Physica Scripta

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Physica Scripta. Vol. 1, 85–88, 1970

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Received February 5, 1970

Abstract

Thermal neutron capture in natural argon. R. Hardell and C. Beer (Chalmers University of Technology, Göteborg and The University of Stockholm, Stockholm, Sweden).
Physica Scripta (Sweden) 1, 85–88, 1970.

The energies and intensities of gamma rays from thermal neutron capture in natural argon have been determined by means of a Ge(Li) pair spectrometer and anti-Compton spectrometer. An internal reactor target has been used. The reaction Q-value, excitation energies and decay schemes of ^{37}Ar and ^{41}Ar have been deduced.

1. Introduction

The gamma ray spectrum following thermal neutron capture in natural argon has previously been studied by Skeppstedt et al. [1] and Lycklama et al. [2]. Most other references up to 1967 on the decay schemes of ^{37}Ar and ^{41}Ar can be found in [3]. In a recent investigation of angular distributions of (d,p) and (d,t) reactions on ^{38}Ar and ^{40}Ar Fitz et al. [4] were able to make spin and parity assignments to several ^{41}Ar levels. The decay modes of these levels seem to indicate that gamma transitions between particle states or between hole states are preferred compared to particle-hole transitions. The present investigation has been performed using the same equipment as in [1] but under more favourable conditions and was undertaken in the hope of revealing more details about the de-excitation of low-lying levels in ^{41}Ar and ^{37}Ar.

2. Experimental arrangement

The measurements were made at the 1 MW heavy-water reactor R1 in Stockholm. An argon gas target at a pressure of 3 atm was introduced in a tube traversing the reactor core. The gamma radiation had to pass a 1.5 m long collimator filled with lead and borated paraffin and with a 6 mm circular hole before reaching the Ge(Li) detector outside the reactor wall. The thermal neutron flux in the centre of the reactor was about $3 \cdot 10^{12}$ cm$^{-2} \cdot$s^{-1}. The capture cross section of natural argon has been reported to be 0.62 b [5].

The 3 cm^3 Ge(Li) detector is staff-shaped and is followed by a cooled FET preamplifier. It was delivered by AB Atomenergi, Studsvik, Sweden and has been used in pair and anticoincidence spectrometer modes. For this purpose the Ge(Li) detector is surrounded by a split annulus of NaI, diam. 15 cm, length 10 cm and with a 4 mm diam. through hole. The two crystals forming the annulus are used in the pair spectrometer arrangement. In front of the Ge(Li) detector a NaI detector, diam. 12.5 cm and length 10 cm and with an 18 mm through hole for the entering gamma rays is located. When the spectrometer is operated in the anticoincidence mode the front NaI crystal as well as the split annulus are used to detect gamma radiation Compton scattered in the Ge(Li) detector. The spectra were recorded in an Intertechnique 4096 channel analyser. Further details about the experimental equipment are found in [6].

The energy calibration of the high-energy part of the spectrum was made by introducing a mixture of nitrogen and argon gases in the reactor channel. The energy values of the argon lines are thus referred to the ^{15}N lines which have been determined accurately in a previous work [7]. In the low-energy region radioactive sources as well as the 1293.64 keV line [8] following the beta decay of ^{41}Ar have been used for energy calibration. The integral linearity of the analyser was studied using a precision pulser and was found to be better than 0.05% between channel numbers 100 and 4 000. The linearity curve was slightly S-shaped but the corrections that should be applied for the energy determination of gamma lines between calibration points were found to be negligible in the present case. The energy resolution of the Ge(Li) detector was about 3.5 keV at 1.3 MeV and about 7 keV at 6 MeV.

