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GAMMA DECAY OF LEVELS IN ^{40}Ca MEASURED WITH THE ^{39}K$(p, \gamma)^{40}$Ca REACTION

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Synopsis

In the proton-energy range E_p = 500–2900 keV fifty-three resonances were observed in the ^{39}K$(p, \gamma)^{40}$Ca reaction. The resonance energies and strengths were determined. The decay modes of most of the resonances and of fifteen lower excited states in ^{40}Ca were determined from single and coincidence gamma-ray spectra.

1. *Introduction.* The energies of the lowest eleven excited states of ^{40}Ca were well determined with the reaction ^{40}Ca$(p, p')^{40}$Ca by Braams[1])[2]) using the M.I.T.-O.N.R. electrostatic generator and a magnetic spectrograph. The main purpose of the present work was to find the decay modes of levels in ^{40}Ca, and particularly of lower levels, through the analysis of the ^{39}K$(p, \gamma)^{40}$Ca reaction.

In addition, some spins were determined through γ—γ angular correlation measurements, but these results will be reported later. This investigation can provide an experimental check of the theoretical interpretation of the ^{40}Ca level scheme by Gillet[3]), and by Horie and Yokozawa[4]).

The gamma spectroscopy of ^{40}Ca levels has been carried out in several laboratories[1])[7])[8]). However, a systematic search for the gamma decay of lower levels in ^{40}Ca has not been reported.

Information on energies, spins and parities of levels in ^{40}Ca has also been obtained from electron[1]), proton[1])[10]) and alpha-particle[1])[9]) inelastic scattering angular distribution measurements, but in general the energy resolution has been insufficient to separate the inelastically scattered particle groups leading to close doublet or triplet levels, e.g. to those centering at 3.8, 5.2 and 5.6 MeV.

The (p, γ) reaction has the advantage that every resonance has its characteristic decay, such that the members of a doublet or triplet will be excited with different intensities at different resonances; in a favourable case only one member will participate in the decay with measurable intensity.

2. *Experimental technique.* Protons were accelerated with the Utrecht 3 MV Van de Graaff generator. The proton energy was selected with a 90°

deflection magnet. A description of the analysing magnet and of the stabilisation of the accelerator has been published previously^{5}).

Targets were prepared by evaporating in vacuo the target material onto 0.3 mm tantalum backings. Both K_2SO_4, enriched to 99.8% in ^{39}K*), and KI, containing potassium of natural isotopic composition (^{39}K 93.1%, ^{41}K 6.9%) has been used. The use of enriched potassium greatly reduces the background caused by the ^{41}K$(p, \gamma)^{42}$Ca and ^{41}K$(p, n)^{41}$Ca ($Q = -1.20$ MeV) reactions. The sulphate has the advantage that, because of the higher melting point, it withstands more beam power than the iodide. A beam current of 5 μA can be tolerated in the $E_p = 1$–3 MeV region for periods up to about 40 hours without observable deterioration of the target. The target backing forms part of the target holder such that it can directly be cooled with water. Of course, using sulphate targets, one has to be aware of the existence of S(p, γ) resonances, but the ^{32}S (95.0%) resonances are few and well known^{1}) and have a low Q value ($Q = 2.29$ MeV), and the other sulphur isotopes have a low abundance (^{33}S 0.8%, ^{34}S 4.2%, ^{36}S 0.014%). The iodide, finally, has the advantage over the sulphate that thin layers can be produced of more uniform thickness. This reduces the "tail" on the high energy side of a resonance, and thus permits better resolution of close doublet resonances.

The gamma rays were detected with two cylindrical NaI crystals, length 10.2 cm and diameter 10.2 cm. The spectra were recorded with a R.I.D.L. 400 channel analyser. Single gamma-ray spectra were taken at various distances (see figure captions) with the axis of the NaI crystal at 55° with the direction of the proton beam. The background, measured at a proton energy just below the relevant resonance, has been subtracted in all the figures shown in this paper.

Most coincidence spectra were taken with both crystals located about one cm from the target ($\theta = 90°$). The resolution of the coincidence circuit amounted to $2\tau = 2$ μs. At weak resonances, coincidence spectra also have to be corrected for background which can be measured at a proton energy just below the resonance in question. In addition, in working with a low-energy gate, one has to correct for the contributions of the compton tails of high-energy lines in the gate. In suitable cases, this can be effected by subtraction of the coincidence spectrum, measured simultaneously with a gate (of the same width) at a higher energy setting.

In the figures of the coincidence spectra decay schemes are given as inserts, showing only the relevant transitions and excited states. The gamma lines present in the coincidence gate are denoted with C in the decay scheme.

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*) Obtained from the Oak Ridge National Laboratory, Oak Ridge, Tennessee, U. S. A.

3. *Yields, energies and decay modes of the resonances.* Gamma-yield curves were measured at 55° with three discriminator channels ($E_\gamma = 2.0$–4.5, 4.5–7.0 and 7.0–12.0 MeV). The distance between the target and the front of the crystal was about 1 cm.

