

GAMMA-RAY BRANCHINGS, ENERGIES AND LIFETIMES OF ^{40}Ca LEVELS

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Abstract: The γ -decay of several $^{39}\text{K}(p, \gamma)^{40}\text{Ca}$ resonances in the range $E_p = 1.1\text{--}2.5$ MeV has been investigated with a 30 cm^3 Ge(Li) detector. The branchings of nine resonances and 19 bound states in ^{40}Ca were determined. Precision γ -ray energy measurements yielded the energies of 19 bound states of ^{40}Ca with errors ranging between 0.3 and 2.0 keV. A determination of the Q -value of the $^{39}\text{K}(p, \gamma)^{40}\text{Ca}$ reaction gave the result $Q = 8329.4 \pm 0.9$ keV. Mean lives (or limits) of 11 bound states in ^{40}Ca were found from measurements of γ -ray Doppler shifts. The results of the various measurements were compared with those given by other authors and with theoretical calculations.

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NUCLEAR REACTION $^{39}\text{K}(p, \gamma)$, $E = 1.1\text{--}2.5$ MeV; measured $\sigma(E; E_\gamma)$, Doppler-shift attenuation; deduced Q . ^{40}Ca deduced levels, $T_{1/2}$, γ -ray branching.
Enriched target, Ge(Li) detector.

1. Introduction

The nucleus ^{40}Ca has been subject to investigation by several authors¹⁾. Various data were obtained for the energies of bound states^{2, 3, 5, 7-9, 11)}, decay modes of states^{4, 5, 11)}, spins^{4, 6-10)}, parities⁶⁻¹⁰⁾ and mean lives^{9, 11, 25)}. The precision in the energy measurements was about 2–10 keV due to the limited resolution of the apparatus used in the experiments. Higher precision can be obtained from γ -ray spectra in the $^{39}\text{K}(p, \gamma)^{40}\text{Ca}$ reaction, when a Ge(Li) detector is used. Such measurements are described in this article. The experiments were highly facilitated by the work (with NaI detectors) of Leenhouts and Endt^{5, 6)}, who determined the resonance energies and strengths of some 50 resonances in the above reaction in the region $E_p = 0.5\text{--}2.9$ MeV as well as decay modes, spins and parities of many levels. In the present work, the γ -ray spectra from a selected number of resonances were analysed with a 30 cm^3 Ge(Li) detector, which enabled the determination of precise γ -ray and excitation energies and of decay modes.

The Q -value of the reaction was obtained from a precision measurement of the energy of the resonance at $E_p = 1345$ keV, in combination with the values found for the γ -ray energies in the cascades $r \rightarrow 3.90 \rightarrow 0$ and $r \rightarrow 3.74 \rightarrow 0$ (see subsect. 3.2.)

From a number of suitable γ -ray spectra, mean lives of bound states in ^{40}Ca were determined with the Doppler shift attenuation method (see subsect. 3.3). Part of the

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results has been compared with the values reported in refs. ^{1,9,11}) and with recent theoretical calculations ¹²⁻¹⁴).

2. Experimental procedure

The apparatus used to investigate (p, γ) reactions at the Utrecht laboratory has been described previously ¹⁵). Protons from the 3 MV Van de Graaff accelerator pass through a 90° analysing magnet and a cooling trap ¹⁶) before hitting the target. The magnetic field of the analysing magnet is measured with a NMR fluxmeter.

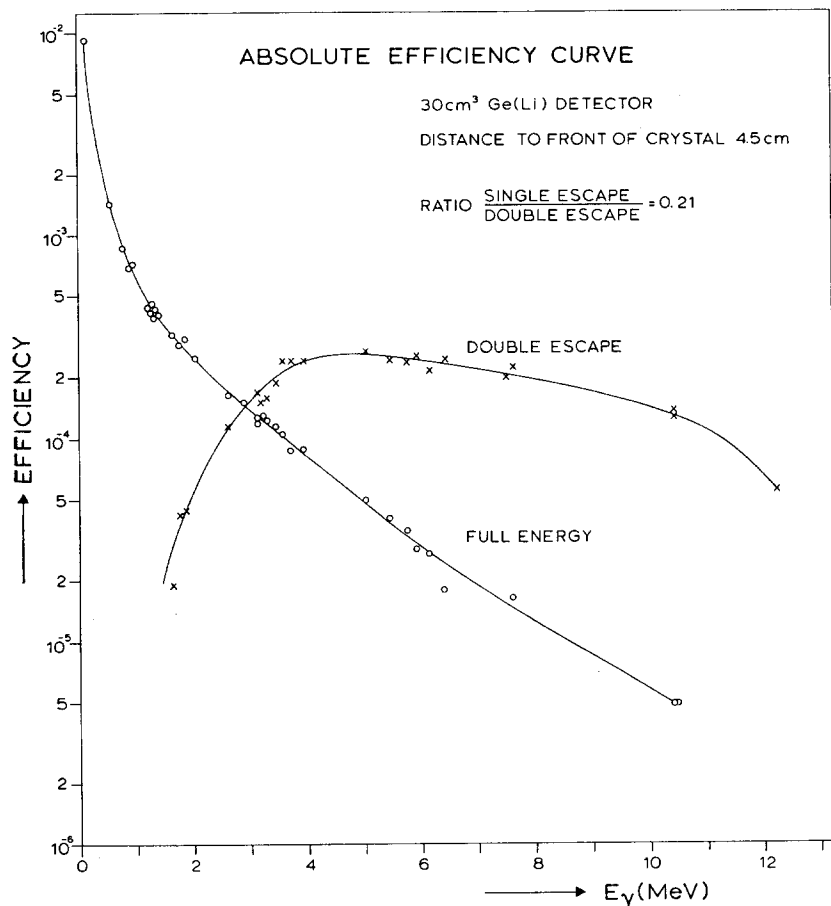


Fig. 1. Efficiency curves for the 30 cm³ Ge(Li) detector.

The targets consisting of K₂SO₄ enriched to 99.8 % in ³⁹K were evaporated onto tantalum backings. The backing forms part of the target holder such that it is water cooled directly. The thickness of the targets was generally between 2.0 and 5.0 keV for protons of 1 MeV (for the Doppler shifts, see subject. 3.3).

