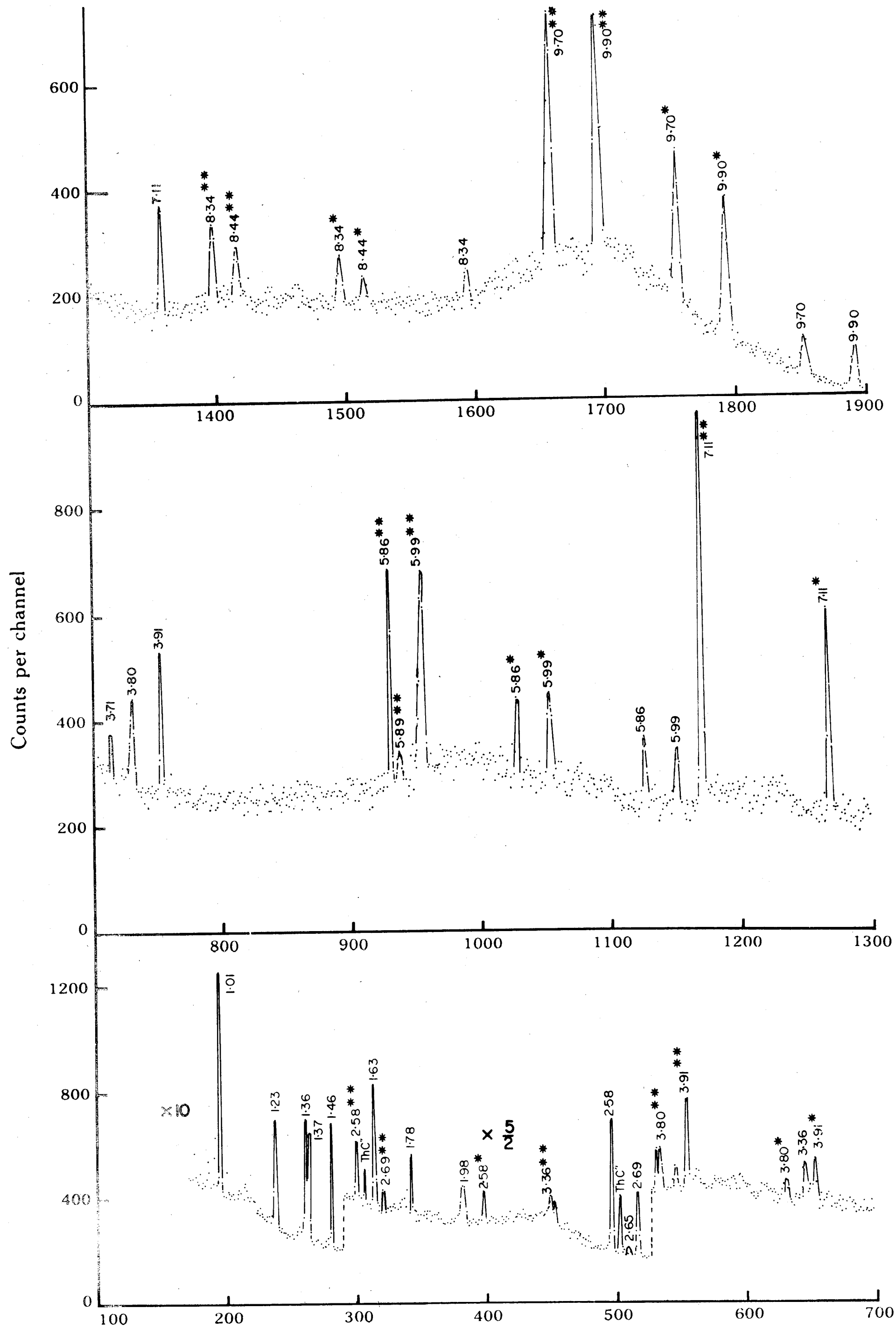

Fig. 8. $E_p = 2010$ keV.