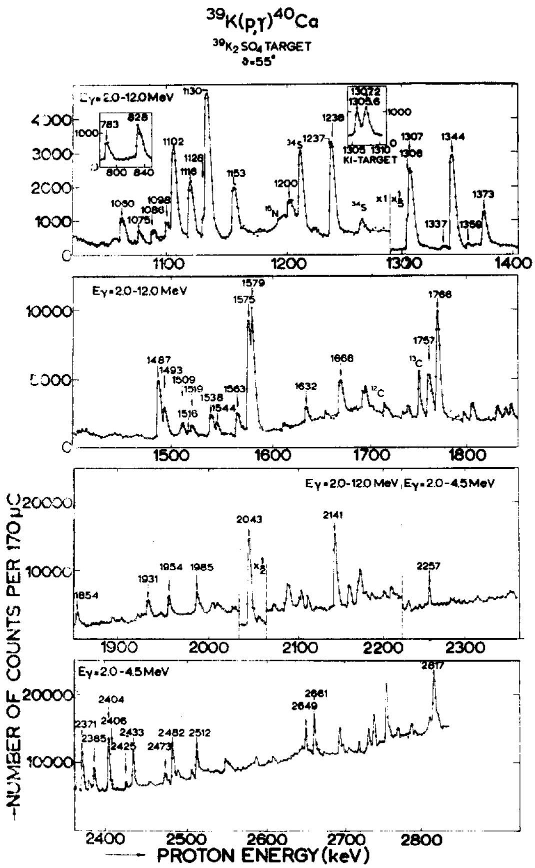

Fig. 1

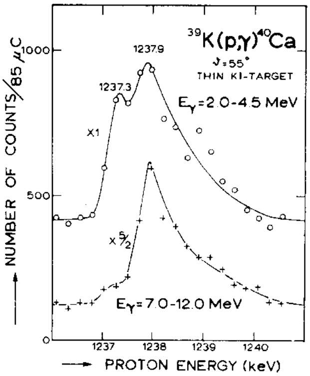

Fig. 2

Fig. 1. Resonance yield curve of the ^{39}K(p, γ) ^{40}Ca reaction (target-crystal distance about 1 cm). Two resonances are attributed to the ^{34}S(p, γ) ^{35}Cl reaction. In addition, some resonances have to be assigned to the contaminants ^{12}C, ^{13}C and ^{15}N, respectively.
Fig. 2. Resonance yield curve of the 1237 keV doublet in the ^{39}K(p, γ) ^{40}Ca reaction.

Fig. 1 shows the yield curve for gamma rays with $E_\gamma = 2.0$–12.0 MeV in the $E_p = 1000$–2225 keV region, and with $E_\gamma = 2.0$–4.5 MeV in the $E_p = 2225$–2800 keV region. The latter channel is chosen to reduce the background contribution of 6–7 MeV gamma radiation due to the ^{19}F(p, $\alpha\gamma$) ^{16}O reaction. An insert gives two resonances in the $E_p = 500$–1000 keV region, which were investigated with the H_2^+ beam. No other resonances were found in this lower energy range. In the region $E_p = 500$–1600 keV all resonances with $(2J+1)\ \Gamma_\gamma\Gamma_p/\Gamma > 0.2$ eV were investigated. For $E_p > 1600$ keV only the relatively strong and well separated resonances were included in the investigation. For all resonances that could be assigned to the ^{39}K(p,γ)^{40}Ca reaction, the measured proton energies are given in fig. 1 and in the first column of table I.

The proton energies were calibrated with the well known $E_p = 992.0$ keV resonance of the ^{27}Al(p,γ)^{28}Si reaction^{1}), and they were corrected relativistically^{5}). The calibration was in good agreement with the energy of the $E_p = 1747.3$ keV resonance of the ^{13}C(p,γ)^{14}N reaction^{6}) (present experiment: $E_p = 1747.6 \pm 1.5$ keV). The energies of the two ^{34}S(p,γ)^{35}Cl resonances found in this experiment are systematically 3 keV lower than the values given in refs. 21 and 22.

All resonances, except the $E_p = 1237.3$–1237.9 keV doublet, could be separated using thin KI targets (see for example the $E_p = 1305.6$–1307.2 keV doublet). The doublet character of the $E_p = 1237$ keV peak was proven by the observation that the maxima in different gamma-ray discriminator channels systematically occur at different proton energies (fig. 2).