Gamma radiation was detected with a 30 cm^3 Ge(Li) detector from Gamma-Tech, Princeton, coupled to a 4096-channel Laben analyser. The resolution ranges from 5 keV at $E_\gamma = 1\text{ MeV}$ to 20 keV at $E_\gamma = 10\text{ MeV}$. The efficiency curve of the detector is given in fig. 1. It has been determined in a manner similar to that described by van der Leun *et al.*¹⁷⁾. Relative efficiencies were found (i) from the yield of γ -rays belonging to a two-step cascade, the intermediate level of which is exclusively fed and de-excited by the γ -rays concerned and (ii) from yields of γ -rays, of which the intensity ratio is well known from branching ratios. The radioactive source ^{56}Co and the reactions $^{30}\text{Si}(p, \gamma)^{31}\text{P}$ and $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ were chosen as quite suitable for these measurements^{18,1)}. The absolute intensity scale was found from yields of γ -rays emitted by calibrated radioactive sources of ^{88}Y , ^{60}Co and ^{24}Na [see ref. ¹⁸⁾]. The two curves in fig. 1 represent the efficiencies of the full-energy and double-escape peaks. The single-to-double escape ratio is constant (0.21) in the range 1.8–10.4 MeV within the limits of the error in the measurements.

For the determination of the γ -ray intensities, spectra were taken at $\theta = 55^\circ$ (see subsect. 3.1).

As described in previous work¹⁹⁾, the centres and areas of the peaks in the pulse-height spectra were determined by fitting the peaks to Gaussian curves with the aid of a computer program. For isolated peaks, a linear background was subtracted. In the Doppler shift measurements, the centres of the peaks were determined with the centroid ("centre of gravity") method (see subsect. 3.3).

With a second computer program, the peak positions were converted into energies [see also ref. ¹⁹⁾]. In this program, the calibration curve (energy versus peak position) is developed in a power series, and for its construction a least-squares procedure is used with the following constraints:

(i) accurately known energies of peaks from radioactive sources and of the annihilation peak, (ii) the 511.006 keV distances between full-energy, single-escape and double-escape peaks and (iii) the requirement that the energies of γ -rays emitted in cascades after correction for recoil should add up to the excitation energy of the resonance state.

Energies of γ -rays were measured at $\theta = 90^\circ$ in order to avoid Doppler shifts (see subsect. 3.2).

For the Doppler shifts, spectra were taken at $\theta = 0^\circ$ and 140° at $\theta = 0^\circ$ and 115° (see subsect. 3.3).

3. Results

3.1. GAMMA SPECTRA AND DECAY MODES OF RESONANCES AND BOUND STATES

From the resonances reported by Leenhouts *et al.*⁵⁾, those at $E_p = 1103, 1153, 1306, 1345, 1374, 1487, 1666, 2141$ and 2433 keV were selected as suitable for the determination of the decay modes of a maximum number of bound excited states in ^{40}Ca . The γ -ray spectra of the various resonances were measured at an angle of 55°

and a distance of 1.5 cm from the target to the front of the crystal. An example of such a spectrum is given in fig. 2.

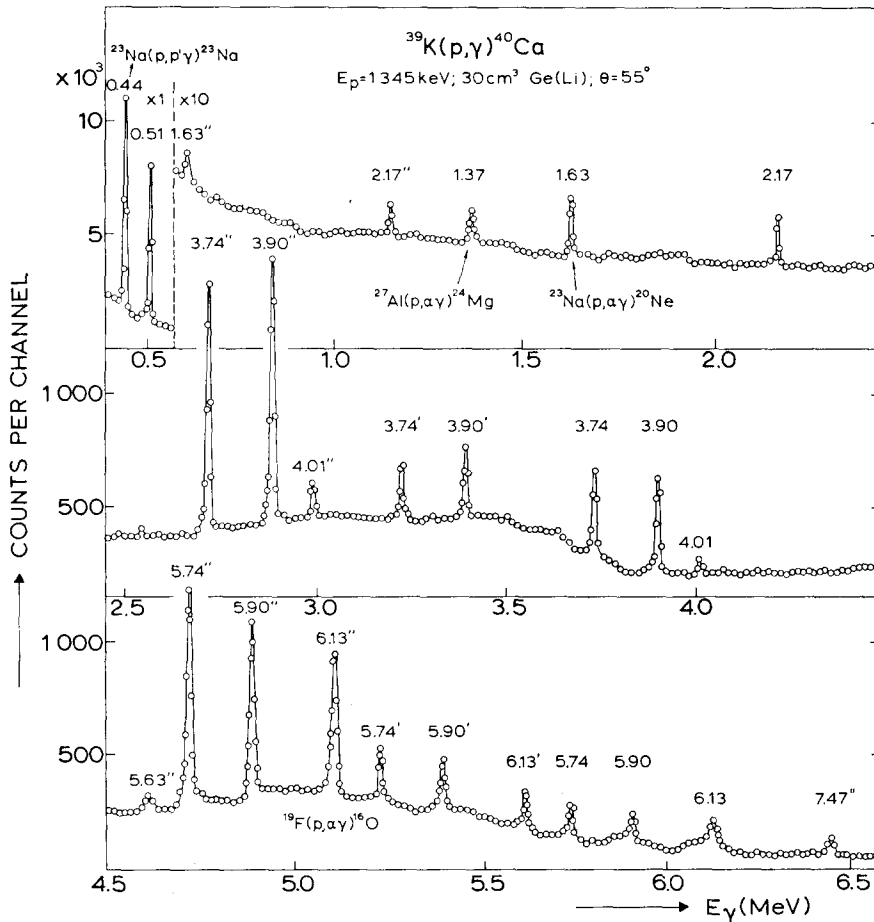


Fig. 2. Gamma-ray spectrum at the $E_p = 1345$ keV $^{39}\text{K}(p, \gamma)^{40}\text{Ca}$ resonance taken with a 30 cm^3 Ge(Li) detector at a distance of 1.5 cm from target to front of crystal and at an angle $\theta = 55^\circ$ to the beam direction. The peaks are labelled with the corresponding γ -ray energies; primes and double primes indicate single- and double-escape peaks, respectively. In the flat areas between the peaks, the averages of up to five consecutive channels are plotted.

