

GAMMA-RAY BRANCHINGS IN ^{34}Cl FROM THE $^{33}\text{S}(p, ^{34}\text{Cl} \gamma)$ REACTION

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Abstract: The gamma-ray yield from the reaction $^{33}\text{S}(p, \gamma)^{34}\text{Cl}$ was measured in the range $E_p = 300\text{--}1300$ keV. Twenty-two resonances were observed with resonance strengths $(2J_r + 1)\Gamma_p\Gamma_\gamma/\Gamma$ between 0.01 and 1.0 eV.

From single and coincidence spectra with scintillation spectrometers the gamma-ray branchings of the resonance levels and of nineteen lower levels in ^{34}Cl were obtained.

The decay of the levels of ^{34}Cl below 2.5 MeV is compared with spin predictions from the shell model.

NUCLEAR REACTION $^{33}\text{S}(p, \gamma)$, $E_p = 0.3\text{--}1.3$ MeV; measured $\sigma(E)$, γ -spectra, $\gamma\gamma$ -coin. ^{34}Cl deduced levels, resonance strengths. Enriched target.

1. Introduction

The $^{33}\text{S}(p, \gamma)^{34}\text{Cl}$ reaction was investigated to obtain information about the decay of lower levels in ^{34}Cl . These levels are of theoretical interest ¹). The excitation energies of ^{34}Cl levels up to 4.15 MeV were known from an investigation of the $^{32}\text{S}(^3\text{He}, p)^{34}\text{Cl}$ reaction by Hinds and Middleton ²). They also found some uncertain levels between 4.5 and 5 MeV.

The main part of this work was carried out with a 850 kV Cockcroft-Walton generator. The low natural abundance of the ^{33}S isotope (0.75%) caused a serious difficulty to obtain good targets. Only two resonances were known from earlier work ³) in the region below $E_p = 850$ keV. In the investigation described in this paper ten resonances were found, from which the branching of sixteen lower levels could be deduced. The results are presented in sect. 3.

With a 3 MV Van de Graaff generator a resonance curve was measured for $E_p = 820\text{--}1300$ keV. Twelve ^{33}S resonances were found in the region above $E_p = 850$ keV, of which two were known from earlier work ⁴). The main decay of the resonance levels was determined. The branching ratios of the excited lower levels proved to be in agreement with the values obtained at the resonances below 850 keV, while moreover the decay of three other lower levels could be obtained.

2. Experimental Technique

Targets were prepared by evaporation in vacuo of CdS (isotopic abundance 74% ^{32}S , 22% ^{33}S and 4% ^{34}S) onto copper or tantalum backings. The enriched

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material was obtained from Oak Ridge National Laboratory, U.S.A. To reduce waste of target material in the evaporation procedure, the following simple method was used. A small tantalum tube (length 20 mm, diameter 4 mm) filled with one or two mg CdS was heated indirectly by a surrounding 50 μm thick tantalum foil (see fig. 1). The tube was placed on tungsten wires to reduce the heat conduction. A current of 30 A through the foil produced enough heat to evaporate the CdS. The backing was placed at a distance of 2 cm from the tube. Using this method three targets could be made per mg CdS. These have a circular, sufficiently homogeneous CdS spot of 15 mm^2 ; the thickness is about 5 keV at $E_p = 500$ keV. The maximum beam power on the targets was kept below 12 W with a beam spot of 6 mm^2 .

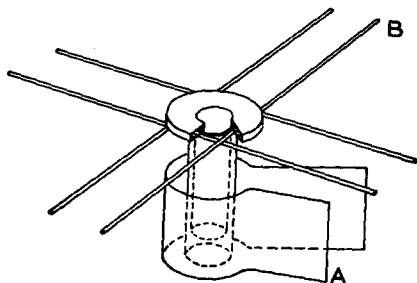


Fig. 1. Arrangement for evaporation of very small quantities of target material. The tantalum tube is surrounded by a thin tantalum foil A for indirect heating and supported by tungsten wires B.

The CdS target material proved to be contaminated with chlorine. The chlorine, however, evaporates at a somewhat lower temperature than CdS. By increasing the temperature of the target material in the tantalum tube very slowly, a rather good separation of chlorine and sulphur could be obtained.

The field of the 90° analysing magnets was measured with a proton resonance fluxmeter. It served as a measure for the energy of the incident protons.

Single γ -ray spectra were taken with a cylindrical NaI crystal, length 10.2 cm and diameter 10.2 cm, at an angle of 55° to the proton beam and a distance of 2 cm between target and crystal. The spectra were recorded on a RIDL 400-channel analyser. Background spectra were taken at a proton energy just below the resonance energy.

Coincidence spectra were measured with an additional 10.2 cm \times 10.2 cm crystal. The crystals were put at angles of +85° and -85°, respectively, to the proton beam, at a distance of 4 cm between target and crystal.

3. The $E_p = 300\text{--}850$ keV Region

3.1. RESONANCE ENERGIES AND YIELDS

In fig. 2 a γ -ray yield curve with discriminator channels of 3.1-6.2 MeV and 6.2-12 MeV is shown for the $E_p = 300\text{--}850$ keV region. The proton energy was determined by calibration of the fluxmeter with the $E_p = 632.3 \pm 0.3$ keV resonance of the $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ reaction.

Resonances in the highest channel can not be assigned to the $^{33}\text{S}(\text{p}, \gamma)^{34}\text{Cl}$ reaction, since the Q value is 5.12 MeV. These could be ascribed, however, to known ^{34}S and ^{13}C resonances. The resonances due to ^{19}F and ^{15}N are also indicated. The ^{33}S resonances were identified by analysis of the spectra obtained at the resonances (see subject. 3.2).