The second column of table I lists the corresponding excitation energies in ^{40}Ca, using the Q-value $Q = 8336.4 \pm 4.3$ keV^{1}). The third column gives the resonance strengths $(2J+1)\ \Gamma_\gamma\Gamma_p/\Gamma$. The relative yields were obtained from the areas under the resonance peaks, corrected for the λ^2 factor in the Breit-Wigner expression. The absolute yield of the $E_p = 2043$ keV resonance was determined from a thick target experiment. The probable errors of the resonance strengths were estimated to be 40%. The fourth column gives references to other work. The following columns list the main decay of the resonances in percentages of the total decay, in most cases rounded off to the nearest 5%. The decay of the resonances (and of the lower excited states) was determined from both single and coincidence spectra analysed with the peeling method^{11}). If possible, the branching ratios were taken from the intensities of the gamma lines in the single spectra.

4. *Decay of levels with $E_x < 8$ MeV.*

Table II lists the decay of levels with excitation energies below 8 MeV.

4.1. The 3.35 MeV level.

This first excited state of ^{40}Ca has been found to decay by internal pair formation^{1}). This is confirmed by the appearance of a strong 0.51 MeV line at resonances with a transition to the 3.35 MeV level, for example at the $E_p = 1575$ keV resonance (fig. 3). In this case the 0.51 MeV gamma radiation is about four times stronger than estimated from external pair formation by the high energy gamma rays present.

4.2. The 3.73 and 3.90 MeV levels.

The second and third excited states of ^{40}Ca only decay to the ground state; this is in agreement with

TABLE

$^{39}K(p, \gamma)^{40}$Ca resonances

E_p (keV)	$E_x(^{40}$Ca) (MeV)	$(2J + 1)\ \Gamma_\gamma \Gamma_p/\Gamma$ (eV)	Ref.	Decay (in percents)[a] to lower			
				0	3.35	3.73	3.90
783.2 ± 1.0	9.100	0.2				70	20
828.1 ± 1.0	9.143	0.4				70	15
1060.3 ± 1.0	9.370	0.3	8				
1075.0 ± 1.0	9.384	0.1				x	x
1085.7 ± 1.0	9.395	0.2				x	x
1097.6 ± 1.0	9.407	0.2	8			65	15
1102.5 ± 1.0	9.411	1.3	8			30	
1116.2 ± 1.0	9.424	0.8	8			30	
1128.1 ± 1.0	9.436	0.3				35	
1130.4 ± 1.0	9.438	3.7	1,8	100			
1153.4 ± 1.0	9.460	1.5	8			20	
1200.4 ± 1.0	9.506	0.3				60	
1237.3 ± 1.0	9.542	1.5				25	15
1237.9 ± 1.0	9.543			70			30
1305.6 ± 1.0	9.609	1.7				20	
1307.2 ± 1.0	9.611	9	1	100			
1337.2 ± 1.0	9.640	0.3				x	x
1344.4 ± 1.0	9.646	9	1			40	50
1359.2 ± 1.0	9.661	0.5		100			
1373.5 ± 1.0	9.675	5				20	5
1486.6 ± 1.0	9.786	4.3				20	20
1493.1 ± 1.0	9.792	1.5		90	10		
1509.1 ± 1.0	9.807	0.3				70	30
1516.2 ± 1.0	9.814	0.3		100			
1519.5 ± 1.0	9.817	0.2				x	
1537.6 ± 1.0	9.836	0.9				35	45
1543.6 ± 1.0	9.842	0.6				70	
1563.4 ± 1.0	9.860	0.7				x	x
1574.6 ± 1.0	9.872	10	1,7	79	12		5
1578.9 ± 1.0	9.876	6	1,7	85	10		5
1632.0 ± 1.0	9.927	0.6				x	
1666.1 ± 1.0	9.960	5				10	9
1757.1 ± 1.5	10.049	2.3					30
1766.2 ± 1.5	10.058	3.4	1			55	20
1854.1 ± 1.5	10.144	1.0	1			40	20
1930.6 ± 1.5	10.219	1.1					
1953.8 ± 1.5	10.241	1.8				100	
1984.6 ± 1.5	10.273	2.0				15	40
2042.8 ± 1.5	10.329	26	1	90	7		2
2140.6 ± 1.5	10.423	7					
2256.9 ± 2.0	10.538	2.2				90	10
2370.8 ± 2.0	10.648	10				40	20
2385.4 ± 2.0	10.661	2.0				25	75
2403.6 ± 2.0	10.670	14				20	80
2406.0 ± 2.0	10.672	1.2		100			
2424.9 ± 2.0	10.700	2.2		x	x		x
2433.1 ± 2.0	10.708	6				25	60
2473.0 ± 2.0	10.747	1.9		x		x	
2482.1 ± 2.0	10.756	10					100
2512 ± 3	10.785	7		30		15	25
2649 ± 3	10.919	3.5				x	
2661 ± 3	10.930	10					x
2817 ± 3	11.073	9				20	60
	all ± 0.005	all ± 40%					

a) Crosses indicate the excistence of transitions with unknown intensity.

states (in MeV)							More than 10% unknown	To other levels
4.48	5.27	5.61	6.28	7.12	7.49	7.69		
	10							
			15					
		35				65		
			x				x	
							x	
20								
			40			15		5.90 : 15
			50					5.90 : (20)
35							40	
			45			35		
	15					25		
			50			10		
			50	25		5		
	x						x	
					10			
			40	30		5		
		35						7.46 (7.57) : 25
							x	
			20					
	30							
							x	
								6.94 : 2, 7.29 : 2
							x	
4	77							
							50	5.62 : 20
				20		5		
20	20							
							x	
					20			6.03 : (25)
					1			
							x	
		20					20	
							x	
15								
							x	
		15					15	
							x	
	x						x	
								5.24 : 20

TABLE II

Decay of lower levels of ^{40}Ca($E_x < 8$ MeV).