The decay schemes of two of these resonances are shown in figs. 3 and 4. The values given in these figures for the (p, γ) resonance strength $S = (2J+1)\Gamma_\gamma\Gamma_p/\Gamma$ and the spins of the resonances are from refs. ^{5,6}). The high-energy resolution enables a detailed analysis of the decay of the resonances, therefore no measurements of coincidence spectra were needed to complete the decay schemes. The error in the intensities ranges from about 10 % for the strong transitions to about 50 % for the weak ones.

The branching ratios of the resonances and of several bound states in ^{40}Ca are summarized in fig. 5. The proton energies and the J^π values are from refs. ⁵⁻¹⁰) except for the resonance energy at 1345.4 ± 0.5 keV, which was determined separately in order to obtain an accurate result for the Q -value of the $^{39}\text{K}(p, \gamma)^{40}\text{Ca}$ reaction (see subsect. 3.2). The excitation energies of the resonances were calculated from this Q -value ($Q = 8329.4 \pm 0.9$ keV) in combination with the proton energies given in ref. ⁵) (again with the exception of the resonance at $E_p = 1345.4$ keV).

The decay schemes and branching ratios, though more detailed than those of Leenhouts *et al.* ⁵), agree largely with the results of these authors.

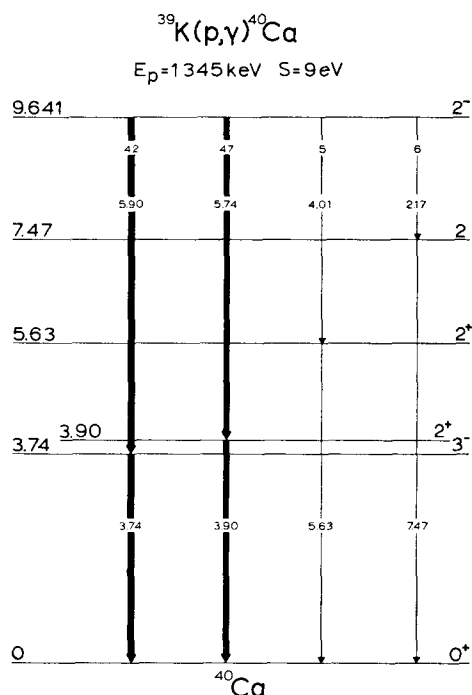


Fig. 3. Decay scheme corresponding to the γ -ray spectrum at the $E_p = 1345$ keV $^{39}\text{K}(p, \gamma)^{40}\text{Ca}$ resonance.

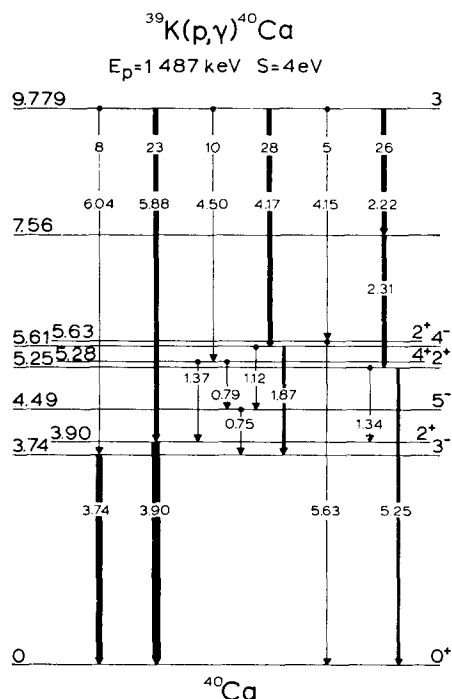


Fig. 4. Decay scheme corresponding to the γ -ray spectrum at the $E_p = 1487$ keV $^{39}\text{K}(p, \gamma)^{40}\text{Ca}$ resonance.

3.2. EXCITATION ENERGIES OF BOUND STATES AND THE REACTION Q -VALUE

Energies of γ -rays were determined by taking γ -ray spectra of the resonances at $E_p = 1103, 1153, 1306, 1345, 1487, 1666$ and 2141 keV at an angle of 90° and a distance of 3.5 cm from the target in the presence of suitable radioactive sources (^{88}Y , ^{60}Co , ^{24}Na and in some cases ^{56}Co). The sources were placed at such a distance from the detector, that the intensities of the calibration peaks and the stronger peaks in the (p, γ) spectrum were about the same (see fig. 6). The energy dispersion in these measurements varied from 1.5 to 2.5 keV per channel.

The calibration curve was constructed from the peaks of the radioactive sources, the annihilation peak and the 511.006 keV escape distances. The energies of the γ -rays emitted by the radioactive sources are from ref. ¹⁸). Frequently, the spectra