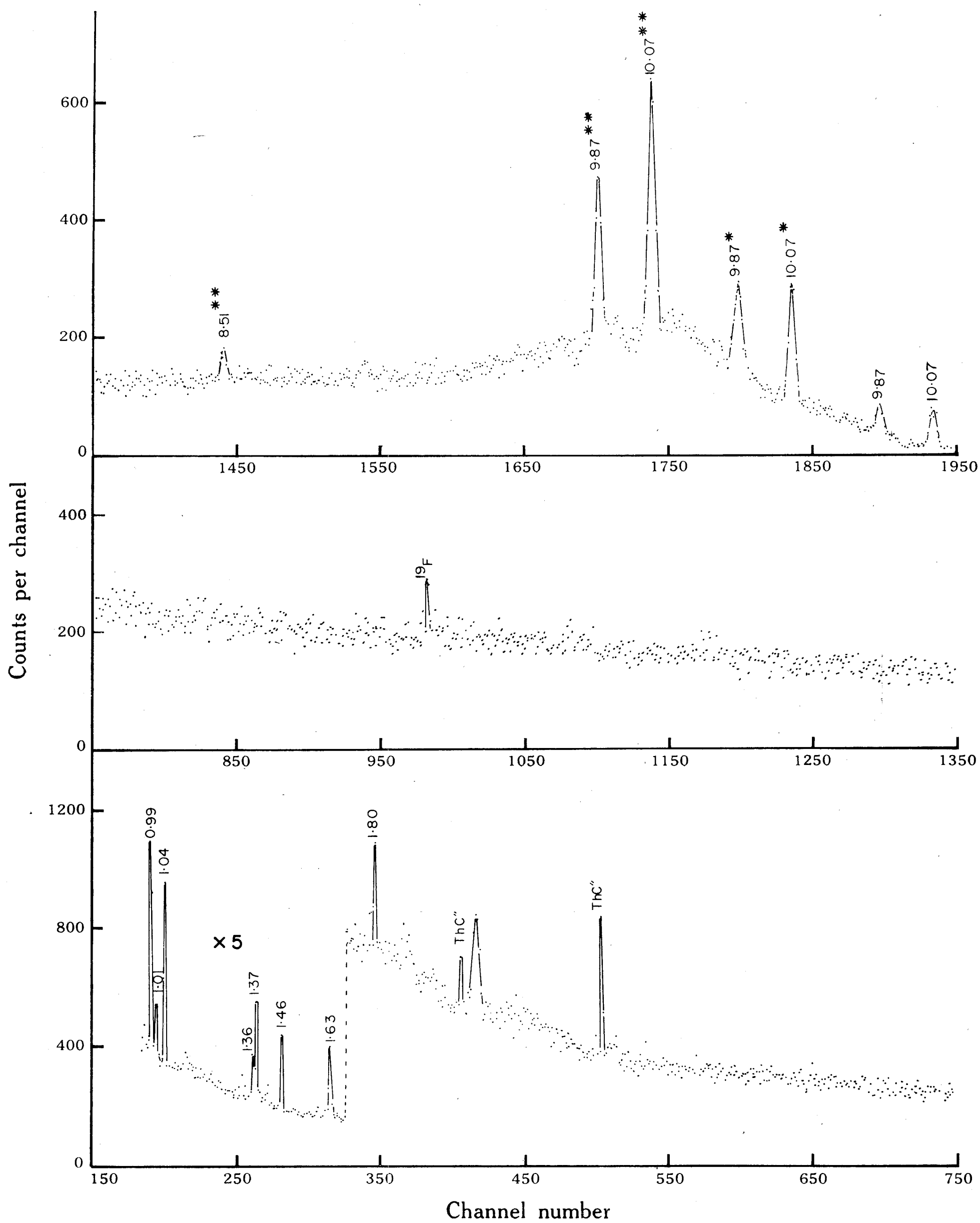

Fig. 9. $E_p = 2175$ keV.