Level energy [a] (MeV)	Branching (in percents) to lower levels 0	3.35	3.73	3.90	4.48	5.24
3.348 ± 0.004	100 (π)					
3.730 ± 0.004	100	<10				
3.900 ± 0.004	100	< 2	<10			
4.483 ± 0.005	< 3	< 3	100	< 2		
5.202 ± 0.008						
5.241 ± 0.006	80 ± 10	< 5	<10	20 ± 10	< 5	
5.272 ± 0.006	<10	< 4	< 8	96 ± 2	4 ± 2	
5.606 ± 0.008	<10	< 5	65 ± 10	<15	35 ± 10	
5.621 ± 0.008	<10	< 5	<10	100	<10	
5.901 ± 0.008	(100)					
6.029 ± 0.008				(100)		
6.28 ± 0.02	<10	< 5	<10	20 ± 5	80 ± 5	
6.94 ± 0.03	100	<20	<20	<30	<10	
7.12 ± 0.03	<20	<30	100	<20	<20	
7.29 ± 0.03	<25	<20	<15	25 ± 10	<10	75 ± 10
7.46 (7.57) ± 0.05	<30	<30	<30	<30	<30	100
7.49 ± 0.03	100	<20	<20	<20	<10	
7.69 ± 0.05	<15	<20	100	<30	<20	

[a] For $E_x < 6.1$ MeV, as given in ref. 2; for $E_x > 6.1$ MeV, as determined in the present experiment.

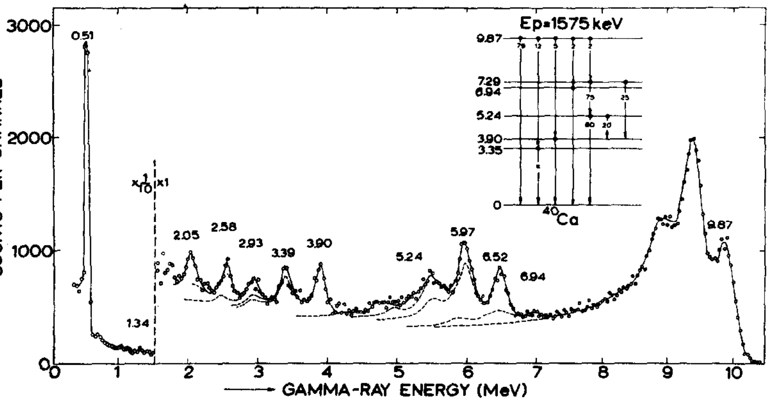

Fig. 3. Single gamma-ray spectrum at the $E_p = 1575$ keV resonance (target-crystal distance 8 cm).

earlier publications[1][12]. These levels are both excited at many resonances (see table I).

4.3. The 4.48 and 6.28 MeV levels. A transition to the fourth excited state was found in the fourfold cascade: (r) → (6.28) → (4.48) → → (3.73) → (0), observed e.g. at the $E_p = 1103$, 1306 (fig. 4*a*) and 1374 (fig. 4*b*) keV resonances. Fig. 5*b* shows the decay of the fourth excited state in a spectrum at $E_p = 1374$ keV coincident with the

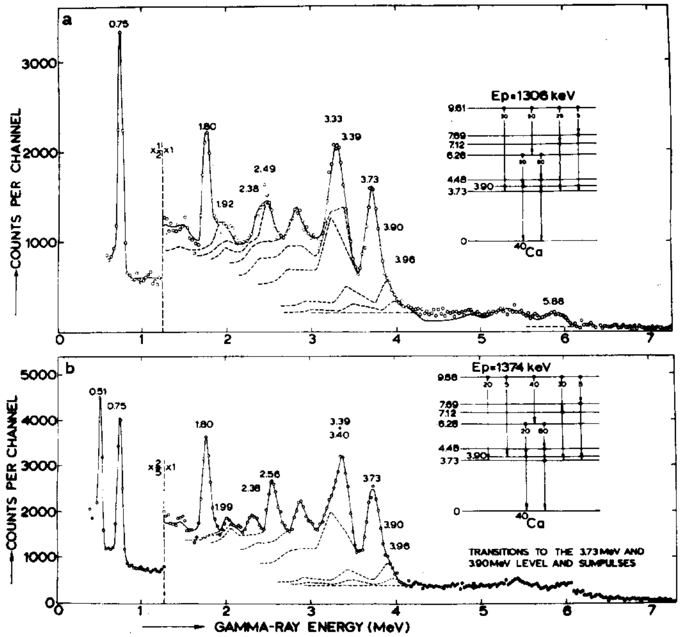

Fig. 4. Single gamma-ray spectra at the E_p = 1306 keV (a) and at the E_p = 1374 keV (b) resonances (target-crystal distance about 4 cm).