The efficiency curve for the Ge(Li) detector when used as a pair spectrometer was determined from the intensities of the ^{15}N lines as reported in [7] and the ^{13}C lines given in [9]. The efficiency

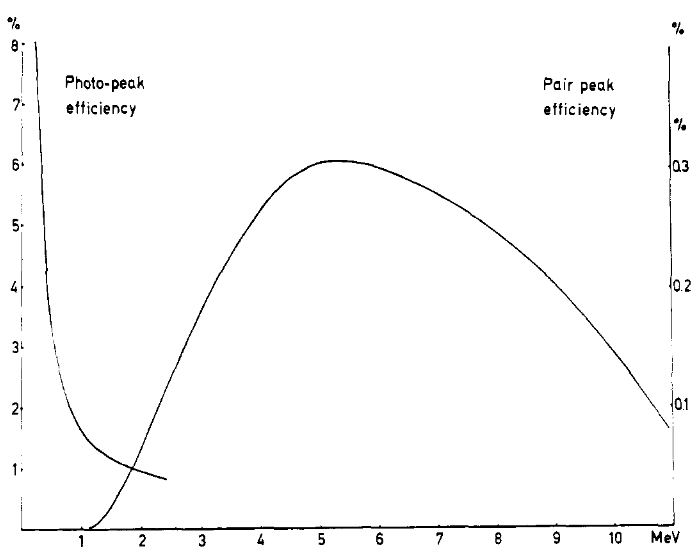

Fig. 1. The efficiency of the Ge(Li) detector in pair and anticoincidence spectrometer arrangements. The efficiency is defined as the ratio between number of counts in a peak and the number of gamma rays of the corresponding energy emitted from a small part of the target which is defined by the collimating system.