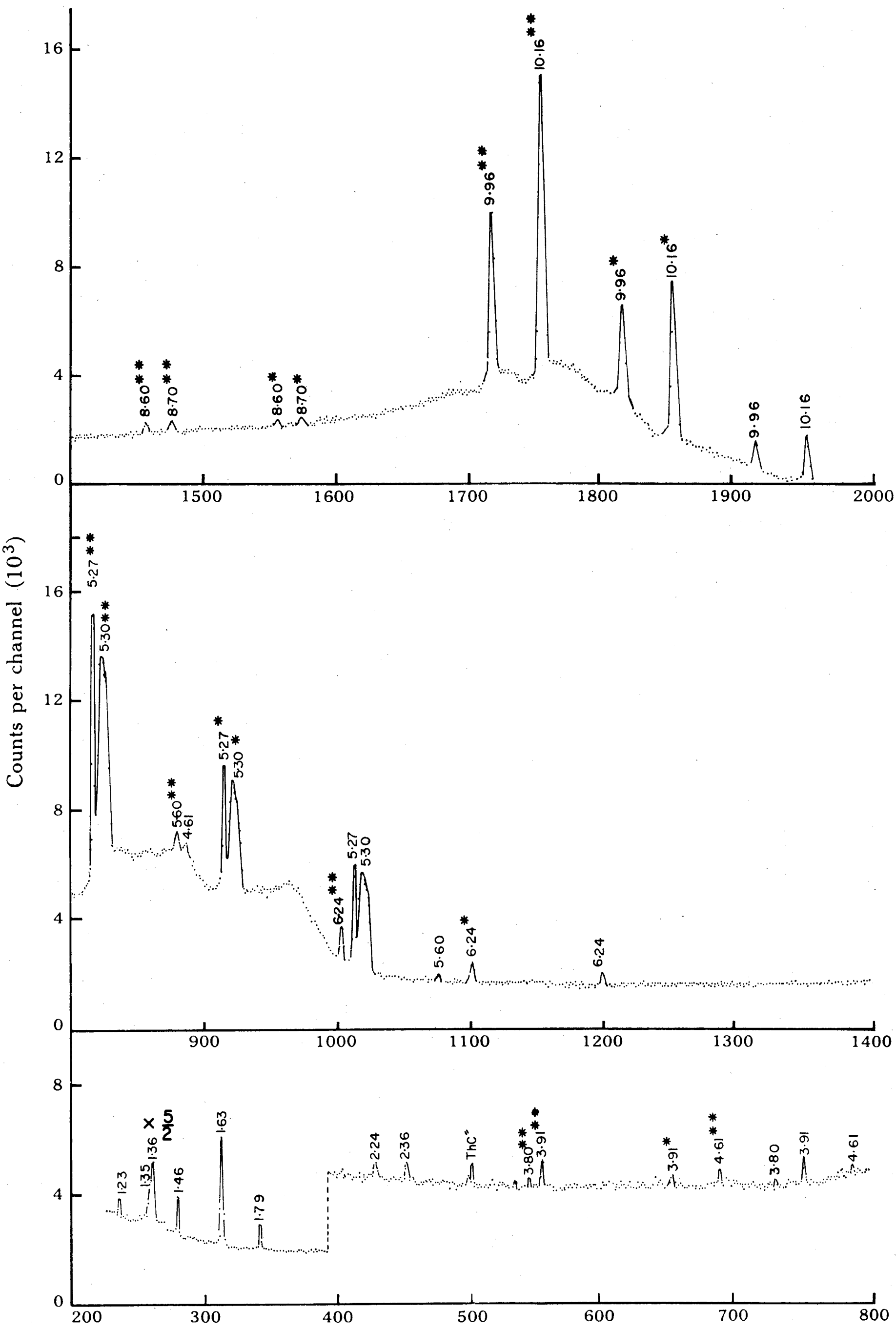

Fig. 10. $E_p = 2260$ keV.

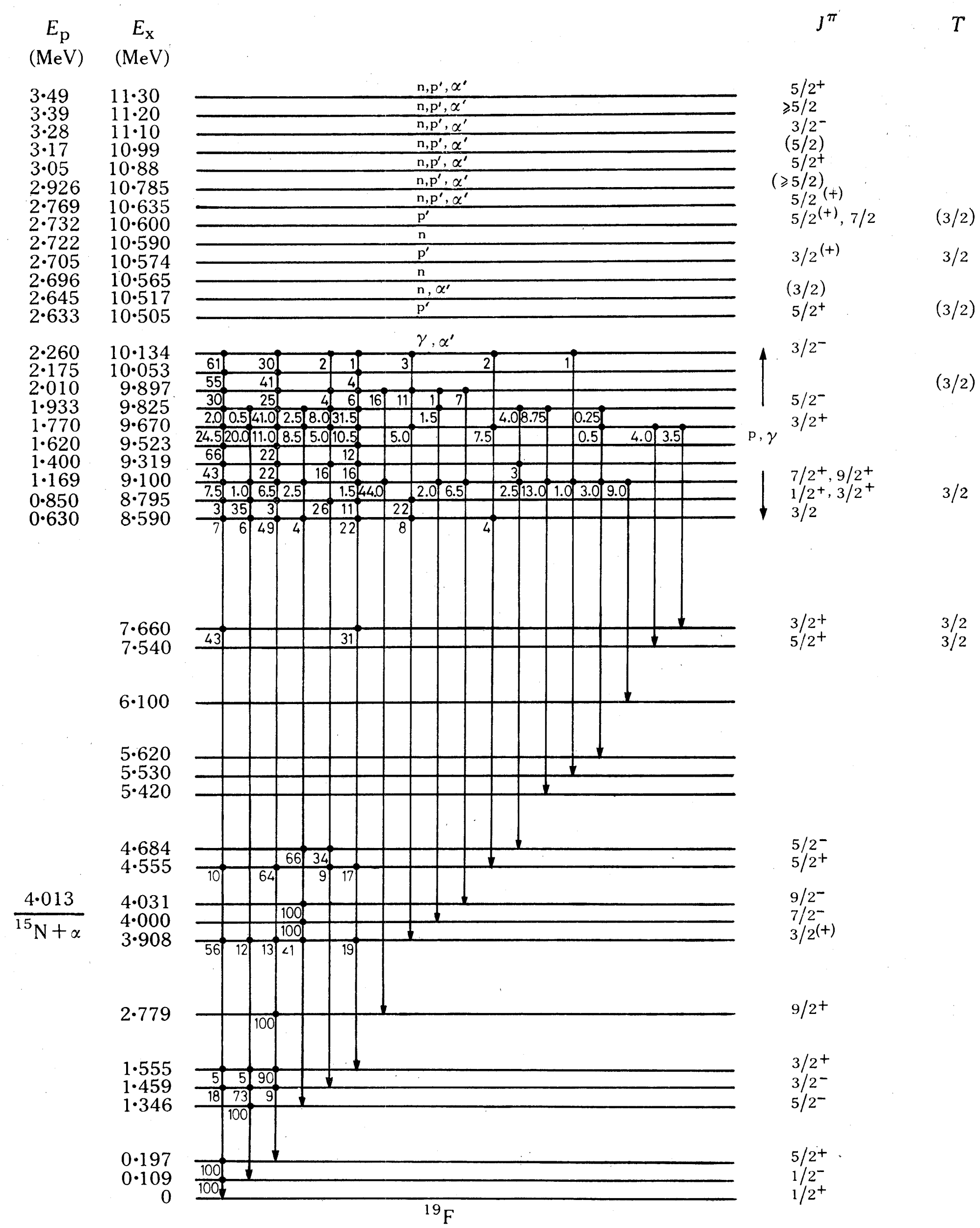

Fig. 11. Decay schemes and branching ratios of 10 (p, γ) resonances in ^{19}F and the bound states fed by these resonances. The spin and parity assignments of the resonance levels are from the present measurements of the angular distributions of the 1·98 MeV γ rays from the five inelastic scattering resonances above $E_p = 3 \cdot 00$ MeV. The levels reported by Prosser *et al.* (1967) are included in the figure. The spins and parities shown for all other levels are taken from the literature.