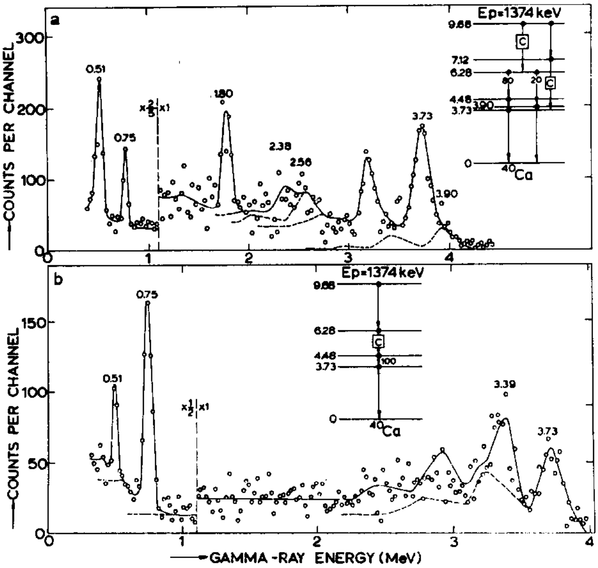

Fig. 5. Spectra coincident with the 3.40 MeV gamma line (a) and with the 1.80 MeV transition (b) at the E_p = 1374 keV resonance. The transitions in the coincidence gate have been marked with C in the decay schemes.

1.80 ± 0.02 MeV line. It proves that, within the experimental error, the 4.48 MeV level only decays to the 3.73 MeV level.

In addition, a gamma spectrum coincident with the 3.40 MeV primary transition was taken at the same resonance to illustrate the deexcitation of the 6.28 ± 0.02 MeV level, which decays 80% to the 4.48 MeV level and 20% to the 3.90 MeV level (fig. 5*a*). From similar spectra at other resonances one can conclude that the 2.56 MeV line in this spectrum is not the (6.26) → (3.73) transition, but belongs to the (*r*) → (7.12) → (3.73) → (0) cascade (see 4.10).

4.4. The 5.24 and 7.29 MeV levels. At the E_p = 1575 keV resonance (fig. 3) three mutually coincident gamma lines with nearly equal intensities were observed with energies E_γ = 2.04 ± 0.02, 2.57 ± 0.03 and 5.25 ± 0.10 MeV. In addition, a weak 3.39 MeV line was found, in coincidence with the 3.90 MeV line. These facts indicate the excitation of a new level at 7.29 ± 0.03 MeV, decaying mainly (75%) through the 5.24 MeV level and weakly (25%) through the 3.90 MeV level.

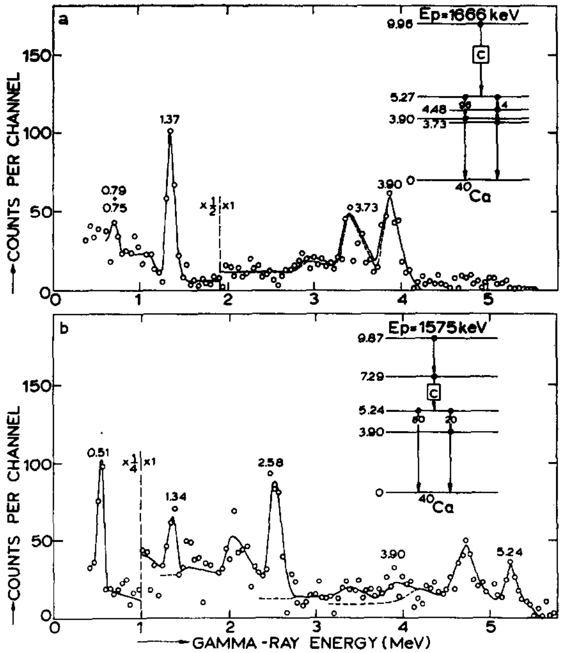

Fig. 6. Spectra coincident with the 4.69 MeV gamma line at the E_p = 1666 keV resonance (a) and with the 2.04 MeV gamma line at the E_p = 1575 keV resonance (b). The transitions in the coincidence gates have been marked with C in the decay schemes.

A spectrum coincident with the 2.04 MeV line (fig. 6*b*) determines the decay of the 5.24 MeV level, 80% to the ground state and 20% to the 3.90 MeV level.