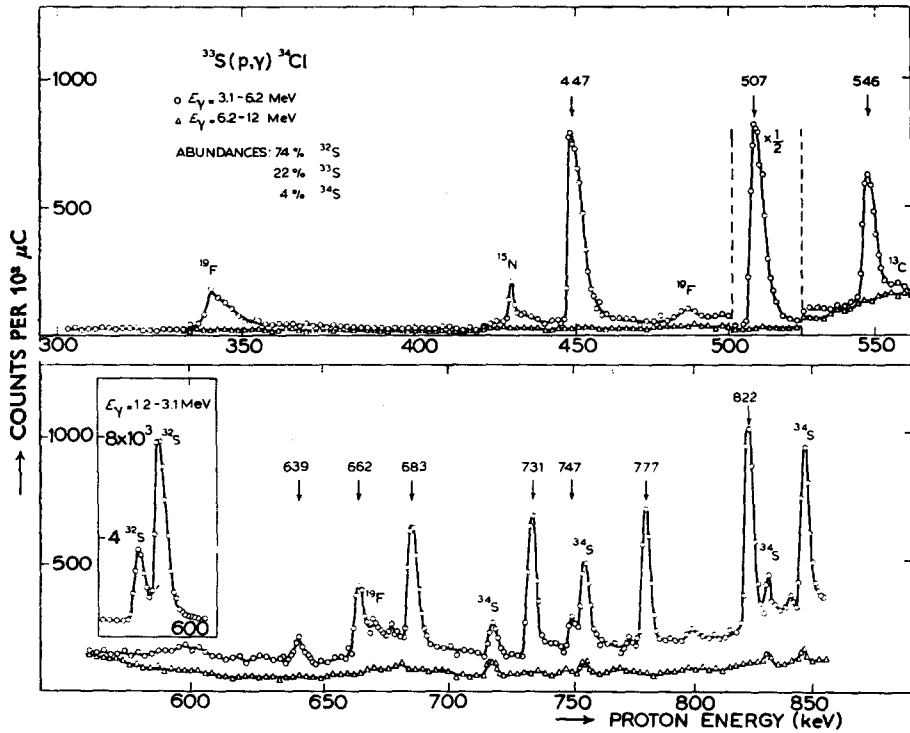


Fig. 2. Yield of the $^{33}\text{S}(\text{p}, \gamma)^{34}\text{Cl}$ reaction in the $E_p = 300\text{--}850$ keV region. Target CdS, distance target to crystal 2 cm, $\theta = 55^\circ$. The ^{33}S resonances are indicated by their proton energy. The energy scale is linear in $E \pm$.

TABLE 1
Energies and strengths of $^{33}\text{S}(\text{p}, \gamma)^{34}\text{Cl}$ resonances ($E_p < 850$ keV)

$E_p(\text{keV})$ all ± 1 keV	$(2J_r + 1) \Gamma_p \Gamma_\gamma / \Gamma(\text{eV})$ all $\pm 50\%$ ^{a)}	$E_p(\text{keV})$ all ± 1 keV	$(2J_r + 1) \Gamma_p \Gamma_\gamma / \Gamma(\text{eV})$ all $\pm 50\%$ ^{a)}
447	0.08	683	0.05
507	0.16	731	0.05
546	0.040	747	0.010
639	0.011	777	0.05
662	0.034	822	0.12

^{a)} The error in the relative yields is 20 %, except for the $E_p = 747$ keV resonance, where it is 40 %.

The relative resonance strengths were calculated from the measured thin target yields⁵). The absolute strengths $\omega\gamma = (2J_r + 1)\Gamma_p\Gamma_\gamma/\Gamma$ were obtained by comparison with the yield of the $E_p = 580$ keV resonance in the $^{32}\text{S}(p, \gamma)^{33}\text{Cl}$ reaction. The absolute yield of this resonance is known⁴) as 27 ± 9 meV. The ^{32}S resonances taken with a 1.2-3.1 MeV channel are shown in the insert of fig. 2. As a check, the yield of the $^{34}\text{S}(p, \gamma)^{35}\text{Cl}$ resonance at $E_p = 848$ keV was also measured. Using the known abundance ratio of the sulphur isotopes, the absolute strength was found as 0.26 ± 0.13 eV, in good agreement with the value of 0.34 ± 0.10 eV given in ref. ⁶).

The resonance energies and strengths are listed in table 1. The weak resonance strengths combined with the 22% isotopic abundance of ^{33}S result in rather low yields during this investigation.

3.2. DECAY SCHEMES

In this section a description shall be given of the main features of all resonances and especially of the information that can be obtained about the decay of lower levels. Most of the lower levels are excited at several resonances. The branching is mentioned only at those resonances, which most accurately yield the intensities. These values are compared with the results obtained at the other resonances.

The gamma-ray branchings of all resonance levels and the lower excited states are shown in fig. 10.

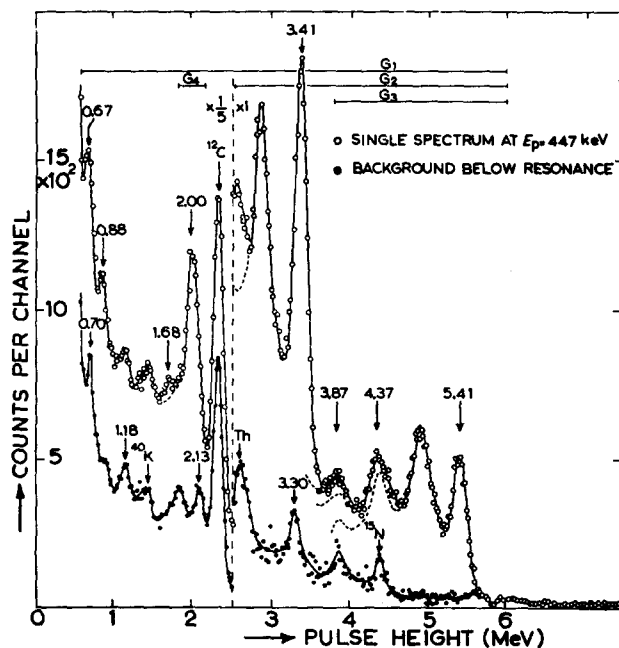


Fig. 3. Single spectra on and below the $E_p = 447$ keV resonance. The symbols G_1 to G_4 denote channels used for gating coincidence spectra.

Gamma rays of $E_\gamma = 1.18, 2.13$ and 3.30 MeV were observed in many resonance spectra and background spectra. They stem from the β^+ decay of the 0.14 MeV isomeric state in ^{34}Cl ($\tau_{1/2} = 32$ min), feeding the first and second excited states in ^{34}S .

The $E_p = 447$ keV resonance. A single spectrum is given in fig. 3. In this figure the channels used in coincidence spectra are indicated. In the same figure the background spectrum obtained just below the resonance energy is shown. The gamma rays from the β^+ decay of the 0.14 MeV level to excited states in ^{34}S are clearly seen. The 0.70 MeV line in the background spectrum might be explained by summing of a 0.51 MeV annihilation and 0.20 MeV scattering peak.

The gamma rays observed at this resonance are listed in table 2. In this and the following tables the intensity of the strongest transition was put equal to 100.