2260 keV Resonance (E_x = *10·134 MeV*)

This resonance (Fig. 10) has its strongest transition (61%) to the ground state and a 30% transition to the level at 0·197 MeV. The weaker transitions are to the levels at 1·459, 1·555, 3·908, 4·555 and 5·530 MeV. In the reported results of Wormald and Wright (1969), the transitions were to the ground state and the 0·197 and 3·908 MeV levels only. This is the first resonance which shows a decay to the first two excited states in ^{15}N from the reaction $^{18}O(p, \alpha'\gamma)^{15}N$ (Prosser *et al.* 1967; Din 1969). The decay to the level at 5·299 MeV is three times stronger than that to the level at 5·270 MeV.

Table 1. γ decay of bound states in ^{19}F

Level No.	E_x (MeV)	Transition levels	E_γ (MeV)	Branching (%)
0	0	Ground state		
1	0·109	1→0	0·109	100
2	0·197	2→0	0·197	100
3	1·346	3→1	1·237	100
4	1·459	4→0	1·459	18±4
		4→1	1·350	73±3
		4→2	1·262	9±2
5	1·555	5→0	1·555	5±1
		5→1	1·446	5±1
		5→2	1·358	90±2
6	2·779	6→2	2·582	100
7	3·908	7→0	3·908	56±2
		7→1	3·799	12±1
		7→2	3·711	13±2
		7→3	2·562	<1
		7→5	2·353	19±2
8	4·000	8→3	2·654	100
9	4·031	9→3	2·685	100
10	4·555	10→0	4·555	10±3
		10→2	4·358	64±3
		10→4	3·096	9±2
		10→5	3·000	17±2
11	4·684	11→3	3·338	66±3
		11→4	3·225	34±2
12	7·660	12→0	7·660	43±3
		12→5	6·105	31±5

(*b*) *Decay Schemes of Bound Levels*

Of the 10 resonances studied here, the 5 at E_p = 630, 850, 1169, 1770 and 1933 keV populated a number of bound levels with relatively stronger transitions and thus made it possible to obtain decay schemes and branching ratios. The values were determined using the primary γ-ray intensities and consequently the sum of the intensities of the secondary γ rays is not necessarily 100%. A brief discussion of the decay schemes of the bound levels is given below. The branching ratios of the cascades are listed in Table 1.

1·346, 1·459 and 1·555 MeV Triplet

In order to study in detail the cascades from these three bound levels, the γ-ray spectra for the resonances at $E_p = 1770$ and 1933 keV were also measured with the high resolution 120 cm^3 Ge(Li) detector. The spectra were stored in a 4096-channel analyser with a dispersion of 2·5 keV per channel. The resulting spectra for E_γ from 1·08 to 1·60 MeV for the two resonances are shown in the separate portions A of Figs 6 and 7. The same section of the spectrum for the resonance at $E_p = 850$ keV is shown in the inset to Fig. 2 with the amplifier gain doubled.

There can be three transitions with $E_\gamma = 1·346$, 1·237 and 1·149 MeV respectively in the decay of the 1·346 MeV level to the ground, first excited and second excited states. Only the 1·237 MeV γ ray was observed here, however. Although the γ ray at 1·346 MeV is very close in energy to the 1·350 MeV radiation from the transition 1·459 $\rightarrow$ 0·109 MeV, the spectra taken with the 120 cm^3 Ge(Li) detector should have shown at least a broad peak at 1·350 MeV if both γ rays had been present. It was therefore concluded that the level at 1·346 MeV decays completely to the first excited state at 0·109 MeV.

The level at 1·459 MeV was strongly populated by the 850 and 1933 keV resonances. Three γ rays of energies 1·459, 1·350 and 1·262 MeV were observed (Fig. 7) for the transitions to the ground, first excited and second excited states. The γ ray at 1·459 MeV, however, was overlapped by the room background radiation from ^{40}K, and the yield for the 1·459 $\rightarrow$ 0 MeV transition was obtained by subtracting this background from the total area under the peak. The relative intensities of the three transitions were found to be 18, 73 and 9 % respectively. The results are in general agreement with those reported previously (e.g. Ajzenberg-Selove 1972) except for minor differences in the branching ratios.

The three resonances at 850, 1770 and 1933 keV had relatively strong transitions to the level at 1·555 MeV. The cascade γ rays are shown in the A sections of Figs 6 and 7 and in the inset to Fig. 2. Transitions to the ground, first excited and second excited states were observed. The 1·358 MeV γ ray from the last transition is quite close to the energy of the transition (1·369 MeV) from the first excited state to the ground in ^{24}Mg which can arise from the contamination reaction $^{27}Al(p, \alpha)^{24}Mg$. The present results are in agreement with those reported previously except for the branching ratio of the transition to the ground state.