4.5. The 5.27 MeV level. The $E_p = 1666$ keV resonance (fig. 7*b*) decays 80% to the 5.27 MeV level with a 4.69 MeV gamma ray. A spectrum coincident with this line (fig. 6*a*) shows that the 5.27 MeV level mainly decays with a 1.38 ± 0.02 MeV line to the 3.90 MeV level. However, from the single spectrum (fig. 7*b*) and from other coincidence spectra

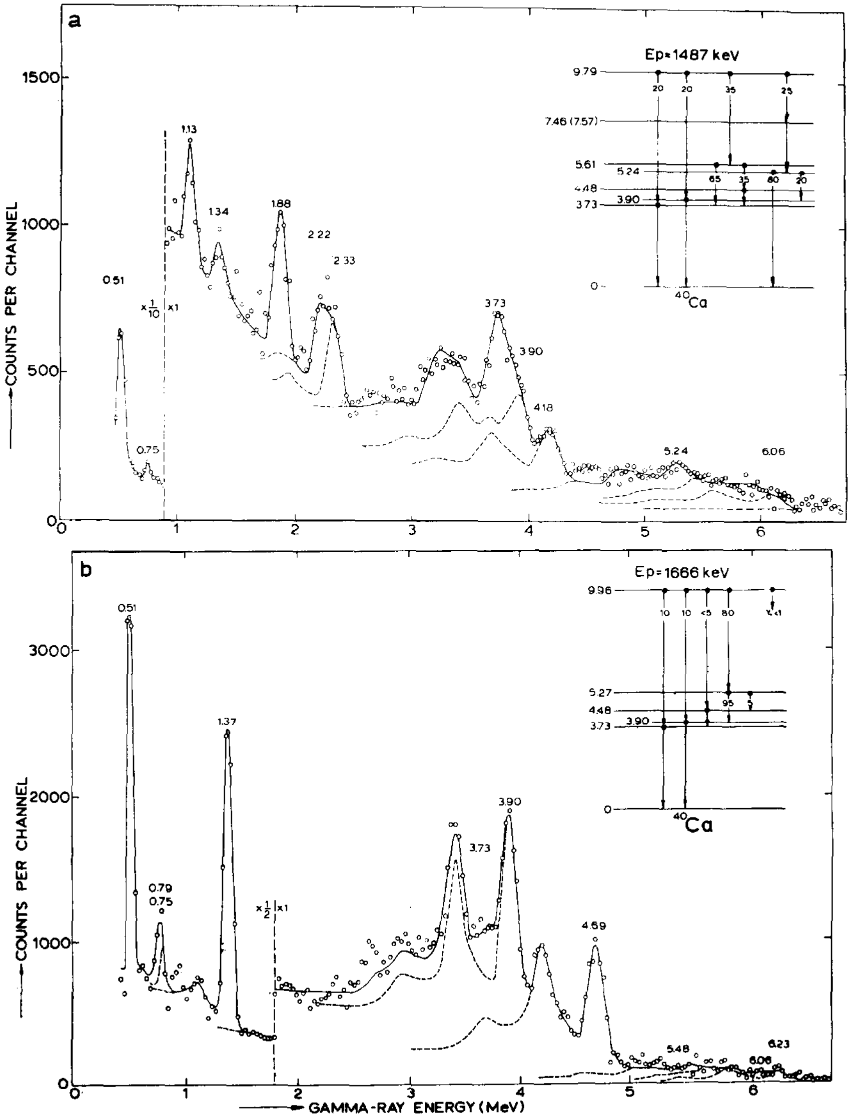

Fig. 7. Single gamma-ray spectra at the $E_p = 1487$ keV (a) and at the 1666 keV (b) resonances (target-crystal distance 8 cm).

the existence of the (5.27) → (4.48) transition could also be established. The branching ratio is 96 : 4.

4.6. **The 5.61 MeV level.** This level is excited at the $E_p = 1487$ keV resonance (fig. 7*a*). The resonance decays 35% with a 4.18 MeV line to the 5.61 MeV level of ^{40}Ca. Coincident with this line are 0.75, 1.13, 1.88 and 3.73 MeV gamma rays (fig. 8). The 5.61 MeV level thus decays to the 3.73 MeV and 4.48 MeV levels, with a branching ratio 65 : 35.

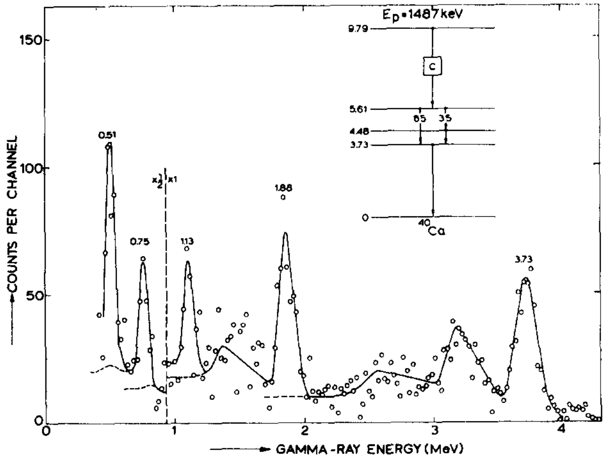

Fig. 8. Spectrum coincident with the 4.18 MeV gamma line (marked with C in the decay scheme) at the $E_p = 1487$ keV resonance.