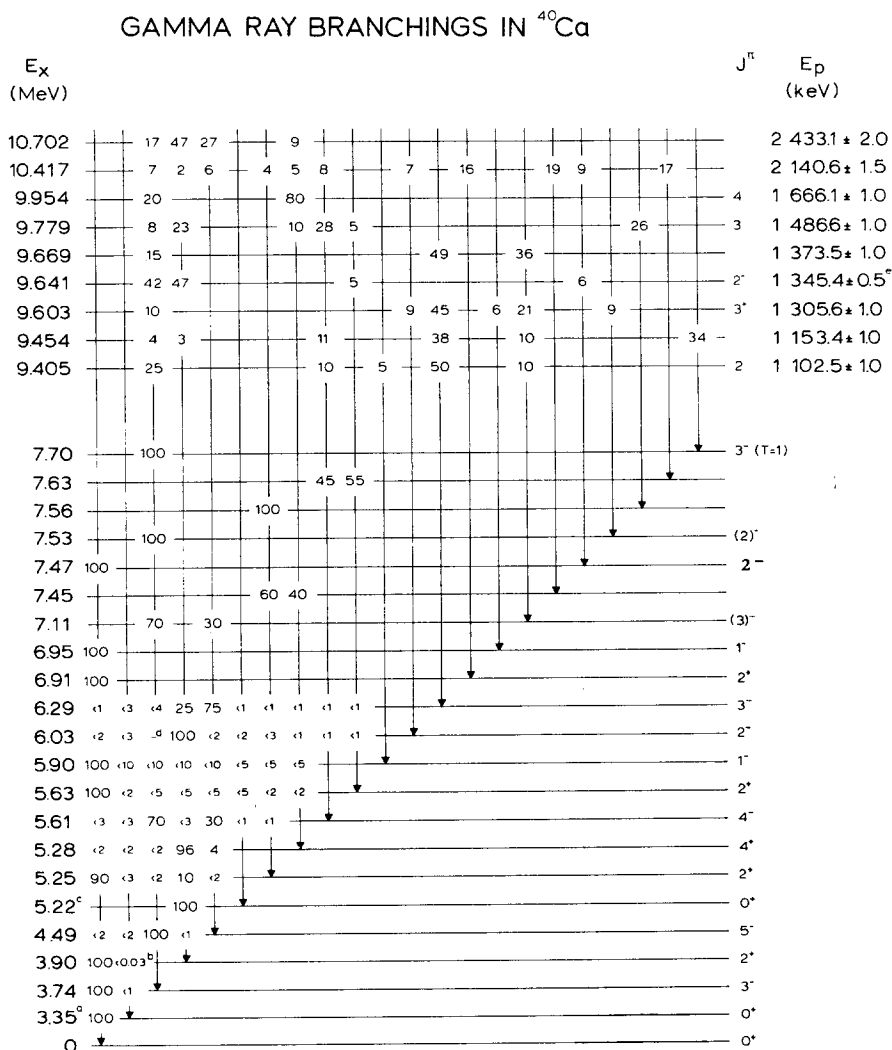


Fig. 5. Branching ratios of resonance levels and bound states in ^{40}Ca . Explanation of the entries: a) decay by internal pair formation, see ref. ¹); b) see ref. ²⁰); c) not excited in the present work, see subject. 4.1; d) decay to the 3.74 MeV level observed, see ref. ²⁸); e) E_p from the measurement described in subject. 3.2, the other E_p values are from ref. ⁵).

show the 6.13 MeV γ -ray peak due to the background reaction $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ with an energy of 6129.3 ± 0.4 keV [see also ref. ¹⁸)]. In such cases, this peak has been advantageously used for the calibration curve.

Sometimes, a γ -ray peak of the spectrum is situated between two calibration peaks lying rather close together. Then, the energy of the γ -ray can already be accurately found from linear interpolation between the positions of the calibration peaks. An example is shown in fig. 6.

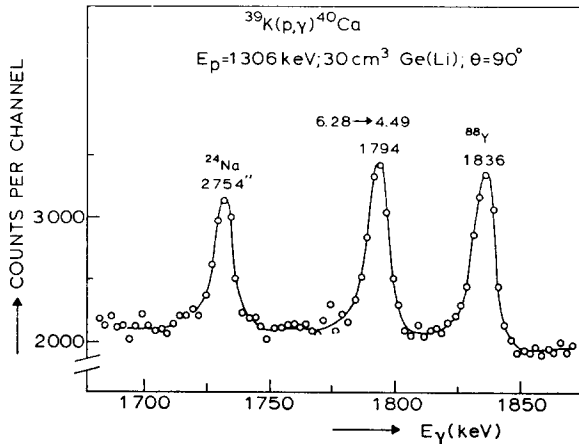


Fig. 6. Measurement of γ -ray energy in the $^{39}\text{K}(p, \gamma)^{40}\text{Ca}$ reaction. The 1.79 MeV γ -ray in the spectrum at the $E_p = 1306$ keV resonance is shown with γ -rays from the radioactive sources ^{88}Y and ^{24}Na . The spectrum was taken with a 30 cm^2 Ge(Li) detector at $\theta = 90^\circ$ and at a distance of 3.5 cm from target to front of crystal.

TABLE 1
Gamma-ray energies from the $^{39}\text{K}(p, \gamma)^{40}\text{Ca}$ reaction at $\theta = 90^\circ$

E_γ ^{a)} (keV)	Assignment (E_x in ^{40}Ca in keV)	E_γ ^{a)} (keV)	Assignment (E_x in ^{40}Ca in keV)
754.8 ± 0.3	$4492 \rightarrow 3737$	2622.4 ± 1.0	$7114 \rightarrow 4492$
1121.5 ± 0.6	$5614 \rightarrow 4492$	3377.0 ± 1.0	$7114 \rightarrow 3737$
1374.5 ± 0.4	$5279 \rightarrow 3905$	3736.8 ± 0.3	$3737 \rightarrow 0$
1793.9 ± 0.6	$6286 \rightarrow 4492$	3795.4 ± 1.0	$7533 \rightarrow 3737$
1877.0 ± 0.3	$5614 \rightarrow 3737$	3904.5 ± 0.3	$3905 \rightarrow 0$
2011.4 ± 1.3	$7626 \rightarrow 5614$	3958.6 ± 1.3	$7696 \rightarrow 3737$
2196.9 ± 1.9	$7447 \rightarrow 5249$	5248.9 ± 0.6	$5249 \rightarrow 0$
2313.0 ± 0.6	$7562 \rightarrow 5249$	5628.3 ± 1.3	$5629 \rightarrow 0$
2380.1 ± 1.0	$6286 \rightarrow 3905$	5902.7 ± 1.1	$5903 \rightarrow 0$

^{a)} Not corrected for recoil losses. When the energy of a certain γ -ray was measured at various resonances, the weighted mean of the measurements is taken. The quoted error is equal to the internal or the external error, whichever is the larger.