2·779 MeV Level

This level was populated by the 1169 and 2010 keV resonances, the transition from the former resonance being much stronger. The level decays completely to the second excited state with $E_\gamma = 2·582$ MeV.

3·908 MeV Level

This level was populated by five resonances but the strongest transition was from $E_p = 850$ keV (Fig. 2). Of the five decays of the bound level observed, four were to the lowest four levels, although the 2·562 MeV γ ray corresponding to the decay to the third excited state was extremely weak (<1 %). The remaining decay was to the 1·555 MeV state, leaving only two levels below 3·908 MeV that were not populated. The sum of the branching ratios agreed with the strength of the primary γ ray to the 3·908 MeV level. Identical results were obtained at the other resonances.

4·000 MeV Level

This level was fed by three resonances but none of the transitions were strong. A peak in the spectra at 2·654 MeV was observed, corresponding to the transition 4·000 → 1·346 MeV. This γ ray is well defined (Fig. 7) but is close to the 2·658 MeV double-escape peak of $E_\gamma = 3{\cdot}680$ MeV (Fig. 3 inset). No other decays for this level were observed.

4·031 MeV Level

The two resonances at 1169 and 2010 keV populated this level. There was a 100% decay to the 1·346 MeV level with $E_\gamma = 2{\cdot}685$ MeV.

4·555 MeV Level

Three resonances populated this level. The strongest transition was from $E_p = 1770$ keV. Four γ rays at 4·555, 4·358, 3·096 and 3·000 MeV were observed, corresponding to transitions to the ground state and the 0·197, 1·459 and 1·555 MeV levels. The relative intensities were 10, 64, 9 and 17 % respectively. Transitions to the levels at 0·109 and 1·346 MeV, as reported by Ajzenberg-Selove (1972), were not found.

4·684 MeV Level

The 1169, 1400 and 1933 keV resonances all had transitions to this level, but the strongest was from 1933 keV. Only two γ rays were observed, at 3·338 and 3·225 MeV, corresponding to transitions to the 1·346 and 1·459 MeV levels with branching ratios of 66 and 34 % respectively.

5·420 MeV Level

Peaks were observed at 3·680 and 4·405 MeV in the γ spectra for the 1169 and 1933 keV resonances respectively (Figs 3 and 7). These peaks indicate population of the 5·420 MeV level if they are taken to be primary γ rays from the transitions 9·100 → 5·420 and 9·825 → 5·420 MeV. The intensities of these transitions were 13 and 9 % respectively. However, there were no γ rays in the spectra which could be identified with the decay of the 5·420 MeV level. The existence of a level at 5·43 MeV with a 70% cascade to 1·35 MeV was reported by Aitken *et al.* (1970). The γ spectra for the 1169 and 1933 keV resonances in the present study do not show a peak at 4·08 MeV corresponding to a 5·420 → 1·346 MeV transition, and it must be concluded that either the 5·420 MeV level here is not the same as that found by Aitken *et al.* or their reported branching ratio is incorrect. The absence of a γ cascade could mean that this level is particle unstable, breaking up into $^{15}N+\alpha$.

5·530 MeV Level

This level was populated by the two resonances at 1169 and 2260 keV but the branching ratios could not be estimated because of the weakness of the transitions (<1 %) from the resonance states.

5·620 and 6·100 MeV Levels

Two γ rays at 3·480 and 3·000 MeV were observed in the spectra measured at the 1169 keV resonance (Fig. 3) which, when considered as primary rays from the resonance, indicate population of the levels at 5·620 and 6·100 MeV respectively.

The former level was also populated, though weakly, at both $E_p = 1770$ and 1933 keV. These two bound levels were reported by Aitken *et al.* (1970) from a study of $^{15}N(\alpha,\gamma)^{19}F$. They found a 66% transition 5·63 → 1·35 MeV and a 62% transition 6·10 → 0·11 MeV. No corresponding 4·28 and 5·99 MeV γ rays were observed in the present study (Fig. 3), although the intensities of the primaries were sufficiently strong to show these transitions had they occurred. In fact no decay scheme for either level could be deduced here, and once again there is the possibility that these levels represent unstable $^{15}N+\alpha$ states.