4.7. **The 5.62 MeV level.** The $E_p = 1757$ keV resonance shows a strong (20%) 4.24 MeV gamma transition. A spectrum coincident with this line (fig. 9) shows two γ rays of 1.72 ± 0.02 and 3.90 MeV. Although it is possible that this indicates a level at 8.33 MeV in ^{40}Ca, it is more likely that this is a cascade through the 5.62 MeV level of ^{40}Ca decaying to the 3.90 MeV level.

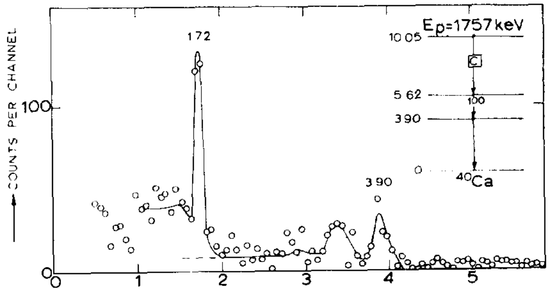

Fig. 9. Spectrum coincident with the 4.24 MeV gamma line (marked with C in the decay scheme) at the $E_p = 1757$ keV resonance.

4.8. The 5.90 and 6.03 MeV levels. These levels were only weakly excited, such that the exact decay could not be established. An estimate of the decay is given in table II.

4.9. The 6.94 MeV level. The $E_p = 1575$ keV resonance (fig. 3) decays 5% to the 6.94 MeV level with a 2.93 ± 0.03 MeV gamma ray. The intensity of the 6.94 MeV line is the same as that of the 2.93 MeV gamma line within the experimental error. This cascade has also been seen in coincidence spectra.

4.10. The 7.12 and 7.69 MeV levels. These two levels mainly are excited at those resonances, which also decay through the states at 3.73 and 6.28 MeV. Fig. 4 shows two single spectra of such resonances at $E_p = 1306$ and 1374 keV. The primary gamma rays in these spectra can be recognized by the observation that they shift upwards in energy by about 70 keV in going from the lower to the upper resonance. From these data one can conclude to the following new cascades, $(r) \to (7.69 \pm 0.05) \to (3.73) \to (0)$ and $(r) \to (7.12 \pm 0.03) \to (3.73) \to (0)$.

4.11. The 7.46 or 7.57 MeV level. At the $E_p = 1487$ keV resonance (fig. 7*a*) three mutually coincident gamma transitions with $E_\gamma = 2.21 \pm 0.05$, 2.32 ± 0.05 and 5.25 ± 0.05 MeV were observed. This triple cascade proceeds through the 5.24 MeV level, because the 1.34 and 3.90 MeV lines from the $(5.24) \to (3.90) \to (0)$ decay were also observed with the correct intensities (25% of that of the 5.24 MeV line, see table II). It is impossible to determine whether the primary gamma ray in the triple cascade feeds a 7.46 or a 7.57 MeV level.

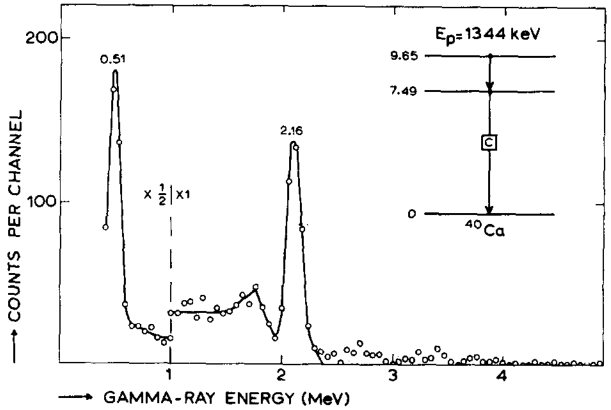

Fig. 10. Spectrum at the $E_p = 1344$ keV resonance coincident with the 7.49 MeV gamma ray. The transition in the coincidence gate has been marked with C in the decay scheme.

4.12. The 7.49 MeV level. This level is excited at the $E_p = 1344$ and 2043 keV resonances. Coincidence spectra at $E_p = 1344$ keV are given in fig. 10, showing the existence of the $(r) \rightarrow (7.49 \pm 0.03) \rightarrow (0)$ cascade. No other gamma rays de-exciting the 7.49 MeV level have been observed.

The gamma decay of the excited states (with $E_x < 8$ Mev) in ^{40}Ca has been compiled in a decay scheme in fig. 11.