The energies found with the above methods for 18 γ -rays de-exciting ^{40}Ca bound states are presented in table 1. With the aid of these values, after recoil correction, the excitation energies of 15 levels in ^{40}Ca were obtained with errors up to 2.0 keV. These are given in table 2. Four additional ^{40}Ca excitation energies with errors up

TABLE 2
Energies of ^{40}Ca bound states

Present work (E_x in keV)	Previous work (E_x in keV)				
	MacDonald <i>et al.</i> ^{a)}	Erskine- Marinov ^{c)}	Grace- Poletti ^{d)}	Braams ^{e)}	J^π
				3352 \pm 4	0 ⁺
3737.0 \pm 0.3	3735.5 \pm 2.0	3738 \pm 5	3731 \pm 10	3734 \pm 4	3 ⁻
3904.7 \pm 0.3	3906.1 \pm 2.0	3907 \pm 4	3900 \pm 10	3904 \pm 4	2 ⁺
4491.7 \pm 0.4		4490 \pm 5	4482 \pm 10	4488 \pm 5	5 ⁻
	5215.5 \pm 3.0		5200 \pm 10	5208 \pm 8	0 ⁺
5249.3 \pm 0.6	5255.5 \pm 5.0		5244 \pm 10	5247 \pm 6	2 ⁺
5279.2 \pm 0.5	5281.4 \pm 3.0	5280 \pm 8	5274 \pm 10	5278 \pm 6	4 ⁺
5613.9 \pm 0.5		5614 \pm 6	5606 \pm 10	5612 \pm 8	4 ⁻
5628.7 \pm 1.3		5625 \pm 8	5619 \pm 10	5627 \pm 8	2 ⁺
5903.2 \pm 1.1		5902 \pm 6	5903 \pm 10	5907 \pm 8	1 ⁻
6025.1 \pm 1.8		6026 \pm 5	6028 \pm 10	6036 \pm 8	2 ⁻ ^{f)}
6285.4 \pm 0.8		6286 \pm 5	6285 \pm 10		3 ⁻
			6509 \pm 10		
			6544 \pm 10		
		6585 \pm 6	6583 \pm 10		3 ⁻
		6752 \pm 6	6750 \pm 10		(0, 2) ⁻
6909.4 \pm 1.1	6911 \pm 2		6909 \pm 10		2 ⁺
			6930 \pm 10		
6949.5 \pm 2.0	6954 \pm 3	6952 \pm 6	6948 \pm 10		1 ⁻
7114.2 \pm 0.8		7116 \pm 6	7114 \pm 10		(3) ⁻
			7240 \pm 10		
			7280 \pm 10		
			7300 \pm 10		0
			7399 \pm 10		
			7426 \pm 10		
7447.1 \pm 1.4			7453 \pm 10		
7468.4 \pm 1.4			7473 \pm 10		2 ⁻
7532.6 \pm 1.1		7532 \pm 6	7531 \pm 10		(2) ⁻
7562.4 \pm 0.9			7558 \pm 10		
			7602 \pm 10		
7625.7 \pm 1.4		7660 \pm 6	7655 \pm 10		4 ⁻
			7676 \pm 10		
7695.8 \pm 1.4		7696 \pm 6			3 ⁻

^{a)} $^{40}\text{Ca}(\text{p}, \text{p}')^{40}\text{Ca}$, see ref. ¹¹⁾.

^{b)} Resonant γ -ray scattering, see ref. ⁹⁾.

^{c)} $^{40}\text{Ca}(\text{p}, \text{p}')^{40}\text{Ca}$ and $^{39}\text{K}(^3\text{He}, \text{d})^{40}\text{Ca}$, see refs. ^{3, 7)}.

^{d)} $^{40}\text{Ca}(\text{p}, \text{p}')^{40}\text{Ca}$, see ref. ⁴⁾.

^{e)} $^{40}\text{Ca}(\text{p}, \text{p}')^{40}\text{Ca}$, see ref. ²⁾; corrected, see subsect. 4.1.

^{f)} Ref. ²⁸⁾, see subsect. 4.1.

to 1.8 keV also appearing in table 2 could be found with the additional aid of the reaction Q -value ($Q = 8329.4 \pm 0.9$ keV) on the basis of the requirement that the energies of the γ -rays emitted in cascades (after correction for recoil) should add up to the excitation energy of the resonance state (see sect. 2).

In columns 2–5 of table 2, the excitation energies are compared with previous results.

The reaction Q -value has been determined with the resonance which is located according to Leenhouts *et al.*⁵⁾ at $E_p = 1344.4 \pm 1.0$ keV. This value was then obtained by calibrating the proton energies of the various ^{40}Ca resonances with the well-known $E_p = 992.0$ keV resonance of the $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ reaction.

In order to determine the Q -value as accurately as possible, the proton energy of the above-mentioned ^{40}Ca resonance was remeasured by calibrating it with the aid of the neighbouring resonances at $E_p = 1316.88 \pm 0.07$ and 1381.3 ± 0.3 keV of the $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ reaction¹⁾. The result of this measurement (a relativistic correction for the proton energy¹⁵⁾ of 0.05 keV is included) was $E_p = 1345.4 \pm 0.5$ keV.

Further, the energies of the 5.74 MeV and 5.90 MeV transitions feeding the 3.90 MeV and 3.74 MeV levels (see fig. 3) were determined by energy measurements in the high-energy region of the γ -spectrum (fig. 2). This region lies between the 3.74 and 5.74 MeV full-energy peaks and contains also the two escape peaks of the above-mentioned 6.13 MeV γ -ray from the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ background reaction. For the calibration, the energies of the 3.74 MeV and 3.90 MeV peaks from table 2 were used in combination with those of the 6.13 MeV background peaks and the four 511.006 keV escape distances. It may be expected that a small error in the 3.74 and 3.90 MeV peaks will only have a minor influence on the values obtained from the calibration curve for the energies of the 5.74 and 5.90 MeV peaks, since these values will largely depend on the data pertaining to the peaks in the highest-energy part of the spectrum. In order to check this point, the conversion of the peak positions into energies was carried out by inserting in the computer program not only the energies of the 3.74 and 3.90 MeV peaks as given in table 2 but also other values differing from the former by ± 1 keV (i.e. about three times the error given in table 2). The various energies thus obtained for the 5.74 and 5.90 MeV peaks showed deviations never exceeding 0.3 keV.