7·540 and 7·660 MeV Levels

These levels were populated only by the 1770 keV resonance, the primary γ rays being 2·130 and 2·010 MeV. No cascades were observed from the 7·540 MeV level. However, the spectra (Fig. 6) showed two peaks at 7·660 and 6·105 MeV which were taken to indicate transitions from the 7·660 MeV level to the ground state (43%) and to the level at 1·555 MeV (31%). Both the 7·540 and 7·660 MeV states were reported by Aitken *et al.* (1969*b*) from their study of the $^{15}N(\alpha,\gamma)^{19}F$ reaction. From two strong isolated resonances at $E_\alpha = 4·468$ and 4·622 MeV, they derived the following decay schemes: the 7·540 MeV level had three transitions to the levels at 0·198 (30%), 1·555 (42%) and 3·908 (28%) MeV; while the 7·660 MeV level also had three transitions, 43% to the ground state, 17% to the first excited state and 40% to the 1·555 MeV level. The weak population of both levels ($\leqslant 4$%) from only one resonance in the present study probably accounts for why these cascades were not observed here, since the efficiency of a Ge(Li) detector is much higher for low energy primary γ rays than for higher energy cascade rays. There is also the possibility that the level at 7·540 MeV observed here corresponds to the $E_\alpha = 4·49$ MeV resonance of 90 keV width ($E_x = 7·56$ MeV) reported by Aitken *et al.* (1969*b*).

4. Results from Inelastic Proton Scattering Reaction

(*a*) *Angular Distribution Data*

In previous work (Din 1969) the excitation functions for the $^{18}O(p,p'\gamma)^{18}O$, $^{18}O(p,\alpha'\gamma)^{15}N$ and $^{18}O(p,n'\gamma)^{18}F$ reactions were measured by simultaneously observing γ yields from the decay of the excited states of the final nuclei as a function of proton energy from 3·00 to 7·00 MeV. Five resonances were found in the p′, α′ and n′ channels below 3·50 MeV. In the present study the angular distributions of the 1·98 MeV γ from $^{18}O(p,p'\gamma)^{18}O$ have been measured at the peaks of resonances at $E_p = 3·05$, 3·17, 3·28, 3·39 and 3·49 MeV. The 1·98 MeV γ-ray spectrum at $E_p = 3·49$ MeV, which is typical of the results obtained, is shown in Fig. 12, while the angular distribution measurements at the five resonances are shown in Fig. 13. The values obtained for the Legendre polynomial coefficients of the least squares fits to the data, together with their standard deviations, are listed in Table 2, where small corrections for finite solid angle have been made.

(*b*) *Analysis and Assignments*

The spins and parities of the ground and first excited states of ^{18}O are 0^+ and 2^+, and the present angular distributions are now analysed to compare the measured values of the coefficients with those predicted for the inelastic scattering processes.

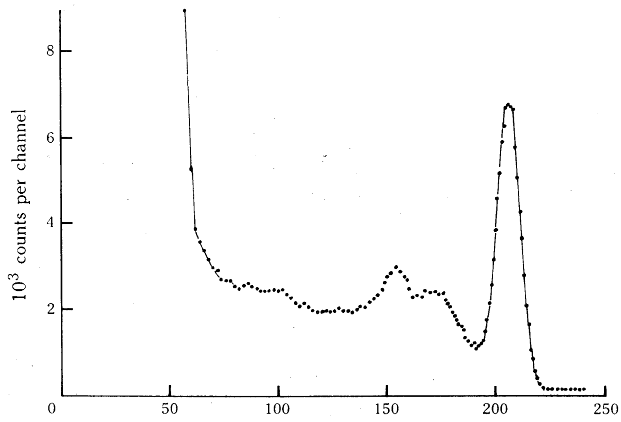

Fig. 12. Full energy peak of the $1 \cdot 98$ MeV γ ray from the reaction $^{18}O(p, p'\gamma)^{18}O$ at $E_p = 3 \cdot 49$ MeV. The pulse height spectrum was measured at 45° to the beam direction with a $7 \cdot 6$ cm by $7 \cdot 6$ cm NaI detector.

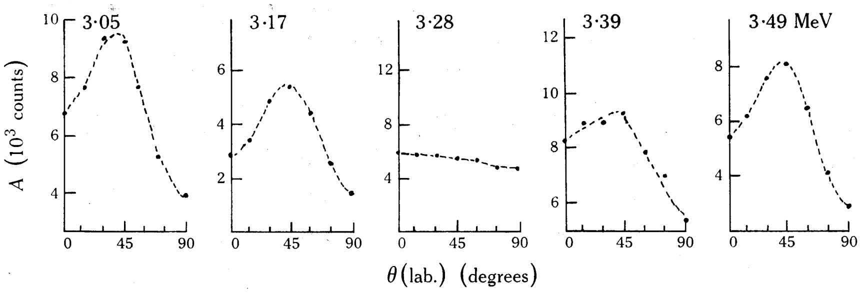

Fig. 13. Angular distributions of the $1 \cdot 98$ MeV γ rays at the five indicated resonances; A is the photopeak area. The dashed curves are least squares fits of Legendre polynomial series to the experimental points.

