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# INVESTIGATION OF $^{36}$Ar WITH THE $^{35}$Cl(p, $\gamma$)$^{36}$Ar REACTION
## (I). Branching ratios, excitation energies and lifetimes of $^{36}$Ar levels

G. A. HOKKEN, J. A. J. G. HENDRICX and J. DE KOGEL
*Fysisch Laboratorium, Rijksuniversiteit, Utrecht, The Netherlands*

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**Abstract:** The $\gamma$-ray spectra of 20 resonances in the $^{35}$Cl(p, $\gamma$)$^{36}$Ar reaction have been measured with a Ge(Li) detector. Branching ratios and energies of the resonances and of 29 bound states have been determined. Two new doublets have been found at $E_x$ = 7.14 and 7.25 MeV. The reaction $Q$-value has been determined as $Q_0$ = 8506.9±0.3 keV; this value was used to deduce accurate proton energies of the resonances. Lifetimes of 22 bound states have been obtained from Doppler-shift attenuation measurements.

E | NUCLEAR REACTIONS $^{35}$Cl(p, $\gamma$), $E$ = 0.8-2.3 MeV; measured $E_\gamma$, $I_\gamma$, Doppler-shift attenuation, $Q$. $^{36}$Ar deduced levels, $\gamma$-branching, $T_{\frac{1}{2}}$. Enriched target.

## 1. Introduction

The level scheme of $^{36}$Ar has been studied via the reactions $^{39}$K(p, $\alpha$)$^{36}$Ar [refs. [1,2])] and $^{35}$Cl($\tau$, d)$^{36}$Ar [ref. [3])]. The latter reaction has given parities and spin restrictions for 31 levels of $^{36}$Ar up to $E_x$ = 8.5 MeV. The $\gamma$-ray spectra of 65 resonances in the $^{35}$Cl(p, $\gamma$)$^{36}$Ar reaction in the energy-range $E_p$ = 0.4–3.1 MeV have been investigated with scintillation spectrometers by Erné [4,5]); spins and parities of many levels have been determined.

The purpose of the present study was to reinvestigate with a Ge(Li) detector the decay scheme of the bound states and of some resonances, to measure accurate excitation energies and finally to establish lifetimes of bound states. In the next paper the results of angular distribution measurements will be given.

## 2. Experimental details

The experiment was performed with the proton beam, typically about 10 to 20 $\mu$A, from the Utrecht 3 MV Van de Graaff accelerator. The apparatus has been described previously by Van Rinsvelt and Smith [6]). The $BaC_2$ targets enriched to 99.3% in $^{35}$Cl were evaporated onto tantalum backings which could be water-cooled directly. The average thickness of the targets was about 4 keV at $E_p$ = 1 MeV.

The $\gamma$-rays were detected with a 45 cm$^3$ Ge(Li) detector coupled to a 4096-channel Laben analyser. The energy resolution was 4 keV at $E_\gamma$ = 1 MeV and 10 keV at

$E_\gamma = 8$ MeV. The $\gamma$-ray intensities were obtained by taking spectra with the detector placed at $\theta = 55°$ with respect to the proton beam direction and the $\gamma$-ray energies were measured at $\theta = 90°$.

A computer program fitted the peaks in the pulse-height spectra to Gaussian curves, from which the areas and center positions of the peaks were determined. With another program the energies of the peaks in the pulse-height spectra were determined. The input data for this second program are accurately known energies of $\gamma$-rays from radioactive sources, distances between full-energy, single- and double-escape peaks, and energy summing relations between cross-over and cascade transitions (especially necessary for the high energy calibration). Peak positions were fitted with a polynomial of which the degree was lower than nine in the $\gamma$-ray energy.

Doppler shifts were measured by taking spectra in many short runs alternatingly at $\theta = 0°$ and 133°.

## 3. Results

### 3.1. DECAY SCHEMES OF RESONANCES AND BOUND STATES

Branchings of 20 resonances and of 29 bound states are shown in figs. 1 and 2, respectively. The strengths of the resonances have been determined by Erné [4]. The spin and parity assignments are from the work of Erné [5], Moinester and Alford [3], Hardy *et al.* [7,8], Bruynesteyn [9]) and from the present work (next paper). Only those resonances were reinvestigated which are not mainly decaying to the $^{36}$Ar ground state or first excited state. The bound-state branchings given in fig. 2 are mostly averages of the results obtained at several resonances. For the excitation energies see subsect. 3.2.