TABLE 2
Gamma rays observed at the $E_p = 447$ keV resonance ($E_x = 5.55$ MeV)

E_γ ^{a)} (MeV)	Relative intensity	Interpretation	Method of ^{b)} observation
(5.55)	<8	(r) \rightarrow 0	S
5.41	51 ± 7	(r) \rightarrow 0.14	S
(4.51)	<2	4.51 \rightarrow 0	C
4.37 ± 0.05	8 ± 2	4.51 \rightarrow 0.14	C
3.87 ± 0.04	5 ± 2	3.87 \rightarrow 0	S
(3.55)	<3	3.55 \rightarrow 0	C
3.41	87 ± 10	3.55 \rightarrow 0.14	S
2.88	3 ± 3	3.55 \rightarrow 0.67	CI
2.02 ± 0.03	100 ± 14	(r) \rightarrow 3.55	S
1.70 ± 0.04	7 ± 3	(r) \rightarrow 3.87	C
1.21 ± 0.03		3.30 \rightarrow 2.13 ^{34}S	C
1.05 ± 0.03	9 ± 3	(r) \rightarrow 4.51	C
0.88 ± 0.03		?	C
0.67 ± 0.02	5 ± 3	0.67 \rightarrow 0	C

^{a)} For lines, which were used for energy calibration or for which only indirect evidence exists (see below), the values computed from known excitation energies are listed. No errors are indicated in these cases. For all other lines a weighted average has been taken of the energies measured in single and/or coincidence spectra. The energies of γ -transitions with intensities smaller than a given upper limit, are put in brackets. In the text and in the figures of spectra, energies are quoted as following from the excitation energies given in ref. ³⁾.

^{b)} In the column "Method of observation" S stands for "single spectrum", C for "coincidence spectrum" and CI for "coincidence spectrum indirect". The latter symbol applies to γ rays, which have not been observed directly, but which have to be present to explain the presence and/or intensity of other γ rays.

The main transition occurs to the 3.55 MeV level. This level decays mainly to the first excited state and probably weakly to the third excited state. These results are in agreement with those obtained at the $E_p = 731$ keV resonance.

Only at this resonance, transitions were found to the 3.87 and 4.51 MeV levels, which decay to the ground state and first excited state, respectively. Both levels are given as possibilities in ref. ²⁾.

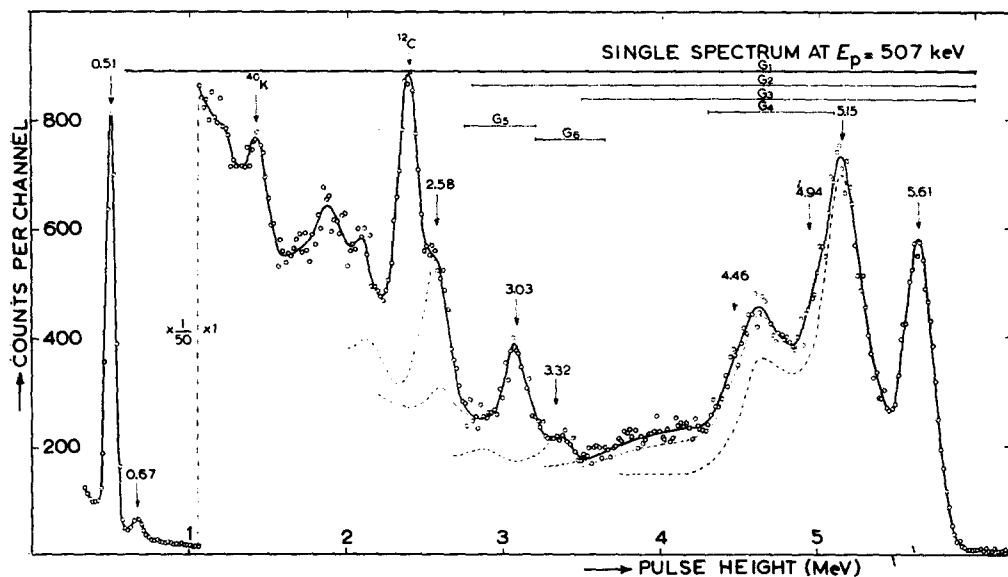


Fig. 4. Single spectrum at the $E_p = 507$ keV resonance. The symbols G_1 to G_6 denote channels used for gating coincidence spectra.

TABLE 3

Gamma rays observed at the $E_p = 507$ keV resonance ($E_x = 5.61$ MeV)

E_γ (MeV)	Relative intensity	Interpretation	Method of ^{a)} observation
5.61	100 ± 13	(r) \rightarrow 0	S
5.15	2 ± 1	(r) \rightarrow 0.46	CI
4.96 ± 0.04	11 ± 3	(r) \rightarrow 0.67	C
(4.60)	< 1	$4.60 \rightarrow 0$	C
4.46 ± 0.04	4 ± 1	$4.60 \rightarrow 0.14$	C
3.34 ± 0.03	3 ± 1	(3.99) \rightarrow 0.67 ^{b)}	S
3.03	17 ± 3	(r) \rightarrow 2.58	S
2.58 ± 0.03	19 ± 4	$2.58 \rightarrow 0$	S
(2.44)	< 2	$2.58 \rightarrow 0.14$	C
(2.12)	< 2	$2.58 \rightarrow 0.46$	C
(1.91)	< 2	$2.58 \rightarrow 0.67$	C
1.65 ± 0.03	3 ± 1	(r) \rightarrow (3.99) ^{b)}	C
1.04 ± 0.03	4 ± 1	(r) \rightarrow 4.60	C
0.67 ± 0.02	10 ± 3	$0.67 \rightarrow 0$	C
0.53 ± 0.01	3 ± 1	$0.67 \rightarrow 0.14$	C
0.46 ± 0.02	2 ± 1	$0.46 \rightarrow 0$	C
(0.21)	< 0.5	$0.67 \rightarrow 0.46$	C

^{a)} For the meaning of the symbols used see table 2.

^{b)} See text.

An unexplained gamma line of 0.88 MeV is found in all single and coincidence spectra.

The $E_p = 507$ keV resonance. This is the strongest resonance below $E_p = 850$ keV. A single spectrum is shown in fig. 4, together with the channels used in coincidence measurements. The resonance level decays most strongly to the ground state. The observed gamma rays are given in table 3.

The intensity of a 3.34 MeV line in the single spectra is too strong compared with the 2.13 and 1.18 MeV lines to be ascribed to the decay of the 3.30 MeV level in ^{34}S .

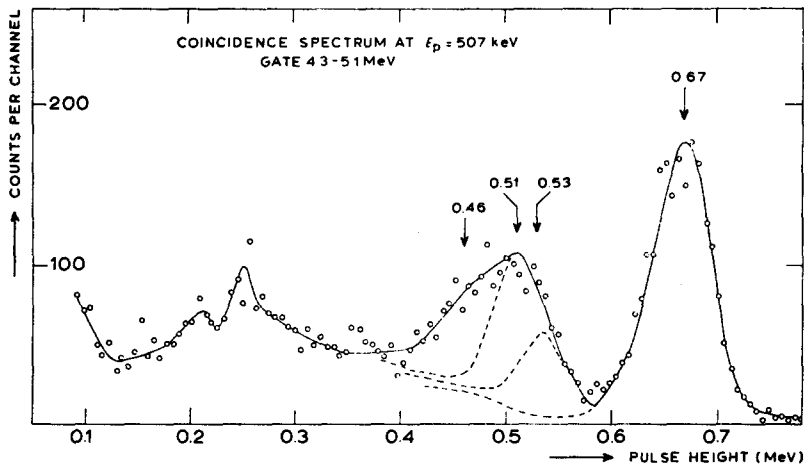


Fig. 5. Spectrum coincident with the primary of the 0.67 MeV level at the $E_p = 507$ keV resonance (channel G_4 in fig. 4).