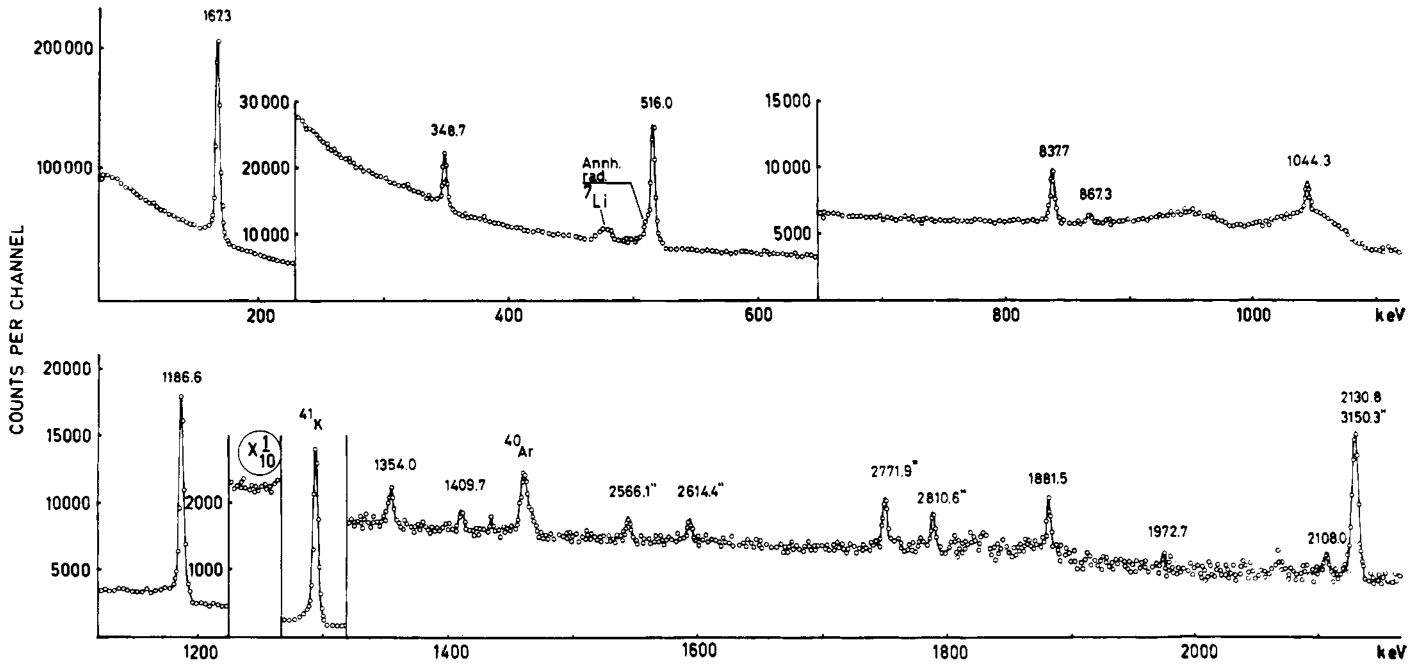

Fig. 2. Anticoincidence spectrum following neutron capture in argon. The spectrum shown has been taken in a 5 h run.

of the detector operated in the anticoincidence mode was determined by means of radioactive sources. The intensities of the gamma rays following the beta decays of ^{165}Dy [10] and ^{192}Ir [11] have been used to find the efficiency curve shown in Fig. 1. The efficiency is here defined as the ratio of the number of counts in a peak and the number of gamma rays of the corresponding energy that are emitted from the target within the solid angle determined by the front surface of the Ge(Li) detector.