It is remarkable that some high-lying states are strongly excited. At the $E_p = 1098$ keV resonance e.g. the $E_x = 7.57$ MeV level is excited via a 21 % branch with $E_\gamma = 2.00$ MeV (see fig. 4).

A comparison of the present level scheme with refs. [1-4]) shows that two new doublets have been found at $E_x = 7.14$ and $7.25-7.26$ MeV. The 7.14 MeV components have different lifetimes (see subsect. 3.4) and branching ratios (fig. 2). The 7.25 and 7.26 MeV levels only have significantly different energies (subsect. 3.2). The 6.84 MeV doublet already mentioned by Erné has been confirmed by means of the different decay schemes (see figs. 2 and 3), energies (subsect. 3.2) and lifetimes (subsect. 3.4) of the components.

### 3.2. EXCITATION ENERGIES AND THE REACTION *Q*-VALUE

The $\gamma$-ray spectra of 12 selected resonances have been measured at $\theta = 90°$ simultaneously with those of radioactive sources such as $^{60}$Co, $^{88}$Y, $^{208}$Tl and $^{24}$Na. The distance of these sources to the detector was chosen in such a way that the number of counts in the calibration peaks was about the same as that in the stronger peaks of the spectrum. An energy calibration curve was constructed as indicated in sect. 2.

The energies of the $\gamma$-rays of the radioactive sources are from ref. [10]) and it is taken into account that the uncertainties in these energies are correlated [ref. [23])]. These spectra yield the precise energies of a number of low-energy ($E_\gamma$ < 4.0 MeV) secondary transitions in $^{36}$Ar from which (after recoil correction) the excitation energies of

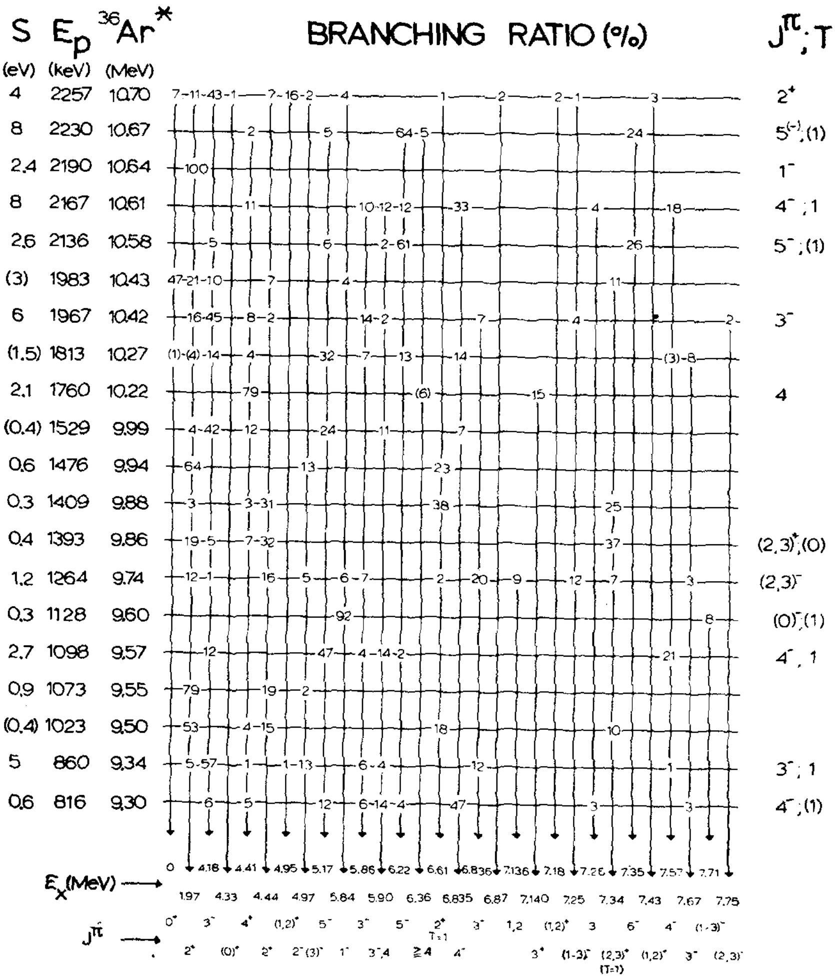


Fig. 1. Branching ratios of $^{35}$Cl(p,$\gamma$)$^{36}$Ar resonance levels. The errors range from 50 % for the weakest transitions to about 5 % for the strong ones; $S = (2J+1)\Gamma_p\Gamma_\gamma/\Gamma$.