The theoretical expression for the angular distribution $W(\theta)$ of a two-stage particle reaction followed by γ emission is given by Sharp *et al.* (1954). In the present experiment, where the entrance channel has a unique channel spin of $\frac{1}{2}$ and sharp angular momentum determined by the spin and parity of the compound state, and the observed γ radiation must be pure E2, the expression for $W(\theta)$ becomes

$$W(\theta) = (-)^{L_{12}-\frac{1}{2}} Z(lj\,lj; \tfrac{1}{2}k)\, W(j2j2; L_{12}\,k)\, Z_1(2222; 0k)\, P_k(\cos\theta),$$

where Z, W and Z_1 are Reach and associated coefficients, l and j are the entrance channel orbital angular momentum and compound state spin and L_{12} is the total angular momentum $(l' \pm \frac{1}{2})$ of the emitted particle. The Z coefficients in this case are independent of l for the two permitted values $j \pm \frac{1}{2}$; hence the distributions are determined entirely by j and L_{12}. Also, L_{12} is restricted by the condition $|j-2| \leqslant L_{12} \leqslant |j+2|$. For the case of $l = 2$ and $l' = 0$, only one value of total angular momentum $L_{12} = \frac{1}{2}$ is possible. This gives

$$W(\theta) = P_0 + 0 \cdot 5\, P_2 \qquad \text{for} \quad j^\pi = 3/2^+$$

and

$$W(\theta) = P_0 + 0 \cdot 57\, P_2 - 0 \cdot 57\, P_4 \qquad \text{for} \quad j^\pi = 5/2^+ .$$

Table 2. Angular distribution data for 1·98 MeV γ ray from five inelastic scattering resonances

The coefficients were obtained from least squares fits of the integrated yield in the full energy peak to the expression
$W(\theta) = A_0\{1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta)\}$

Resonance energy (MeV)	A_0 (counts $(10^{-4}\,C)^{-1}$)	A_2	A_4
3·05	14236	0·50±0·02	−0·53±0·02
3·17	7455	0·53±0·01	−0·77±0·03
3·28	10420	0·17±0·01	−0·04±0·01
3·39	15450	0·34±0·04	−0·22±0·04
3·49	115922	0·54±0·01	−0·61±0·01

For $l = l' = 1$ and $j^\pi = 3/2^-$ for the compound state, two values of L_{12}, namely 1/2 and 3/2, are possible and one obtains

$$W(\theta) = a_{1/2}^2 W_{1/2} + a_{3/2}^2 W_{3/2},$$

where

$$W_{1/2} = P_0 + 0 \cdot 5 P_2, \qquad W_{3/2} = P_0, \qquad \text{with} \qquad a_{1/2}^2 + a_{3/2}^2 = 1.$$

The assignments made in the present investigation and from the results of Din (1969) are summarized in Table 3.

Table 3. Resonances in $^{18}O(p, p'\gamma)^{19}F$, $^{18}O(p, n'\gamma)^{18}F$ and $^{18}O(p, \alpha'\gamma)^{15}N$

E(lab.) (MeV)	E_x (MeV)	Decay channel	J^π	Lab. width (keV)
3·05	10·88	n, α′, p′	$5/2^+$	30
3·17	10·99	n, α′, p′	(5/2)	25
3·28	11·10	n, α′, p′	$3/2^-$	40
3·39	11·20	n, α′, p′	$\geqslant 5/2$	20
3·49	11·30	n, α′, p′	$5/2^+$	25

The angular distributions measured at the 3·05 and 3·49 MeV resonances agree well with the theoretical prediction for $l = 2$, $l' = 0$ and $j^\pi = 5/2^+$. On the other hand, the result for the weaker resonance at 3·17 MeV is not in very good agreement with the theoretical prediction for $j^\pi = 5/2^+$. The small departure from a pure $5/2^+$ angular distribution could be caused by several possible perturbations, e.g. the presence of a small undetected resonance or of a small amount of $l' = 2$ inelastic scattering. For the resonance at 3·28 MeV, the measured distribution agrees with the theoretical prediction for $l = l' = 1$ with $j^\pi = 3/2^-$. The presence of a small but definite $P_4(\cos\theta)$ term may be explained as due to interference from a $5/2^-$ channel spin or to a possible underlying resonance not discernible in the yield curve. The shape of the angular distribution for the 3·39 MeV resonance, unlike the other resonances, departs widely from any pure assignment, indicating either strong interference with neighbouring resonances or the presence of large contributions from higher angular momenta in the inelastic channel. The $P_4(\cos\theta)$ term, if attributable to this resonance, requires $j \geqslant 5/2$.

5. Conclusions

The present investigation of the (p, γ) and (p, p$'\gamma$) reactions has provided much further information on the excited levels of ^{19}F. The study of the 10 (p, γ) resonances with the 120 cm^3 high resolution and high efficiency Ge(Li) detector has helped to separate closely spaced γ rays and also to observe weak transitions. As a consequence, the branching ratios of the bound levels at 1·346, 1·459, 1·555, 2·779, 3·908, 4·000, 4·031, 4·555 and 4·684 MeV have either been confirmed or revised. The existence of levels at 5·420, 5·530, 5·620, 6·100, 7·540 and 7·660 has also been tentatively confirmed, although their cascade decays have mostly not been observed. The two resonances above 2·00 MeV proton bombarding energy at $E_p = 2 \cdot 010$ and 2·175 MeV are reported for the first time here. In addition, the angular distribution measurements of the 1·98 MeV γ ray from five resonances have made it possible to assign spins and parities to the excited states at 10·88, 10·99, 11·10, 11·20 and 11·30 MeV.