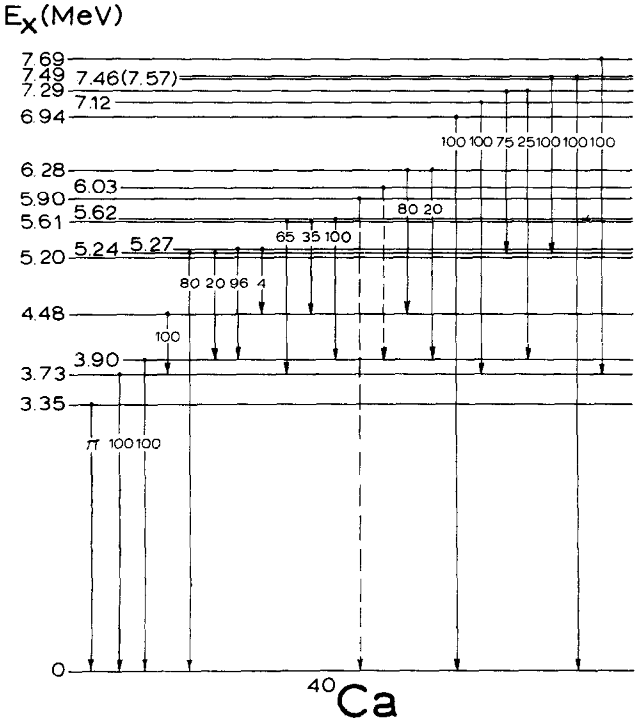

Fig. 11. Gamma-ray branching of energy levels ($E_x < 8$ MeV) in ^{40}Ca. The sum of the intensities of all gamma rays de-exciting a given level has been normalized to 100. The excitation energies are those given in table II rounded off to 10 keV. Above 6.3 MeV more excited states are known. In this figure, however, only those levels are given that were excited in the present experiment.

5. *Conclusions.* In the $E_p = 500$–2900 keV region fifty-three resonances could be assigned to the ^{39}K$(p, \gamma)^{40}$Ca reaction (table I). The existence of thirteen of these resonances was established earlier[1])[7])[8])[18]). The three resonances, at $E_p = 883 \pm 10$, 925 ± 10 and 980 ± 10 keV, given in ref. 15, have very probably to be ascribed to the ^{19}F$(p, \gamma)^{20}$Ne reaction. The energies and decay modes of corresponding resonances are in reasonable agreement with the present work, except for the decay given in ref. 18. It is possible that some gamma rays reported there and not observed in the

present work, stem from ^{41}K contamination. In particular, it seems unnecessary to assume the existence of a 4.70 MeV level in ^{40}Ca^{18}). The strengths given in ref. 8 and the strength of the $E_p = 1575$ keV resonance given in ref. 7 are in reasonable agreement with our data. However, the strength of the 1579 keV resonance given in the latter paper, is too high; this is probably caused by a contribution of the $E_p = 1577.2 \pm 1.0$ keV resonance in the ^{41}K(p, γ)^{42}Ca reaction. This assumption would also explain the large width of the $E_p = 1579$ keV resonance given in ref. 7. In the present experiment there is no indication that the width of the $E_p = 1579$ keV resonance is larger than that of the $E_p = 1575$ keV resonance.

The gamma decay of fifteen levels with an excitation energy up to 8 MeV has been determined; the results are tabulated in table II. All the eleven levels below $E_x = 6.1$ MeV, given by Braams^{2}), except the $E_x = 5.20$ MeV level, are excited at one or more resonances in the ^{39}K(p, γ)^{40}Ca reaction. Seven levels are excited in the $E_x = 6.1 - 8.0$ MeV region. By Poletti^{10}), eleven levels were found between 6.2 and 7.4 MeV with the ^{40}Ca($p, p' \gamma$)^{40}Ca reaction, but, with the exception of the 6.29 ± 0.02 MeV level, it is difficult to identify these levels with levels found in the present work, because of the increasing density of excited states above 6.5 MeV. By Bauer *e.a.*^{9}) Blum *e.a.*^{17}), Newton *e.a.*^{16}), Rowe *e.a.*^{14}), Springer *e.a.*^{20}) and Gray *e.a.*^{19}) altogether nine levels were found in the $E_x = 6.2$–8.0 MeV range, of which four easily can be identified with levels in the present experiment, viz. those at $E_x = 6.28$, 6.94, 7.12 and 7.49 MeV.

The present results on the gamma decay of ^{40}Ca levels with excitation energies up to 8 MeV are in agreement with earlier publications concerning the 3.73$^{1})^{12}$), 3.90$^{1})^{7})^{12}$), 4.48$^{12})^{14}$) and 6.28^{10}) MeV levels. Gamma branchings of other levels have not been published.

With the present knowledge of the level scheme of ^{40}Ca, it is tempting to speculate about spins and parities, but the authors would prefer to wait for the results of the gamma-gamma angular correlation measurements, mentioned in section 1.

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