17 bound states could be obtained. Some of these levels (like those at 4.18, 4.44 and 4.95 MeV) not only decay by means of a cascade through the first excited state (used for the energy determination), but also show a ground state transition. The latter then were used as secondary internal standards to extend the energy calibration up to $E_\gamma$ = 6 MeV. With this calibration the energies of another 12 bound states could be

obtained, mainly by means of the $\gamma$-rays by which they decay, although for some weakly excited states also primary transitions have been used. This latter method was only applied at resonances which also decay through cascades of low-energy $\gamma$-rays. The results for the bound states are given in table 1.

The excitation energies of the resonance levels (except for the $E_p = 1073$ keV

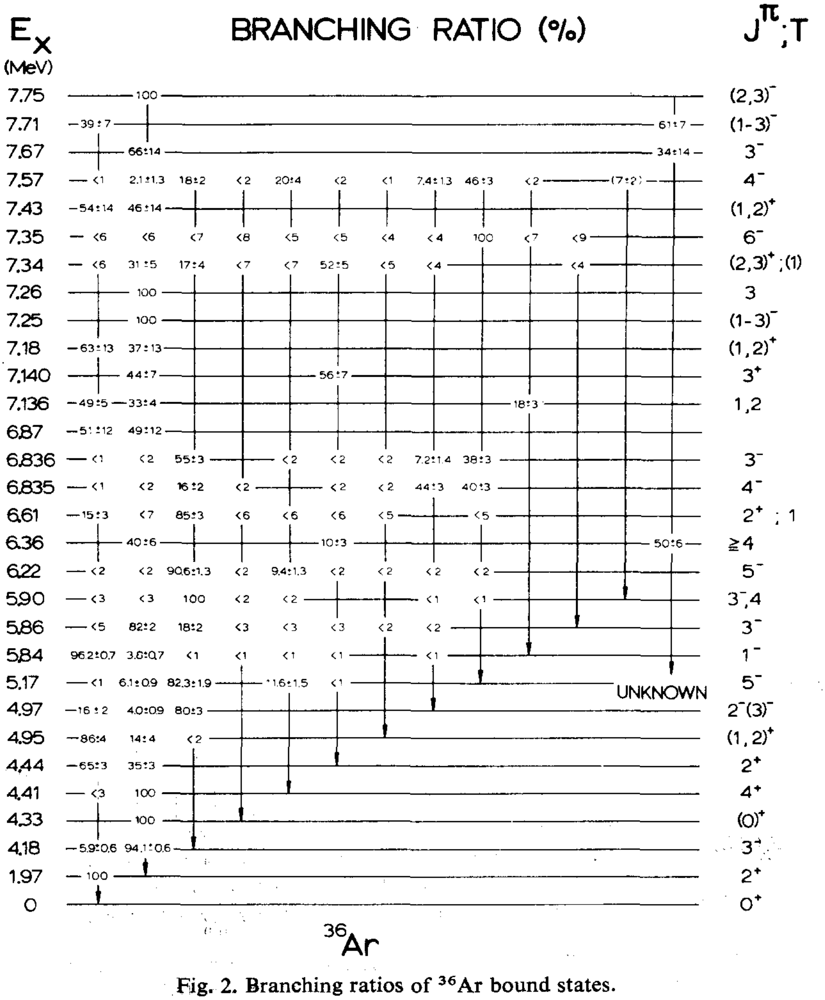


Fig. 2. Branching ratios of $^{36}$Ar bound states.

resonance, see below) could also be obtained accurately because all of them decay by one or more primary $\gamma$-rays with $E_\gamma < 6$ MeV. The excitation energies of some resonances have been calculated from a $\theta = 0°$ or $55°$ spectrum, taking into account Doppler shifts and recoil shifts. For the excitation energies obtained see table 2. An accurate reaction $Q$-value was determined as follows. The proton energies of the $E_p = 1073$ and 1098 keV resonances were calibrated against the $E_p = 991.907\pm$