Finally, the energies of the 5.74 MeV and 5.90 MeV transitions were calculated by taking the weighted mean of the energy values obtained for the corresponding peaks with a fourth-degree calibration curve. The errors in the resulting energies were evaluated by taking into account the uncertainties in the peak positions, in the 3.74 and 3.90 MeV energies (as described above) and in the energy and position of the 6.13 MeV peaks. The results are (after correction for recoil)

$$E(5.74) = 5736.7 \pm 0.8 \text{ keV}; E(5.90) = 5903.8 \pm 0.8 \text{ keV}.$$

From these energies, the excitation energies of the 3.74 and 3.90 MeV levels (see table 2) and the above resonance proton energy, the Q -value for the $^{39}\text{K}(p, \gamma)^{40}\text{Ca}$ reaction is calculated

$$Q = 8329.4 \pm 0.9 \text{ keV}.$$

This result is in agreement with but far more accurate than the value given in the 1964 mass table of Mattauch *et al.*²¹⁾; $Q = 8333.4 \pm 4.1$ keV.

3.3. MEAN LIVES OF BOUND STATES

The high resolution of the Ge(Li) detector made it also possible to determine mean lives of bound states in ^{40}Ca by means of Doppler shift measurements, although the shifts are small for this relatively heavy nucleus and at the low proton energies used here. For short-lived states, the shift for a γ -ray of $E_\gamma = 2$ MeV emitted in the direction of motion of the nucleus amounts to 3.30 keV at $E_p = 2$ MeV.

As a result of the low initial velocity of the recoiling ^{40}Ca ions ($v/c < 0.002$), the stopping process takes place in the target material, while the specific energy loss due to atomic collisions dominates the electronic part. The specific energy loss function given by Lindhard *et al.* ²²⁾ and the formulae of Blaugrund ²³⁾ for the evaluation of the Doppler shift (taking into account direction straggling) were used for the computation of the attenuation factor F as a function of the mean life τ_m as described in previous work ¹⁹⁾. In the computations, the correction for the electronic stopping cross section found by Ormrod *et al.* ²⁴⁾ resulting in a periodic variation around the Lindhard curve has been applied.

In the measurements of the Doppler shifts, γ -ray spectra were taken at $\theta = 0^\circ$ and 140° (distance target to front of crystal 5 cm) or at $\theta = 0^\circ$ and 115° (distance 4 cm) and stored in the two 2048-channel halves of the pulse-height analyser. The measurements were performed with relatively thick targets (between 20 and 50 $\mu\text{g}/\text{cm}^2$) to make sure that the ^{40}Ca ions were stopped in the target layer and not partly in the backing. The spectra were measured at a proton beam energy just above the low-energy edge of the resonance.

The measurements at the two angles were carried out in many short runs of 15–20 min as a precaution against gain drifts. The target room was temperature controlled, but no special gain stabilization was used. Drifting effects were checked by observing the positions of peaks from radioactive sources recorded simultaneously with the γ -spectrum and (or) peaks in the spectrum corresponding to transitions from long-lived states. It was found that the corrections due to gain drifts were at most 5 % of the maximum shift.

The correction resulting from the fact that the Ge(Li) detector was not an ideal point detector was estimated to be less than 3 % in the observed Doppler shift, which could be neglected.

The peak positions were determined with the centroid method. The energy dispersion used in the measurements varied between 1.9 and 3.2 keV per channel. An illustrative example of the results obtained is given in fig. 7.

In all cases except one (the 5.25 MeV level), the Doppler shifts were measured for transitions from levels, which were directly fed by the resonance state. Then, the mean lives of the resonance levels, all being smaller than 1 fs, can be neglected. Also, no correction is needed for the recoil caused by the primary γ -rays, because the angular distribution is symmetrical around $\theta = 90^\circ$. The 5.25 MeV level is excited in a cascade through the 7.56 MeV state (see fig. 4). Here, again no correction for recoil caused

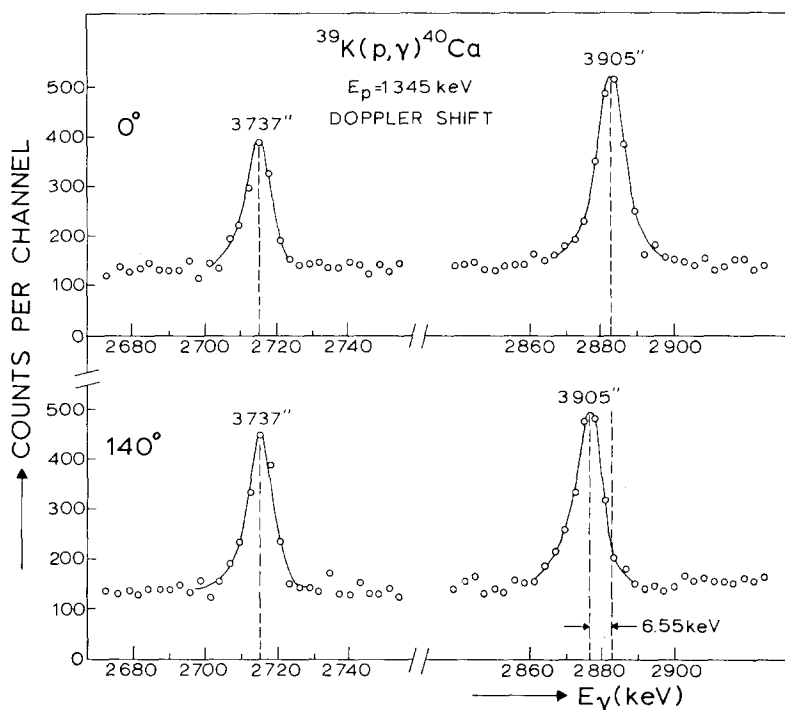


Fig. 7. Doppler shift measurement for the double-escape peaks of the 3.74 MeV and 3.90 MeV γ -rays in the spectrum of the $E_p = 1345$ keV resonance. The spectra are taken at a distance of 5.5 cm from target to front of crystal and at angles $\theta = 0^\circ$ and 140° . The 3.90 MeV peak shows a shift of 6.55 keV, which corresponds to 70 % of the full shift. For the 3.74 MeV peak no shift is observed within the experimental error.