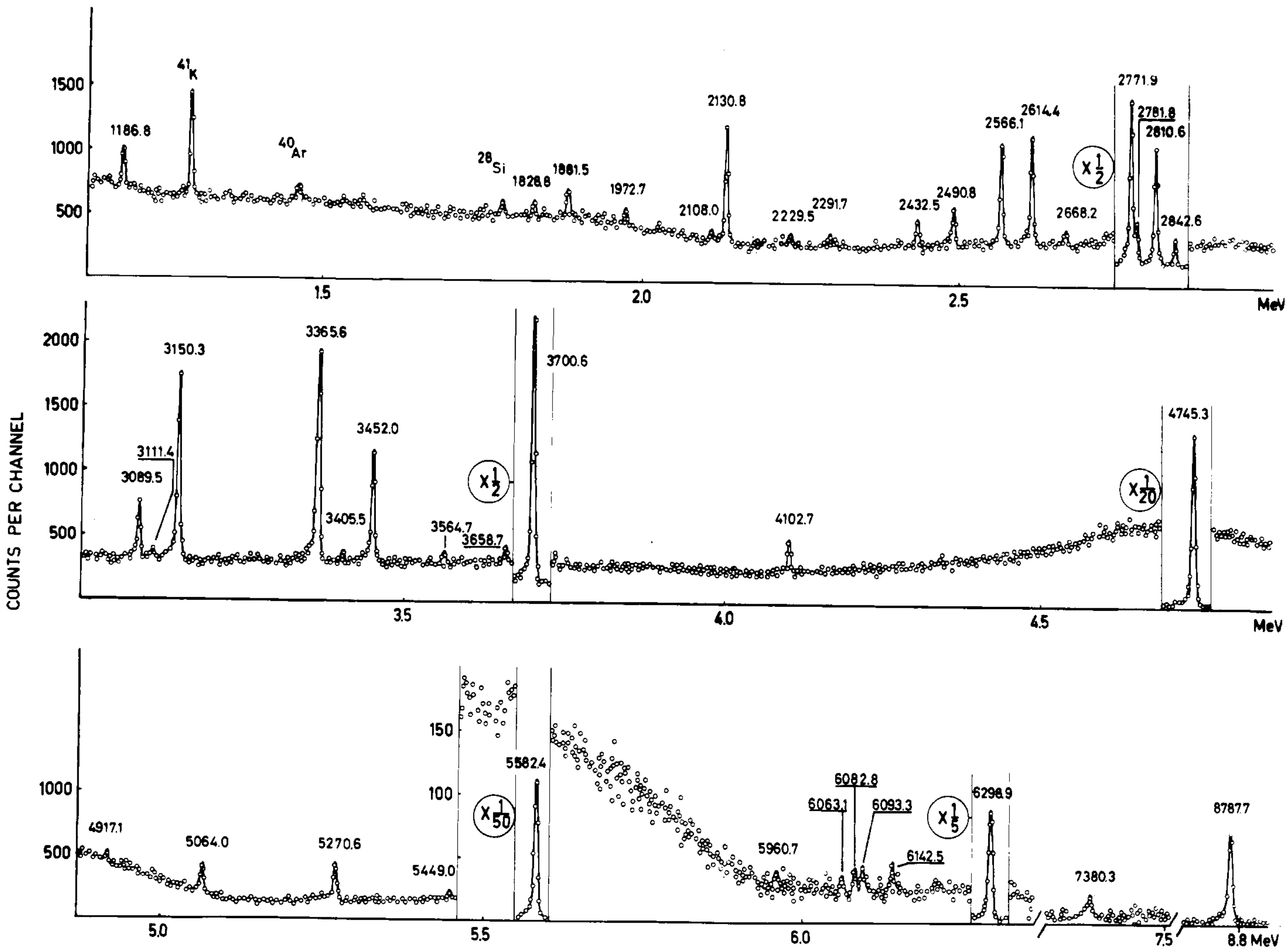

Fig. 3. Pair spectrum from neutron capture in natural argon. Measuring time 20 h.

Table I

$E\gamma$ (keV)	$I\gamma$ (photons/ 100 captures)	Isotope	Assignment
167.3±0.2	79.6	41	167→0
348.7±0.3	6.6	41	516→167
516.0±0.3	25.3	41	516→0
837.7±0.3	9.6	41	1 354→516
867.3±0.6	1.1	41	1 035→167
1 044.3±0.4	6.0	41	2 398→1 354
1 186.8±0.3	52.2	41	1 354→167
1 354.0±0.4	2.3	41	1 354→0
1 409.7±1.0	0.8	37	1 410→0
1 828.8±1.2	1.0	41	C→4 270
1 881.5±1.0	1.4	41	2 398→516
1 972.7±1.2	0.54	41	3 327→1 354
2 108.0±1.5	0.48	37	3 518→1 410
2 130.8±0.8	4.4	41	C→3 968
2 229.5±2.0	0.29	41	2 398→167
2 291.7±2.0	0.20	41	3 327→1 035
2 432.5±0.8	0.84	41	2 949→516
2 490.8±0.8	1.1	37	2 491→0
2 566.1±0.8	2.8	41	2 733→167
2 614.4±0.8	2.9	41	3 968→1 354
2 668.2±2.0	0.51	41	(3703→1035) (C→3431)
2 771.9±0.8	8.6	41	C→3 327
2 781.8±1.5	1.7	41	2 949→167
2 810.6±0.8	5.9	41	3 327→516
2 842.6±1.0	0.88	41	3 010→167
3 089.5±1.0	1.1	41	C→3 010
3 111.4±2.2	0.40	41	(3 111→0) (3 278→167)
3 150.3±1.0	4.0	41	C→2 949
3 365.6±1.0	4.2	41	C→2 733
3 405.5±2.5	0.08	41	(C→2 694) (3 573→167)
3 452.0±1.0	2.0	41	3 968→516
3 564.7±2.5	0.13	41	(3 565→0, 3 732→167)
3 658.7±1.8	0.25		
3 700.6±0.8	9.8	41	C→2 398
4 102.7±1.5	0.3	41	4 270→167
4 745.3±0.8	55.0	41	C→1 354
4 917.1±2.0	0.07		
5 064.0±1.0	0.26	41	C→1 035
5 270.6±1.2	0.47	37	C→3 518
5 449.0±2.5	0.05		
5 582.4±0.8	11.6	41	C→516
5 960.7±2.5	0.01		
6 063.1±2.5	0.04		
6 082.8±2.5	0.02		
6 093.3±2.5	0.03		
6 142.5±2.5	0.02		
6 298.9±1.0	0.96	37	C→2 491
7 380.3±2.0	0.04	37	C→1 410
8 787.7±2.0	0.26	37	C→0