The characteristic which may be expected to identify most clearly the $T = 3/2$ states in ^{19}F is an absence of decay through the neutron and α particle channels, which both require $T = 1/2$. The two lowest $T = 3/2$ states in ^{19}F are at 7·540 ($5/2^+$) and 7·660 ($3/2^+$) MeV (Aitken *et al.* 1969*a*, 1969*b*; see Section 3*b* above), and these correspond to the ground state ($5/2^+$) and first excited state ($3/2^+$) in ^{19}O. The next $T = 3/2$ states would be expected to correspond to ^{19}O states at $E_p = 9 \cdot 011$ ($E_x = 1 \cdot 417$), 9·911 (2·371), 10·607 (3·067) and 10·694 (3·154) MeV. The 850 keV resonance in the (p, γ) reaction ($E_x = 8 \cdot 795$ MeV) could possibly correspond to the 1·417 ($1/2^+$) MeV level in ^{19}O, as it is still unresolved whether the spin of the 8·795 MeV level is $1/2^+$ or $3/2^+$. The next excited state in ^{19}O is at 2·371 MeV (9/2), and the resonance at 2·010 MeV ($E_x = 9 \cdot 897$ MeV) can be considered as a likely candidate. Its spin is not known, but it has a transition to the level at 2·779 MeV ($9/2^+$). There is a possibility that the two levels at 9·897 and 9·100 MeV are split analogues of the 2·371 MeV level in ^{19}O, even though there is nearly an 800 keV displacement between the levels. A similar case has been observed by the author for the ^{58}Ni(p, γ)^{59}Cu reaction (to be published). The next $T = 3/2$ state in ^{19}F at 10·574 MeV ($3/2^+$) was proposed by Prosser *et al.* (1967) to correspond to the 3·067 MeV ($3/2^+$) level in ^{19}O. This level generally fulfills the above criterion in that it almost completely decays by inelastic proton scattering. There is some very weak α particle decay to the ground state of ^{15}N but this can be assumed to be due to isobaric impurity in the compound states. The levels at 10·505 and 10·600 MeV in ^{19}F were identified by Prosser *et al.* as a split $T = 3/2$ analogue of the 3·154 MeV ($5/2^+$) level in ^{19}O.

The properties of the ^{19}F nucleus have been described by both collective and independent particle models (Elliott and Flowers 1955; Paul 1957; Chi and Davidson 1963; Benson and Flowers 1969) and it is hoped that the further experimental information provided by the present study will help to explore the regions of validity of the different descriptions.

Acknowledgments

The author gratefully acknowledges the assistance afforded by Mr M. A. Awal in recording the data for the (p, γ) reaction. Dr T. R. Ophel is thanked for his assistance in calculating the coefficients and for helpful discussions. Dr Asko Antilla is also thanked for providing the research facilities at the Accelerator Laboratory, University of Helsinki, to carry out the research work during the summer of 1975. Finally, the author is indebted to Professor Sir Ernest Titterton for his interest and constant support during the experiment at ANU.

References

Aitken, J. H., Allen, K. W., Azuma, R. E., Litherland, A. E., and Rogers, D. W. O. (1969*a*). *Phys. Lett.* B **28**, 653.

Aitken, J. H., Azuma, R. E., Litherland, A. E., Charlesworth, A. M., Rogers, D. W. O., and Simpson, J. J. (1970). *Can. J. Phys.* **48**, 1617.

Aitken, J. H., Litherland, A. E., Dixon, W. R., and Storey, R. S. (1969*b*). *Phys. Lett.* **B 30**, 473.

Ajzenberg-Selove, F. (1972). *Nucl. Phys.* A **190**, 1.

Allen, J. P., Howard, A. J., Bromley, D. A., and Olness, J. W. (1965). *Phys. Rev.* B **140**, 1245.

Benson, H. G., and Flowers, B. H. (1969). *Nucl. Phys.* A **126**, 305.

Butler, J. W., and Holmgren, H. D. (1959). *Phys. Rev.* **116**, 1485.

Chi, B. E., and Davidson, J. P. (1963). *Phys. Rev.* **131**, 366.

Din, G. U. (1969). *Nucl. Phys.* A **134**, 655.

Elliott, J. P., and Flowers, B. H. (1955). *Proc. R. Soc. London* A **229**, 536.

Nelson, J. W., and Hudspeth, E. L. (1962). *Phys. Rev.* **125**, 301.

Paul, E. B. (1957). *Philos. Mag.* **2**, 311.

Prosser, F. W., Jr, Din, G. U., and Tolbert, D. D. (1967). *Phys. Rev.* **157**, 779.

Rogers, D. W. O., Beukens, R. P., and Diamond, W. T. (1972). *Can. J. Phys.* **50**, 2428.

Sharp, W. T., Kennedy, J. M., Sears, B. J., and Hyle, M. G. (1954). Atomic Energy of Canada Ltd Rep. No. AECL–97.

Thomas, M. F., Lopes, J. S., Ollerhead, R. W., Poletti, A. R., and Warburton, E. K. (1966). *Nucl. Phys.* **298**, 318.

Wormald, M. R., and Wright, I. F. (1969). Proc. Int. Conf. on Properties of Nuclear States, p. 691 (Montreal Univ. Press).

Manuscript received 1 February 1977, revised 30 December 1977