TABLE 1
Excitation energies (in keV) of $^{36}$Ar bound states

| Present work | Ref. [1] [a] | Ref. [3] | Present work | Ref. [1] [a] | Ref. [3] |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 6 835.2±0.2 | 6 830±20 | 6 830 |
| 1 970.39±0.05 | 1 970.1± 0.7 | 1 976 | 6 836.5±0.2 | | |
| 4 178.33±0.11 | 4 177.9± 0.7 | 4 179 | 6 868.5±1.0 | 6 860±20 | 6 861 |
| 4 329.7 ±0.8 | 4 330 ± 5 | 4 331 | 7 136.3±1.8 | 7 140±20 | 7 131 |
| 4 414.36±0.17 | 4 413 ± 5 | 4 416 | 7.139.5±0.4 | | |
| 4 440.1 ±0.2 | 4 440.1± 1.2 | 4 442 | 7 178.7±0.9 | 7 180±20 | 7 171 |
| 4 951.9 ±0.5 | 4 957 ± 5 | 4 948 | 7 247.3±0.7 | 7 250±20 | 7 241 |
| 4 974.05±0.19 | 4 976 ± 5 | 4 971 | 7 258.5±1.0 | | |
| 5 171.14±0.16 | 5 171 ± 5 | 5 165 | | 7 310±30 | |
| | 5 190 ±10 | 5 203 | 7 335.6±0.7 | 7 330±30 | 7 330 |
| 5 835.9 ±0.8 | 5 830 ±10 | 5 826 | 7 354.0±0.3 | 7 350±30 | |
| 5 856.7 ±0.2 | 5 860 ±10 | 5 847 | 7 432.9±0.9 | 7 430±30 | 7 424 |
| 5 895.9 ±0.2 | 5 890 ±10 | | | 7 520±30 | |
| | 6 130 ±10 | | | (7 560±30) | |
| 6 217.1 ±0.3 | 6 210 ±10 | | 7 573.1±0.3 | 7 580±30 | 7 567 |
| 6 356.1 ±0.9 | 6 350 ±10 | | 7 671.9±0.7 | 7 680±30 | 7 667 |
| 6 610.8 ±0.3 | 6 611.9± 0.9 | 6 605 | 7 710.7±1.8 | 7 720±30 | 7 706 |
| | 6 630 ±20 | | 7 749.9±0.6 | 7 750±30 | 7 743 |
| | 6 730 ±20 | 6 721 | | | all ±10 |
| | | all ±10 | | | |

[a]) Ref. [1]), as corrected in ref. [3]).

TABLE 2
Proton and excitation energies of some $^{35}$Cl(p, $\gamma$)$^{36}$Ar resonances

| $E_p$ (keV) | | $E_x$ (keV) | |
|---|---|---|---|
| present work | ref. [15]) | present work | |
| 816.2±0,4 | 817.4±1.0 | 9 300.2±0.3 | |
| 859.9±0.4 | 860.1±1.0 | 9 342.7±0.3 | |
| 1 023.1±1.3 | 1 024 ±2 | 9 501.3±1.2 | [a]) |
| 1 073.0±0.3 | 1 074 ±2 | 9 550.0±0.4 | |
| 1 098.1±0.3 | 1 098 ±2 | 9 574.0±0.3 | |
| 1 128.3±1.7 | 1 130 ±2 | 9 603.6±1.6 | [a]) |
| 1 264.0±0.9 | 1 268 ±2 | 9 735.5±0.8 | |
| 1 393.0±0.9 | 1 397 ±2 | 9 860.9±0.8 | [a]) |
| 1 409.1±1.1 | 1 413 ±2 | 9 876.5±1.0 | |
| 1 475.6±1.2 | 1 478 ±2 | 9 941.2±1.1 | [a]) |
| 1 528.6±0.9 | 1 529 ±2 | 9 992.7±0.8 | [a]) |
| 1 759.9±0.8 | 1 762 ±3 | 10 217.5±0.7 | |
| 1 813.3±0.6 | 1 816 ±3 | 10 269.4±0.5 | |
| 1 967 ±3 | 1 970 ±3 | 10 418 ±3 | [b]) |
| 1 983 ±3 | 1 985 ±3 | 10 434 ±3 | [a, b]) |
| 2 135.7±1.3 | 2 136 ±3 | 10 582.7±1.2 | [a]) |
| 2 166.9±0.5 | 2 169 ±3 | 10 613.1±0.4 | |
| 2 190 ±3 | 2 192 ±3 | 10 635 ±3 | [a, b]) |
| 2 230.4±0.7 | 2 232 ±3 | 10 674.8±0.6 | |
| 2 256.7±0.9 | 2 257 ±3 | 10 700.3±0.8 | |

[a]) This excitation energy is calculated from a $\theta = 0°$ or 55° spectrum (energies are corrected for Doppler shifts).