A coincidence spectrum with this line (channel G_6 in fig. 4) shows 1.65 and 0.67 MeV transitions. The latter is much too strong to be explained only by direct excitation of the 0.67 MeV level from the resonance state. A weak $(r) \rightarrow 3.99 \rightarrow 0.67$ MeV cascade is in agreement with these measurements. At 3.97 MeV a possible level is given in ref. ²). However, a much stronger excitation of a 3.97 MeV level with a complete different decay is found at the $E_p = 1057$ and 1096 keV resonances (see sect. 4). A doublet at 3.97 MeV would explain these results.

A coincidence spectrum with a 4.3–5.1 MeV channel is given in fig. 5. This spectrum clearly shows the decay of the 0.67 MeV level to the ground state and first excited state. A 0.46 MeV line in this spectrum has to be explained by gating pulses from the transition $(r) \rightarrow 0.46$ MeV, since the intensity of the $0.67 \rightarrow 0.46$ MeV transition is smaller than 5%. The line at 0.25 MeV may be explained as a scattering peak.

The decay of the 2.58 MeV level is determined at this resonance, in combination with the results obtained at $E_p = 683$ keV. Only the transition $2.58 \rightarrow 0$ MeV is observed.

A 4.60 MeV level is excited only at this resonance. The transitions $(r) \rightarrow 4.60$ and $4.60 \rightarrow 0.14$ MeV are seen in coincidence spectra, while the intensity of the $4.60 \rightarrow 0$ MeV transition is smaller than 25%.

The $E_p = 546$ keV resonance. The resonance strongly decays to the ground state and weakly to a number of low-lying levels. The observed gamma rays are listed in table 4.

The 3.13 MeV level is excited only at this resonance. The branchings obtained for the other low-lying levels are in agreement with the values found at other resonances.

Excitation of the level at 2.61 MeV instead of 2.58 MeV is not excluded.

TABLE 4
Gamma rays observed at the $E_p = 546$ keV resonance ($E_x = 5.65$ MeV)

E_γ (MeV)	Relative intensity	Interpretation	Method of *) observation
5.65	100 ± 20	(r) \rightarrow 0	S
4.98 ± 0.06	8 ± 3	(r) \rightarrow 0.67	C
4.44 ± 0.06	3 ± 2	(r) \rightarrow 1.23	S
3.76 ± 0.04	3 ± 2	(r) \rightarrow 1.89	C
3.50 ± 0.03	14 ± 3	(r) \rightarrow 2.16	S
3.15 ± 0.04	6 ± 3	3.13 \rightarrow 0	S
3.07 ± 0.03	8 ± 2	(r) \rightarrow 2.58	S
(2.99)	< 2	3.13 \rightarrow 0.14	S
2.59 ± 0.03	6 ± 2	2.58 \rightarrow 0 ^{b)}	C
2.52 ± 0.03	4 ± 2	(r) \rightarrow 3.13	C
2.17 ± 0.04	7 ± 2	2.16 \rightarrow 0	C
2.03 ± 0.03	4 ± 2	2.16 \rightarrow 0.14	C
1.75 ± 0.03	2 ± 1	1.89 \rightarrow 0.14	C
1.70 ± 0.03	9 ± 3	2.16 \rightarrow 0.46	S
1.35 ± 0.06	2 ± 1	1.89 \rightarrow 0.46	C
1.10 ± 0.04	2 ± 1	1.23 \rightarrow 0.14	S
0.67 ± 0.02	10 ± 2	0.67 \rightarrow 0	S
0.46 ± 0.02	11 ± 4	0.46 \rightarrow 0	C

*) For the meaning of the symbols used see table 2.

b) See text.

TABLE 5
Gamma rays observed at the $E_p = 639$ keV resonance ($E_x = 5.74$ MeV)

E_γ (MeV)	Relative intensity	Interpretation	Method of *) observation
5.74	56 ± 11	(r) \rightarrow 0	S
3.60 ± 0.04	100 ± 18	(r) \rightarrow 2.16	S
2.16 ± 0.03	37 ± 9	2.16 \rightarrow 0	S
2.02 ± 0.05	15 ± 4	2.16 \rightarrow 0.14	S
1.71 ± 0.03	51 ± 9	2.16 \rightarrow 0.46	S

*) For the meaning of the symbols used see table 2.

The $E_p = 639$ keV resonance. The gamma rays found in single spectra are listed in table 5. Only transitions to the ground state and the level at 2.16 MeV are observed at this very weak resonance. The branching of the 2.16 MeV level agrees with that found at the much stronger $E_p = 822$ keV resonance.

The $E_p = 662$ keV resonance. The resonance level decays most strongly to the first excited state. The observed gamma rays are shown in table 6.

A transition to the 3.38 MeV level is found only at this resonance. Transitions from the 3.38 MeV level to the first, second and third excited states are observed in single and coincidence spectra.

TABLE 6
Gamma rays observed at the $E_p = 662$ keV resonance ($E_x = 5.76$ MeV)

E_γ (MeV)	Relative intensity	Interpretation	Method of ^{a)} observation
(5.76)	<20	(r)→0	S
5.62	100±16	(r)→0.14	S
(5.09)	<1	(r)→0.67	C
4.55 ±0.05	26± 8	(r)→1.23	S
3.62 ±0.03	40± 8	(r)→2.16	S
(3.38)	<3	3.38→0	S
3.24 ±0.03	13± 3	3.38→0.14	S
2.92 ±0.03	12± 4	3.38→0.46	S
2.71 ±0.05	7± 2	3.38→0.67	C
2.39 ±0.03	44±10	(r)→3.38	S
2.16 ±0.05	11± 4	2.16→0	C
1.70 ±0.04	23± 6	2.16→0.46	S
1.20 ±0.03		3.30→2.13 ³⁴ S	C
1.08 ±0.05	9± 4	1.23→0.14	C
0.95 ±0.04	5± 3	2.16→1.23	C
0.77 ±0.03	8± 3	1.23→0.46	C
0.67 ±0.02	10± 3	0.67→0	S

^{a)} For the meaning of the symbols used see table 2.