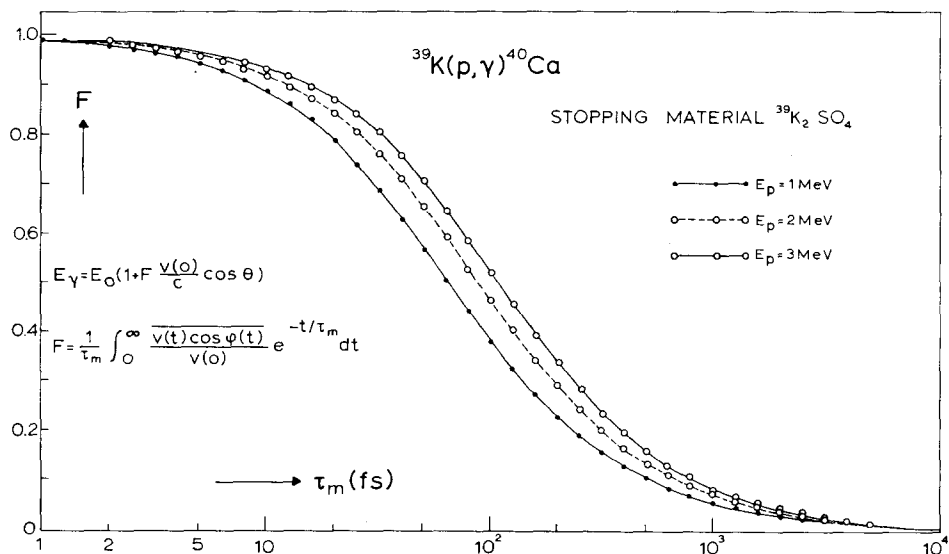


Fig. 8. The Doppler shift F expressed as a fraction of the full shift as a function of the mean life τ_m computed from the theory mentioned in subject. 3.3.

TABLE 3
Values or limits for the mean lives of ^{40}Ca bound states

E_x (MeV)	decay to E_x (MeV)	Present work			Previous work			
		$E_p^a)$ (keV)	$F^b)$	$\tau_m^c)$ (fs)	experimental τ_m (fs)	ref.	theoretical τ_m (fs) $^e)$	ref.
3.74	0	1345	0.02 ± 0.10	≥ 500	$(85 \pm 21) \times 10^3$	¹⁾	$(45 - 400) \times 10^3$	¹³⁾
3.90	0	1345	0.77 ± 0.06	$25 \pm 6^d)$	45 ± 15	¹⁾ ^{d)}	$(60 - 160) \times 10^3$	¹⁴⁾
4.49	3.74	2433	0.10 ± 0.15	≥ 250	≥ 1500	¹¹⁾	$120 - 140$	¹²⁾
5.25	0	1487	0.20 ± 0.05	220 ± 100	190 ± 30	¹¹⁾	$(19 - 38) \times 10^6$	¹⁴⁾
5.28	3.90	1666	0.10 ± 0.14	≥ 190	260 ± 80	¹⁾	$540 - 730$	¹²⁾
5.61	3.74	1153	0.40 ± 0.18	100 ± 80			$4000 - 9000$	¹⁴⁾
6.29	4.49	1306	0.12 ± 0.05	500 ± 300	410 ± 120	¹¹⁾	$600 - 1000$	¹³⁾
							$400 - 1400$	¹⁴⁾
6.91	0	2141	0.95 ± 0.15	≤ 50	3.3 ± 0.7	⁹⁾	$7 - 8$	¹²⁾
7.11	3.74	1306	0.63 ± 0.07	450 ± 130				
7.56	5.25	1487	0.60 ± 0.09	52 ± 18				
7.70	3.74	1153	1.00 ± 0.05	≤ 9			$0.8 - 1.6$	¹⁴⁾

^{a)} The proton energy of the resonance in the decay of which the transition is observed.

^{b)} Ratio between the measured shift and the full shift (for an infinitely short-lived level). The stopping material is in all cases $^{39}\text{K}_2\text{SO}_4$.

^{c)} Lower or higher limits correspond to the measured F -value plus or minus two times the standard deviation.

^{d)} Weighted mean; see subject 3.3.

^{e)} In this column both the maximum and the minimum values resulting from the theoretical calculations in refs. ¹²⁻¹⁴⁾ are given.

3.90 MeV γ -ray in the γ -ray spectrum at $E_p = 1345$ keV (see fig. 3), and the result is 32 ± 10 fs.

To have another check, a coincidence measurement was carried out. Coincidences were observed between the γ -rays de-exciting the 3.90 MeV level (detected with the Ge(Li) detector) and the feeding 5.74 MeV γ -rays for the detection of which a NaI scintillation crystal of 10 cm length and 10 cm diam. was used. In order to obtain an unshifted comparison peak, the discrimination channel was chosen such that it also contained the three peaks of the 5.90 MeV transition to the 3.74 MeV level [$\tau_m = 85 \pm 21$ ps, see ref. ¹⁾] as well as those of the 5.74 MeV transition to the 3.90 MeV level. Fig. 9 shows the main peaks of this spectrum.

The axis of the NaI detector made an angle of -90° with the direction of the proton beam, while the Ge(Li) detector was alternately placed at angles $\theta = +6.5$ and $+116.5^\circ$. The angle of 6.5° is the angle between the direction of the proton beam and the velocity of those ^{40}Ca nuclei which recoiled after the emission of a primary γ -ray to the NaI detector. The setting of 116.5° was dictated by the geometry of the apparatus and the aim to keep the distance from the target to the Ge(Li) detector small.

The coincidence measurement has two advantages. (i) It makes sure that the mean life of the 3.90 MeV level is measured without possible errors caused by feeding of the level from other bound states. (ii) The background in the coincidence spectrum is low (see fig. 9), therefore the error in the peak position is diminished. On the other hand there is, of course, the disadvantage of the low counting rate. The energy dispersion used in this experiment was 2.05 keV per channel. The peak positions were determined with the centroid method.