[b]) These resonances have a relatively large $\Gamma_t$ [ref. [4])].

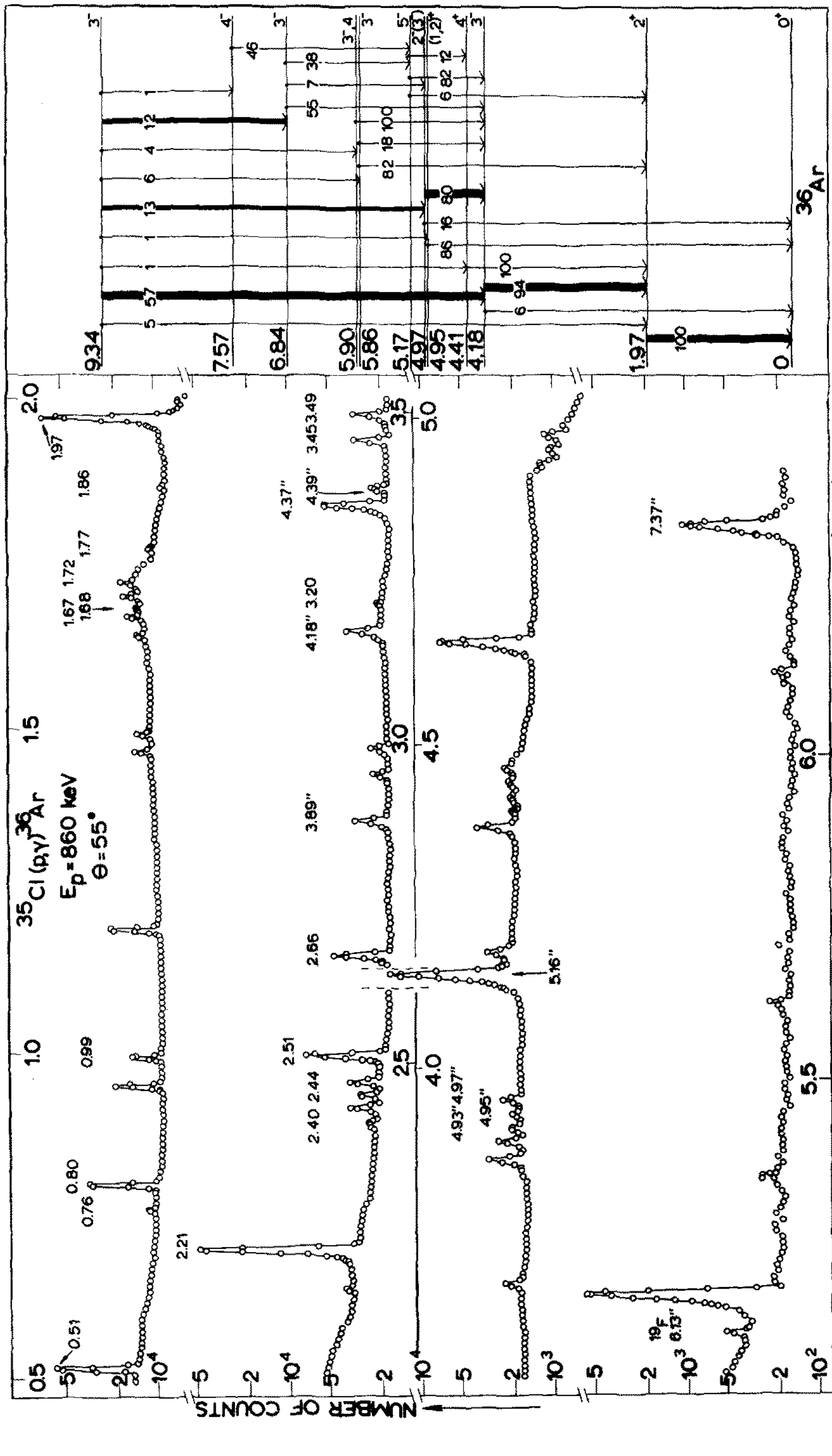


Fig. 3. Gamma-ray spectrum and decay scheme at the $E_p$ = 860 keV $^{35}$Cl(p, γ)$^{36}$Ar resonance, measured with a 45 cm$^3$ Ge(Li) detector at $\theta$ = 55°. Double primes indicate double-escape peaks. In the flat areas between peaks, the averages of four consecutive channels are plotted.