TABLE 7
Gamma rays observed at the $E_p = 683$ keV resonance ($E_x = 5.78$ MeV)

E_γ (MeV)	Relative intensity	Interpretation	Method of ^{a)} observation
(5.78)	<30	(r)→0	S
5.64	72±16	(r)→0.14	S
5.33 ±0.04	100±21	(r)→0.46	S
5.12 ±0.05	38±10	(r)→0.67	S
3.92 ±0.04	16± 5	(r)→1.89	S
3.32 ±0.05		3.30→0 ³⁴ S	S
3.20	58±12	(r)→2.58	S
2.57 ±0.03	60±12	2.58→0	S
(2.44)	<6	2.58→0.14	S
2.11 ±0.03		2.13→0 ³⁴ S	S
1.75 ±0.03	10± 3	1.89→0.14	S
1.17 ±0.03		3.30→2.13 ³⁴ S	S
0.67 ±0.02	51±12	0.67→0	S

^{a)} For the meaning of the symbols used see table 2.

The $E_p = 683$ keV resonance. The main transition from the resonance level occurs to the 0.46 MeV level. In table 7 the observed gamma rays are listed. The 2.58 MeV level is rather strongly excited. The decay of this level was found by combining the results obtained at this resonance with those from the $E_p = 507$ keV resonance.

TABLE 8
Gamma rays observed at the $E_p = 731$ keV resonance ($E_x = 5.83$ MeV)

E_γ (MeV)	Relative intensity	Interpretation	Method of ^{a)} observation
(5.83)	<15	(r)→0	S
5.69	100±20	(r)→0.14	S
5.16	7±3	(r)→0.67	CI
4.65 ±0.05	36±11	(r)→1.23	S
3.95 ±0.10	24±7	(r)→1.89	S
3.68 ±0.05	16±7	(r)→2.16	S
3.40 ±0.05	20±7	3.55→0.14	S
2.85 ±0.10	3±2	3.55→0.67	S
2.30 ±0.05	19±4	(r)→3.55	S
2.13 ±0.02		2.13→0 ³⁴ S	S
(1.89)	<2	1.89→0	C
1.75 ±0.03	13±4	1.89→0.14	C
1.70 ±0.03	8±5	2.16→0.46	S
1.42 ±0.04	10±3	1.89→0.46	C
(1.23)	<1	1.23→0	C
(1.22)	<1	1.89→0.67	C
1.17 ±0.02		3.30→2.13 ³⁴ S	S
1.09 ±0.02	12±3	1.23→0.14	C
0.77 ±0.02	10±3	1.23→0.46	S
0.67 ±0.02	13±3	0.67→0	S
0.56 ±0.02	8±3	1.23→0.67	C
0.46 ±0.02	25±7	0.46→0	C

^{a)} For the meaning of the symbols used see table 2.

The $E_p = 731$ keV resonance. This resonance is interesting, because it has relatively strong transitions to the 1.23 and 1.89 MeV levels. The main transition occurs to the first excited state. The observed gamma rays are given in table 8.

In fig. 6(A) a spectrum coincident with the (r) → 1.23 MeV transition is given. It is seen that the 1.23 MeV level decays to all lower levels except to the ground state. The small peak at 1.23 MeV is due to sumpulses.

A coincidence spectrum with a 3.0–4.3 MeV channel, given in fig. 6(B), shows the decay of the 1.89 MeV level. The spectrum is somewhat complicated by the fact, that the transitions (r) → 2.16 MeV and (r) → 1.23 MeV also give pulses in the gating channel. The 1.89 MeV level decays to the first and second excited states. The intensity of the ground-state transition (< 3%) follows from measurements at $E_p = 1165$ keV (see sect. 4). The broad peak at 1.7 MeV is a doublet of 1.70 and 1.75 MeV lines corresponding to the transitions 2.16 → 0.46 MeV and 1.89 → 0.14 MeV, respectively.

The $E_p = 747$ keV resonance. At this resonance, the weakest which has been found, only a transition to the 0.14 MeV level was observed.

The $E_p = 777$ keV resonance. The resonance level decays to the four lowest states and to the 4.15 MeV level. From the latter level only a ground-state transition is

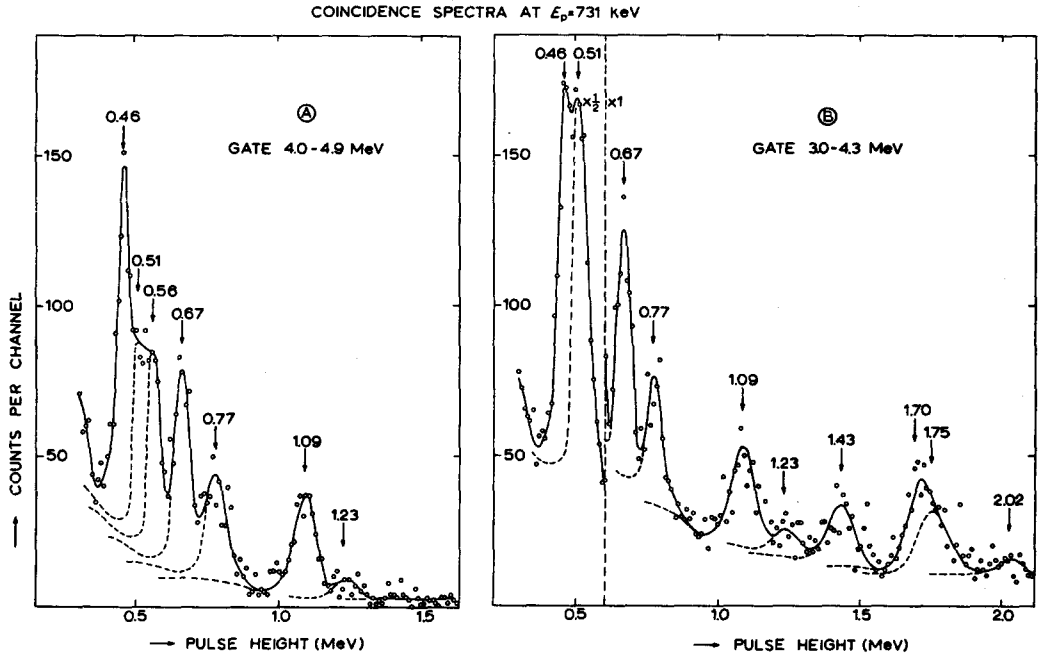


Fig. 6. Coincidence spectra at $E_p = 731$ keV. Spectrum A shows the decay of the 1.23 MeV level. The bump at 1.23 MeV is due to sumpulses. The decay of the 1.89 MeV level can be determined from spectrum B (see text).