For the calculation of the mean life, the 3.90 MeV double-escape peak and the full-energy peak were used (the statistics of the single-escape peaks are too poor). During the long period of measurement (60 h), shifts of -0.60 ± 0.40 and -0.20 ± 0.40 keV in the position of the corresponding 3.74 MeV peaks were taken into account. For the 3.90 MeV double-escape and full-energy peaks, the measured shift is 5.65 ± 0.55 keV and 5.65 ± 0.60 keV, respectively, compared with the maximum possible shift for the above angles of 7.10 keV. The mean value of $F = 0.80 \pm 0.06$ gives a mean life of 21 ± 7 fs.

The weighted mean of this value and of the value of 32 ± 10 fs found from the measurement of the single spectrum mentioned above is $\tau_m(3.90) = 25 \pm 6$ fs. The quoted error is the internal one (which is larger than the external error).

4. Discussion

4.1. EXCITATION ENERGIES OF ^{40}Ca BOUND STATES

Table 2 shows that the excitation energies obtained from the present measurements are in agreement with (but more accurate than) those found by other authors. The excitation energies of Braams in column 5 of this table have been corrected in order to account for the change in the calibration energy upon which his measurements

were based. The value for the energy of the ^{210}Po alpha particles used by Braams was 5298.8 keV [ref. ²⁶], while the current value is 5304 ± 5 keV [ref. ²⁷].

Recent measurements by Anderson *et al.* ²⁸) show that the 6.03 MeV level is in fact a doublet, of which the components are 2 to 4 keV apart. In the present work, the component with a 100 % decay to the 3.90 MeV level was observed.

The 5.22 MeV level appearing in the branching scheme of fig. 5 has been investigated by Grace and Poletti ⁴) and by MacDonald *et al.* ¹¹), who proved that it has $J^\pi = 0^+$. Neither in the (p, γ) measurements of Leenhouts *et al.* ⁵) nor in the present work was this level excited, while transitions from the resonance state to the 0^+ ground state and the 0^+ level at $E_x = 3.35$ MeV were observed in various resonances.

4.2. LIFETIMES

The first measurements of mean lives in ^{40}Ca were carried out by Blum *et al.* ²⁵). Recently, the mean lives of five excited states in this nucleus were measured by MacDonald *et al.* ¹¹) and those of two other states by Metzger ⁹). From the present Doppler shift measurements, the mean lives (or limits) of 11 bound states could be determined; four of them were not measured previously.

TABLE 4
Strengths of γ -transitions between bound states of ^{40}Ca

Transition (E_x in MeV)	$J_i^\pi \rightarrow J_f^\pi$	I_γ^a (meV)	Strength in Weisskopf units $ M ^2$	
			M1 ($\times 10^3$)	E2
3.90 \rightarrow 0	$2^+ \rightarrow 0^+$	26 \pm 8		4.5 ± 1.5
3.90 \rightarrow 3.35	$2^+ \rightarrow 0^+$	< 0.008		< 23
5.61 \rightarrow 3.74	$4^- \rightarrow 3^-$	5 \pm 3	32 \pm 25	2.1 ± 1.7^b)
5.61 \rightarrow 4.49	$4^- \rightarrow 5^-$	2 \pm 1	45 \pm 35	53 \pm 41 ^e)
7.11 \rightarrow 3.74	$(3)^- \rightarrow 3^-$	1.0 \pm 0.3	1.3 \pm 0.4 ^d)	
7.11 \rightarrow 4.49	$(3)^- \rightarrow 5^-$	0.5 \pm 0.2		0.6 ± 0.2
7.70 \rightarrow 3.74	$3^- \rightarrow 3^-$	≥ 73	$\geq 57^e$)	

^a) Obtained from the mean life measurements, see table 3.

^b) Mixing ratio is 0.27 ± 0.05 , see ref. ⁶).

^c) Mixing ratio is 0.7 ± 0.2 , see ref. ⁶).

^d) Pure M1 transition assumed, see also ref. ⁸).

^e) Pure M1 transition assumed ($\Delta T = 1$).

Theoretical calculations of transition probabilities were reported by Gerace *et al.* ^{12,13}) and Dieperink *et al.* ¹⁴). In the work of the former authors, even-parity states in ^{40}Ca are described as mixtures of low-lying deformed states with one-particles-one-hole shell-model states. The calculations of Dieperink *et al.* are based on spherical one-particle-one-hole shell-model states. There is rather good agreement between the results of the two authors.

Table 3 shows that the experimental values found for the mean lives in the present work are in good agreement with those obtained by other measurements, while the theoretical values generally agree roughly with the experimental data within a factor 2 or 3. In subsect. 3.3, the mean life of the 3.90 MeV level has already been discussed.

Table 4 shows the strengths of the γ -rays transitions from the levels at 5.61, 7.11 and 7.70 MeV, of which the mean lives were not measured previously, and from the level at 3.90 MeV, of which the mean life was found with more precision than before (subsect. 3.3). As may be expected for this self-conjugated nucleus, the $\Delta T = 0$ M1 transitions are strongly inhibited in agreement with the results of other authors.

Measurements of Doppler shifts can be helpful when uncertainty exists about the decay of a resonance level. Such a case occurs at the $E_p = 1487$ keV resonance, as has been remarked by Leenhouts *et al.*⁵). The resonance level decays either by the cascade $r \rightarrow 7.47 \rightarrow 5.25$ with a feeding γ -ray of 2.312 MeV and a de-exciting 2.218 MeV γ -ray or by the cascade $r \rightarrow 7.56 \rightarrow 5.25$ where the energy of the feeding γ -ray would be 2.218 MeV and that of the de-exciting one 2.312 MeV. A Doppler shift measurement showed that the 2.218 MeV peak had full shift, while the 2.312 MeV peak was only partially shifted ($\tau_m = 52 \pm 18$ fs). This proves that the resonance state ($\tau_m < 1$ fs) in this case decays to the 7.56 MeV level.

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