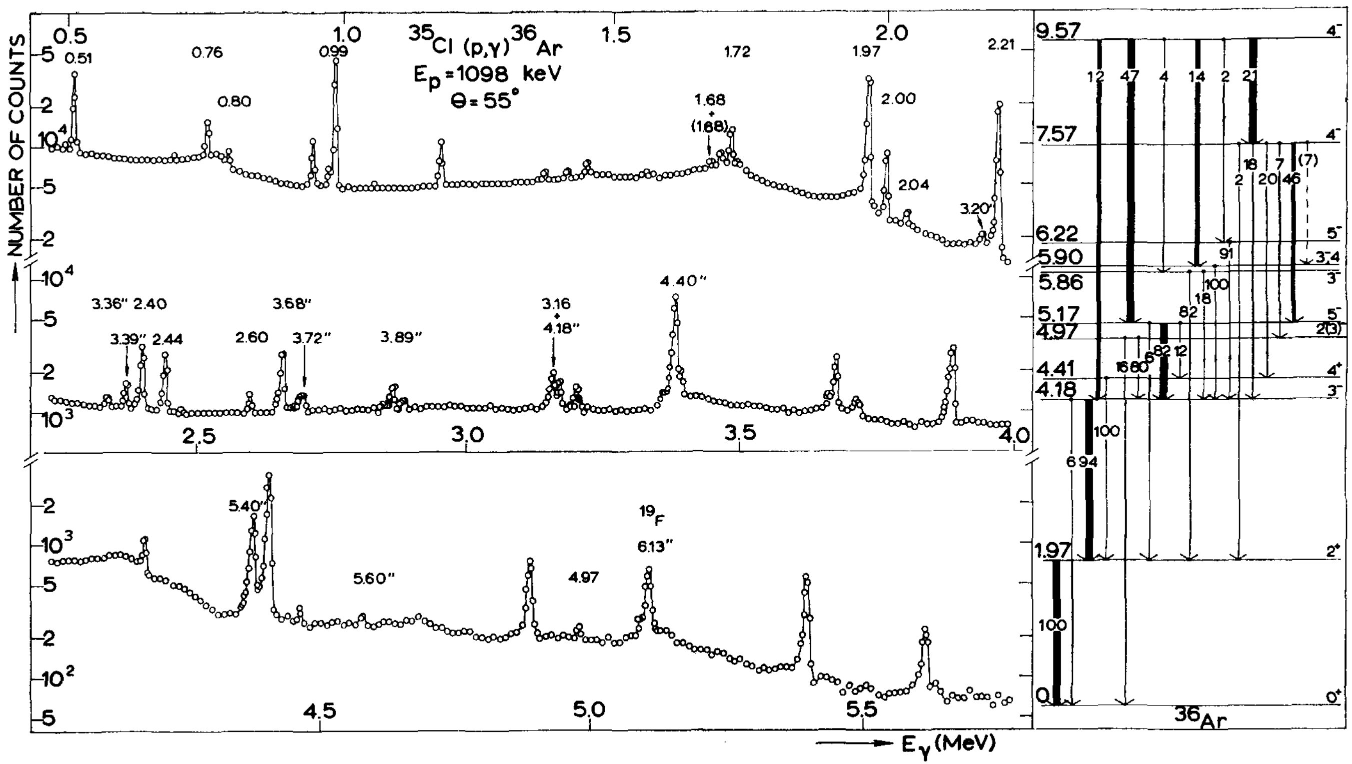


Fig. 4. Gamma-ray spectrum and decay scheme at the $E_p = 1098$ keV $^{35}$Cl(p, γ)$^{36}$Ar resonance, measured with a 45 cm$^3$ Ge(Li) detector at $\theta = 55°$. For notation, see caption of fig. 3.