TABLE 9

Gamma rays observed at the $E_p = 777$ keV resonance ($E_x = 5.87$ MeV)

E_γ (MeV)	Relative intensity	Interpretation	Method of *) observation
5.85 ± 0.06	28 ± 10	(r) $\rightarrow 0$	S
5.70 ± 0.05	73 ± 20	(r) $\rightarrow 0.14$	S
5.40 ± 0.05	100 ± 30	(r) $\rightarrow 0.46$	S
5.20 ± 0.05	43 ± 18	(r) $\rightarrow 0.67$	S
4.13 ± 0.05	35 ± 16	$4.15 \rightarrow 0$	S
(4.01)	< 8	$4.15 \rightarrow 0.14$	S
3.35 ± 0.05		$3.30 \rightarrow 0$ ^{34}S	S
2.14 ± 0.03		$2.13 \rightarrow 0$ ^{34}S	S
1.72 ± 0.03	24 ± 8	(r) $\rightarrow 4.15$	S
0.67 ± 0.03	27 ± 9	$0.67 \rightarrow 0$	S

*) For the meaning of the symbols used see table 2.

found. The intensity of the $4.15 \rightarrow 0.14$ MeV transition is weaker than 25%. The gamma rays observed at this resonance are listed in table 9.

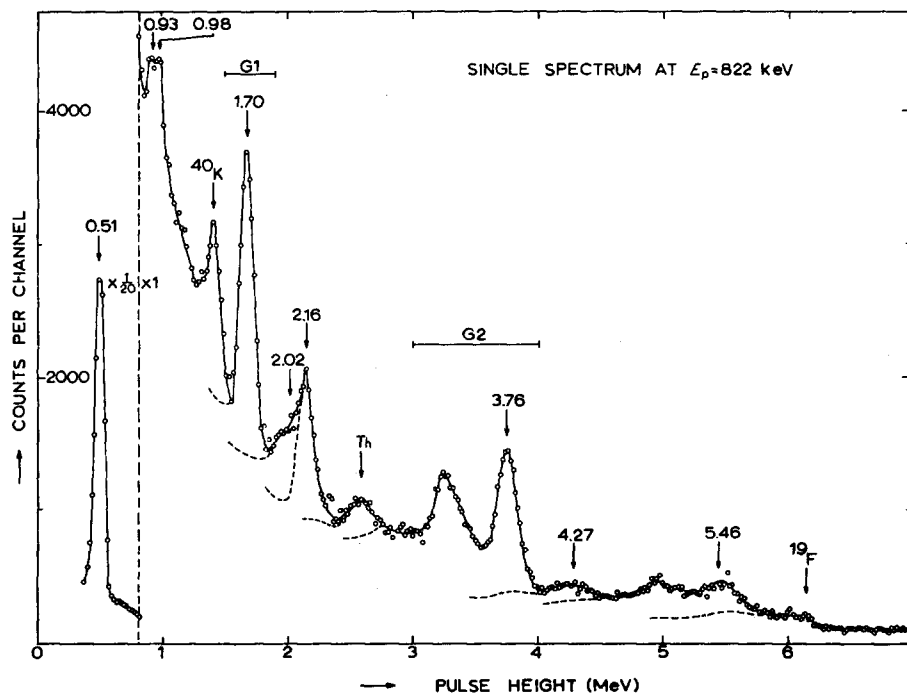


Fig. 7. Single spectrum at the $E_p = 822$ keV resonance. The symbols G_1 and G_2 denote channels used for gating coincidence spectra.

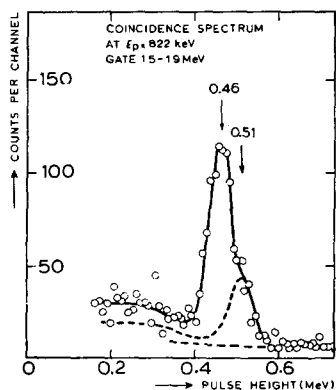


Fig. 8. Coincidence spectrum at the $E_p = 822$ keV resonance. This spectrum, taken with channel G_1 (see fig. 7), shows the decay of the 0.46 MeV level.

The $E_p = 822$ keV resonance. The decay of the resonance level is characterized by a very strong transition to the 2.16 MeV excited state. Transitions from the latter

level to the ground state and levels at 0.14, 0.46 and 1.23 MeV can be seen clearly in the single spectrum shown in fig. 7. A spectrum coincident with the $2.16 \rightarrow 0.46$ MeV transition, given in fig. 8, shows the ground-state decay of the 0.46 MeV level.

Weak transitions are observed to the levels at 0.46 and 4.94 MeV. The existence of the latter level could be deduced from the peaks in the single spectrum at 0.98 and 4.27 MeV (explained as $(\text{r}) \rightarrow 4.94$ MeV and $4.94 \rightarrow 0.67$ MeV transitions, respectively). The intensity of the 0.67 MeV line in a spectrum coincident with channel G_2 (see fig. 7) is in agreement with this decay. The gamma rays observed are listed in table 10.

TABLE 10
Gamma rays observed at the $E_p = 822$ keV resonance ($E_x = 5.92$ MeV)

E_γ (MeV)	Relative intensity	Interpretation	Method of ^{a)} observation
(5.92)	<5	(r)→0	S
(5.78)	<5	(r)→0.14	S
5.47 ± 0.05	12 ± 5	(r)→0.46	S
4.27 ± 0.05	6 ± 3	(4.94)→0.67 ^{b)}	S
3.76	100 ± 18	(r)→2.16	S
2.16 ± 0.03	36 ± 7	$2.16 \rightarrow 0$	C
2.01 ± 0.04	19 ± 5	$2.16 \rightarrow 0.14$	C
1.70	65 ± 14	$2.16 \rightarrow 0.46$	S
(1.49)	<4	$2.16 \rightarrow 0.67$	C
0.98 ± 0.03	9 ± 3	(r)→(4.94) ^{b)}	S
0.93 ± 0.03	7 ± 2	$2.16 \rightarrow 1.23$	C
0.77 ± 0.03	3 ± 1	$1.23 \rightarrow 0.46$	C
0.67 ± 0.03	5 ± 2	$0.67 \rightarrow 0$	C
0.46 ± 0.02	54 ± 9	$0.46 \rightarrow 0$	C
(0.32)	<2	$0.46 \rightarrow 0.14$	C

^{a)} For the meaning of the symbols used see table 2.

^{b)} See text.

4. The $E_p = 850$ -1300 keV Region

4.1. RESONANCE ENERGIES AND YIELDS

With the Van de Graaff generator a resonance curve was measured with discriminator channels of 2.0-3.6 MeV, 3.6-5.3 MeV and 5.3-7.3 MeV. The sum of the number of counts in the three channels is shown in fig. 9. The proton energy was calibrated with the well-known $^{27}\text{Al}(\text{p}, \gamma)^{28}\text{Si}$ resonance at $E_p = 991.8 \pm 0.2$ keV. Above $E_p = 1300$ keV the background increased considerably, and therefore this region was not further investigated. A CdS target on a tantalum backing was used with an isotopic abundance as given in sect. 2. The resonances from ^{33}S and ^{34}S are indicated, as well as those from the $^{19}\text{F}(\text{p}, \alpha\gamma)^{16}\text{O}$ and $^{15}\text{N}(\text{p}, \alpha\gamma)^{12}\text{C}$ reactions. For the identification of the resonances, spectra are taken on and below the resonance energies. The gamma rays from the β^+ decay of the 0.14 MeV level sometimes facilitated the identification.