0.049 keV [ref. [11])] $^{27}Al(p, \gamma)^{28}Si$ resonance and were determined as $E_p = 1073.0 \pm 0.3$ and $1098.1 \pm 0.3$ keV, respectively. The excitation energy of the $E_p = 1073$ keV resonance level was determined from the 7.58 MeV primary transition to the first excited state. The energy of this $\gamma$-transition has been calibrated with the 7.63–7.65 MeV doublet from the reaction $^{56}Fe(n, \gamma)^{57}Fe$. The method used has been described by Van der Leun and De Wit [12]). The energies of the iron doublet lines as given in ref. [13]), $E_\gamma = 7632.22 \pm 0.16$ and $7646.63 \pm 0.16$ keV, have been used. The $Q$-value found at this resonance was $Q = 8507.1 \pm 0.5$ keV. The excitation energy of the $E_p = 1098$ keV resonance, $E_x = 9574.0 \pm 0.3$ keV (see table 2), was determined from low-energy primary transitions to the $E_x = 7.57$ and 5.90 MeV levels. The $Q$-value found from this experiment was $Q = 8506.7 \pm 0.4$ keV. The average is $Q = 8506.9 \pm 0.3$ keV. This result is in excellent agreement with (but more accurate than) the value given in the 1971 mass tables [14]) $Q_m = 8506.7 \pm 1.0$ keV.

### 3.3. ACCURATE PROTON ENERGIES OF THE RESONANCES

The proton energies of the resonances can be deduced from the excitation energies of the resonance levels given in table 2 and the $Q$-value from subsect. 3.2; a relativistic correction has to be applied. In table 2 these proton energies are compared with those of other authors as reviewed by Endt and Van der Leun [15]). In general the proton energies of the present work are 1–4 keV lower than those of ref. [15]).

### 3.4. LIFETIMES OF BOUND STATES

Gamma-ray Doppler shifts have been obtained from spectra taken at 13 resonances. The full Doppler shift, measured at $\theta = 0°$ and 133°, amounts to $\Delta E_\gamma / E_\gamma = 3.2 \times 10^{-3}$ at $E_p = 2200$ keV. The measurements were performed with relatively thick targets (between 25 and 50 $\mu g/cm^2$) to make sure that the $^{36}Ar$ ions were stopped in the target and not partly in the backing. The measurements at the two angles were alternated in many short (20 min) runs to average gain drifts. The spectra were stored in the two 2048 channel halves of the analyser. The target room was temperature controlled, but no special gain stabilization was used.

Resonances were selected at which the level in question is strongly excited through a primary transition. The lifetimes of the $E_x = 4.97$ and 5.17 MeV levels have been corrected for indirect excitations via the $E_x = 6.836$ and 7.57 MeV levels, respectively.

Mean lives were computed from the measured Doppler shifts by applying the slowing-down theory developed by Lindhard *et al.* [16]) and elaborated by Blaugrund[17]). Corrections in the stopping power from the work of Ormrod *et al.* [18]) have been taken into account. Because of the low initial velocity of the $^{36}Ar$ ions ($v/c \approx 0.002$) the specific energy loss due to atomic collisions dominates the electronic part.

The measured shifts and the computed mean lives are given in table 3. If Doppler shifts for a certain level have been measured at different resonances the individual $F(\tau_m)$ values were transposed to the same $F(\tau_m)$ curve, and then the lifetime $\tau_m$ (see table 3) was obtained from the averaged $F(\tau_m)$ values. The quoted errors in the