The energies of the ^{34}S resonances are all found to be 2 or 3 keV lower than given in ref. ⁴). A more serious discrepancy is the energy of the resonance observed at $E_p = 830$ keV; the value $E_p = 838$ keV, given in ref. ⁴), is also in disagreement with the resonance curve shown in ref. ⁶).

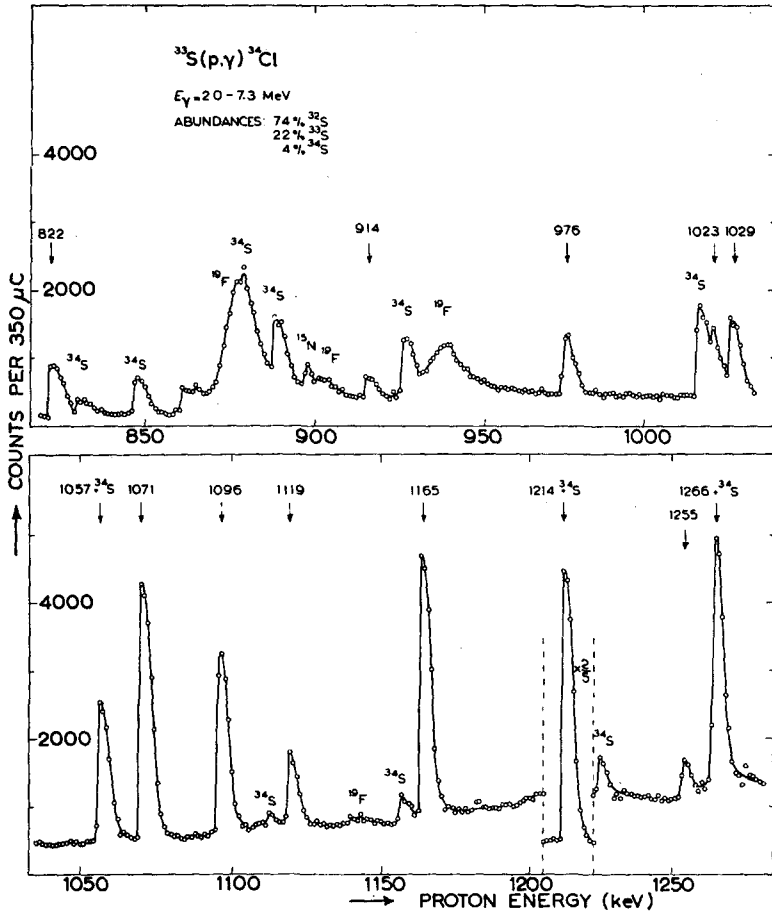


Fig. 9. Yield curve of the $^{33}\text{S}(p, \gamma)^{34}\text{Cl}$ reaction in the $E_p = 820$ -1300 keV region. Target CdS, distance target to crystal 2 cm, $\theta = 55^\circ$. The ^{33}S resonances are indicated by their proton energy. The energy scale is linear in $E_p^{\frac{1}{2}}$.

The ^{33}S resonances at $E_p = 1057$, 1214 and 1266 keV coincide with ^{34}S resonances. The $E_p = 1057$ keV resonance should be double because a very weak ^{34}S resonance is known at this energy ⁴). The doublet character of the $E_p = 1214$ keV resonance could be observed from a yield curve taken in smaller steps and from gamma-ray spectra measured at $E_p = 1213$ and 1216 keV; the strong ^{34}S resonance is found at $E_p = 1211$ keV. The resonance at $E_p = 1266$ keV is double as could be

determined from the gamma-transitions found in the spectra; the main decay of the ^{34}S resonance occurs to the ground state and the lowest two excited states of ^{35}Cl .

The resonance energies and absolute yields are given in table 11. The yields have been measured relative to the yield of the $E_p = 822$ keV resonance. The yield of this resonance was taken as 0.12 eV (see subject. 3.1).

TABLE 11
Energies and strengths of $^{33}\text{S}(\text{p}, \gamma)^{34}\text{Cl}$ resonances ($E_p = 850$ -1300 keV)

$E_p(\text{keV})$ all ± 2 keV	$(2J_r+1)\Gamma_p\Gamma_\gamma/\Gamma(\text{eV})$ all ± 50 %	$E_p(\text{keV})$ all ± 2 keV	$(2J_r+1)\Gamma_p\Gamma_\gamma/\Gamma(\text{eV})$ all ± 50 %
914	0.05	1096	0.29
976	0.13	1119	0.21
1023	0.02	1165	0.76
1029	0.15	1214	0.19
1057	0.45	1255	0.05
1071	0.60	1266	0.23

4.2. GAMMA-RAY BRANCHINGS

The main branching ratios of the resonance levels, shown in fig. 10, could be determined from single spectra. Only some coincidence spectra were measured, since almost all transitions occur to lower levels with a decay known from resonances below $E_p = 850$ keV. Altogether the decay of three other lower levels was determined.

The strongest resonance, at $E_p = 1165$ keV, mainly decays to the 2.38 MeV excited state and only a $2.38 \rightarrow 0.14$ MeV transition is observed, while the intensity of the ground-state transition is weaker than 3%. The decay of the 1.89 MeV level, found at the $E_p = 731$ keV resonance, could be obtained more accurately at the $E_p = 1165$ keV resonance. The upper limit for the intensity of the ground-state transition is 3%.

The resonance level at $E_p = 1119$ keV decays rather strongly to the 2.72 MeV excited state. From this level transitions to the ground state and second excited state are observed in coincidence spectra. At the same resonance a transition to the 3.78 MeV level is found which only decays to the ground state.

At $E_p = 1057$ and 1096 keV rather strong transitions are found to an excited state at 3.97 MeV. This level decays to the states at 0.14 and 2.16 MeV.

5. Conclusions

The results obtained are summarized in fig. 10. Most of the lower levels are excited at several resonances. The branching ratios determined at these resonances are found to be in agreement with each other.

Up to 2.58 MeV all known lower levels are excited; no transitions are observed ²⁾ to the levels at 2.61, 3.34, 3.59, 3.64 and 4.09 MeV. The levels at 3.87, 3.97 and 4.51 MeV, given as uncertain levels in ref. ²⁾, are also found in the present investigation. The 3.97 MeV level might be double.

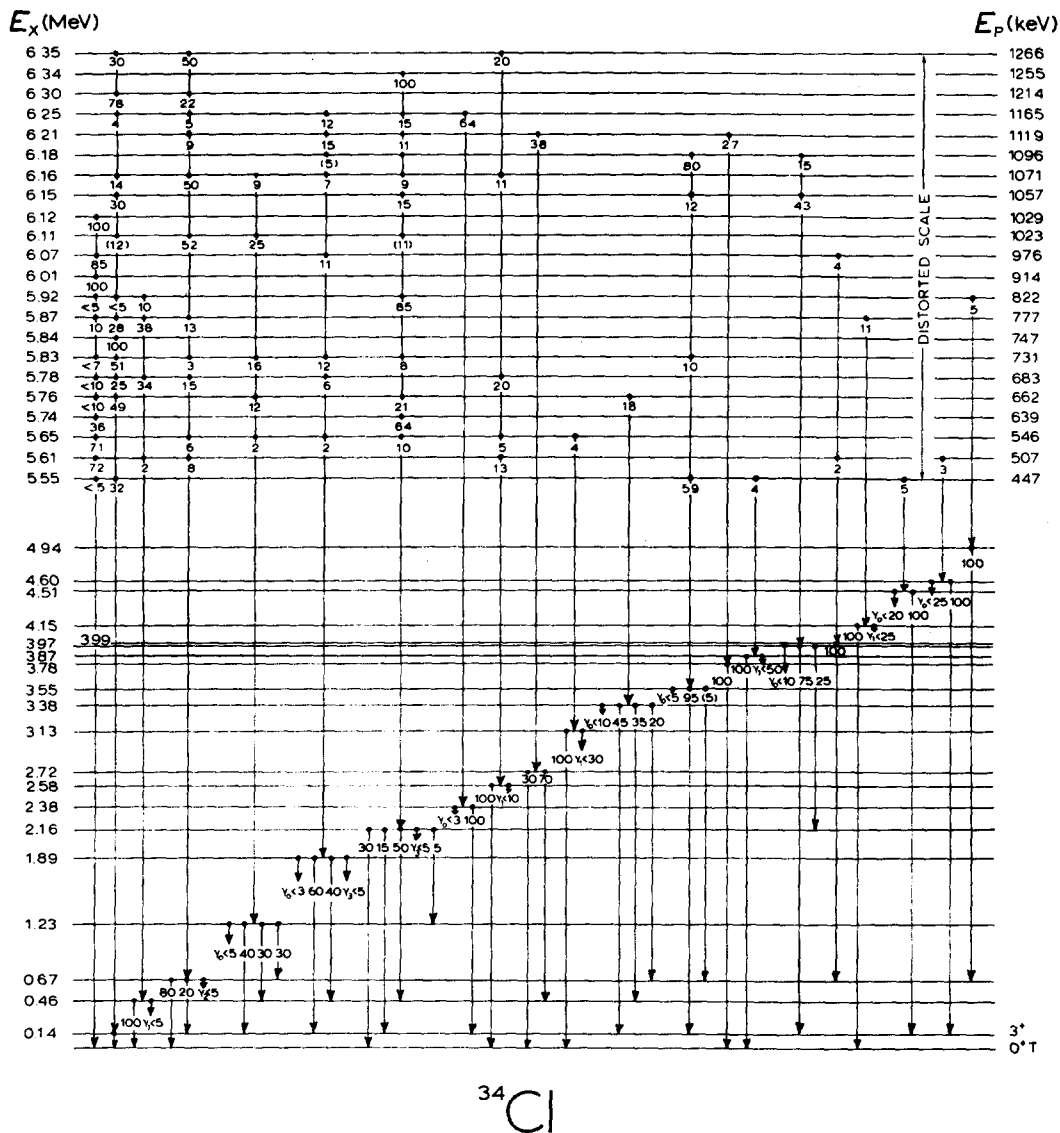


Fig. 10. Gamma-ray branching of energy levels in ^{34}Cl . The sum of the intensities of all gamma rays de-exciting a given level has been normalized to 100. The excitation energies are those given by Hinds and Middleton ²⁾, except for the levels at 3.99 and 4.94 MeV, which are only found in the present experiment.

Shell model predictions of the spins of the lower levels¹⁾ of ^{34}Cl may be compared with the observed decay of these excited states. The experimental and calculated levels up to $E_x = 2.5$ MeV are shown in fig. 11. In this region the number of calculated levels equals the number of experimentally observed levels. The lower two states of ^{34}S are also given, since these correspond to $T = 1$ states of ^{34}Cl .

The calculated ground state and first excited state show good agreement with experiment, although the order is reversed. The 2.16 MeV level of ^{34}Cl most likely corresponds to the first excited $J^\pi = 2^+(T = 1)$ state of ^{34}S at 2.13 MeV. The calculated excitation energy of this level shows excellent agreement with experiment.

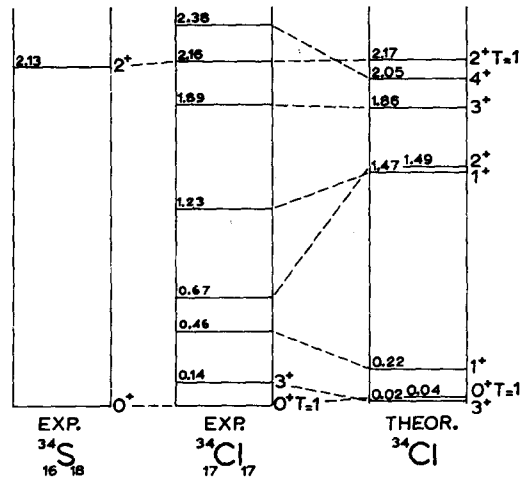


Fig. 11. Comparison between theoretical and experimental levels of ^{34}Cl below 2.5 MeV. The calculated excitation energies are given relative to the experimental ground-state energy

Assuming only even parity levels below $E_x = 2.5$ MeV, one may make the following tentative spin assignments (see dotted lines in fig. 11). The theoretical $J^\pi = 1^+$ level at 0.22 MeV may correspond to the second excited state, because of the observed excitation energy (0.46 MeV) and decay to the ground state.

The interpretation of the calculated doublet at 1.5 MeV is still dubious. The levels at 0.67 and 1.23 MeV are candidates for the calculated levels at 1.47 ($J^\pi = 1^+$) and 1.49 MeV ($J^\pi = 2^+$). The decay schemes of these two levels do not show any preference to one of the two alternative spin assignments that are possible. The absence of an observed ground-state transition of the 1.23 MeV level is explained by neither of the two spin assignments. However, the calculations indicate¹⁾ that the assignments $J^\pi = 2^+$ to the 0.67 MeV level and $J^\pi = 1^+$ to the 1.23 MeV level are more probable.

The experimental 1.89 MeV level probably is the $J^\pi = 3^+$ state calculated at 1.86 MeV. From this spin assignment it is clear why no ground-state transition of this level is observed. The calculated $J^\pi = 4^+$ level most likely corresponds to the ex-

perimental level at 2.38 MeV. This is in agreement with the observed 100% decay to the first excited state having $J^\pi = 3^+$.

For a better comparison between theory and experiment angular correlation measurements will have to be performed.

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