TABLE 3

Lifetime measurements of $^{36}$Ar states

| $E_{xi} \rightarrow E_{xf}$ (MeV) | $E_p$ (keV) | Present experiment $F(\tau_m)$ | $\tau_m$ (fs) | Previous work [b]) $\tau_m$ (fs) |
|---|---|---|---|---|
| 1.97 → 0 | 2 190 | 0.21±0.05 | 350±120 | 400±100 [a]) |
| 4.18 → 1.97 | 2 257 | 0.00±0.04 | ≧1800 | ≧2000 |
| 4.41 → 1.97 | 1 409 | 0.41±0.15 | 86± 18 | 125± 20 |
| 4.41 → 1.97 | 1 760 | 0.51±0.02 | | |
| 4.44 → 0 | 1 073 | 0.41±0.10 | 100± 40 | 94± 30 |
| 4.44 → 1.97 | | 0.44±0.17 | | |
| 4.95 → 0 | 2 257 | 0.77±0.19 | ≦70 | |
| 4.97 → 4.18 | 860 | 0.00±0.06 | ≧1000 | ≧1000 |
| 5.17 → 4.18 | 1 098 | 0.03±0.04 | ≧850 | ≧1000 |
| 5.84 → 0 | 1 128 | 0.91±0.03 | 8± 3 | 6± 4 |
| 5.86 → 1.97 | 816 | 0.16±0.25 | | |
| 5.86 → 1.97 | 860 | 0.16±0.10 | 340±170 | 840±300 |
| 5.86 → 1.97 | 2 167 | 0.21±0.09 | | |
| 5.90 → 4.18 | 816 | 0.18±0.15 | $400^{+1400}_{-200}$ | 800±350 [c]) |
| 5.90 → 4.18 | 860 | 0.09±0.12 | | |
| 6.22 → 4.18 | 1 098 | 0.03±0.27 | | |
| 6.22 → 4.18 | 2 167 | 0.11±0.09 | 280± 90 | 350± 80 [c]) |
| 6.22 → 4.18 | 2 231 | 0.26±0.03 | | |
| 6.22 → 4.41 | | 0.50±0.22 | | |
| 6.61 → 4.18 | 1 264 | 0.96±0.12 | 23± 19 | |
| 6.61 → 4.18 | 1 409 | 0.67±0.10 | | |
| 6.835 → 4.18 | 816 | 0.00±0.05 | | |
| 6.835 → 4.97 | | 0.08±0.08 | | |
| 6.835 → 5.17 | | 0.16±0.15 | ≧800 | 800±250 [c]) |
| 6.835 → 4.18 | 2 167 | 0.02±0.14 | | |
| 6.835 → 4.97 | | 0.03±0.07 | | |
| 6.836 → 4.18 | 860 | 0.18±0.07 | | |
| 6.836 → 5.17 | | 0.11±0.18 | 230± 80 | 330±140 |
| 6.836 → 4.18 | 1 264 | 0.28±0.08 | | |
| 6.836 → 5.17 | | 0.19±0.12 | | |
| 7.136 → 1.97 | 1 264 | 0.90±0.15 | ≦27 | |
| 7.140 → 1.97 | 1 760 | 0.50±0.13 | 100± 50 | |
| 7.140 → 4.44 | | 0.40±0.16 | | |
| 7.25 → 1.97 | 1 264 | 0.87±0.11 | ≦30 | |
| 7.26 → 1.97 | 2 167 | 0.93±0.08 | ≦19 | |
| 7.34 → 1.97 | 1 393 | 0.85±0.12 | | |
| 7.34 → 4.18 | | 0.64±0.35 | 15± 7 | |
| 7.34 → 4.44 | | 0.84±0.07 | | |
| 7.34 → 4.44 | 1 409 | 1.01±0.21 | | |
| 7.35 → 5.17 | 2 231 | 0.34±0.10 | 190± 90 | 240± 75 [c]) |
| 7.43 → 0 | 2 257 | 0.66±0.20 | $50^{+60}_{-40}$ | |
| 7.57 → 4.18 | 1 098 | 0.21±0.27 | | |
| 7.57 → 4.97 | | 0.13±0.21 | 300±100 | |
| 7.57 → 5.17 | | 0.19±0.05 | | |
| 7.57 → 5.17 | 2 167 | 0.23±0.11 | | |

[a]) Also: 460±110 [ref. [19])]; and 430±170 [ref. [21])]. [b]) Ref. [20]) unless indicated otherwise.
[c]) Ref. [22]).

mean lives result from a quadratic addition of the statistical errors, which are directly related to the standard deviations in $F$, and an error of 20 % due to uncertainties in the stopping theory. It is seen that $F(\tau_m)$ values of different $\gamma$-rays de-exciting the same level agree nicely. Similarly, the values of $F(\tau_m)$ of $\gamma$-rays de-exciting a level studied at different resonances show good agreement. The mean lives measured by other authors (see table 3) are also from (p, $\gamma$) work [20, 22]; only the mean life of the first excited state has also been determined from ($\alpha$, $\gamma$) work [19] and from measurements of the reorientation effect in projectile Coulomb excitation [21]. The four values are in good agreement. In general the mean lives of the other states agree also well with those from other work.

## 4. Conclusion

The present paper reports measurements of the branchings, energies and lifetimes of most of the bound states of $^{36}$Ar up to $E_x = 7.75$ MeV. In the next paper the results of angular distribution measurements will be given.

A theoretical discussion of the results awaits the outcome of a shell model calculation for the $A = 34$–$40$ region, in a relatively large configuration space, which is being carried out at present.

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