3. Experimental results

The anticoincidence and pair spectra are shown in Figs. 2 and 3. The peak at 478 keV is due to the $^{10}B(n,\alpha)^{7}Li$ reaction. In the anticoincidence spectrum the 1 293.64 keV line has been used to determine the absolute intensities of the ^{41}Ar lines. In the pair spectrum this line appears as a very small line in the beginning of the spectrum due to the low probability for pair production. It is consequently not suitable as an intensity reference for high-energy lines. The absolute intensities of these lines have therefore been estimated by setting the intensity sum of the primary gamma rays equal to 100 gamma rays per 100 neutron captures. The ratio $\sum_i E_i\, I_i/100\, B$ ($B = 6\,099$ keV) was calculated to be 0.99 for the ^{41}Ar lines, which is very close to the theoretical value 1. The gamma ray energies corrected for recoil and the intensities are given in Table I. The relative errors in the intensity values are mainly dependent on the accuracy in the efficiency curves and the statistics in the peak area determinations. The pair peak efficiency curve has been found to be accurate to about ±10% in the energy region 2.5 to 8 MeV, indicating that the intensities of strong lines in this energy region may be determined to ±15% or better.

Table II. *Excitation energies and intensity balances for ^{37}Ar and ^{41}Ar*

	E_x (keV)	Intensity balance I_{in}/I_{out}	Energy sum for cascading gamma rays (keV)
^{37}Ar	1 409.7±1.0	0.5/0.8	8 790.0±2.3
	2 490.6±0.8	1.0/1.1	8 789.7±1.3
	3 518.1±1.0	0.5/0.5	8 788.3±2.2
^{41}Ar	167.3±0.2	65.6/79.6	
	516.0±0.3	31.3/31.9	6 098.4±0.9
	1 034.7±0.6	0.5/1.1	6 098.6±1.2
	1 354.0±0.4	64.4/64.1	6 099.4±0.9
	2 398.3±0.6	9.8/7.7	6 099.0±1.0
	2 733.4±0.7	4.2/2.8	6 099.0±1.3
	2 948.5±0.7	4.0/2.5	6 098.8±1.3
	3 009.7±0.8	1.1/0.9	6 099.4±1.5
	3 326.7±0.8	8.6/6.6	6 098.5±1.2
	3 968.2±0.7	4.4/4.9	6 099.3±1.2
	4 270.1±1.0	1.0/0.3	6 098.8±2.0

Outside this energy region the error in the pair peak efficiency curve is expected to increase successively. At 1.5 MeV the error is estimated to be about ±25%. The intensities of the gamma lines up to 1 410 keV have been calculated only from the anticoincidence spectrum. The error in the photo-peak efficiency curve is estimated to be about ±10% in the energy region 300–1 500 keV. At lower energies the efficiency values obtained from different experiments have been found to be at variance. The uncertainty in the efficiency curve was thus estimated to be about 25% at 150 keV. For very weak gamma lines the error is mainly determined by the statistical error which may be ±50% or more due to varying background conditions.

Most gamma lines given in Table I have been ascribed to neutron capture in ^{40}Ar. From values of the cross sections of the three stable argon isotopes [12, 13] and the composition of natural argon one can estimate the contributions to the gamma spectrum from neutron capture in ^{36}Ar and ^{38}Ar to be 3.4 and 0.08%, respectively, of the part of the spectrum following neutron capture in ^{40}Ar. The interpretation of the lines has been made using a computer to calculate and order the differences between all known levels in ^{37}Ar and ^{41}Ar. Most gamma lines have been fitted into the decay schemes but for a few lines more than one interpretation has been possible. The assignments given in parentheses in Table I are based only on the gamma ray energies and have not been included in the decay schemes shown in Fig. 4. For a few weak lines no probable interpretation has been found but these lines have been ascribed to neutron capture in argon as no background lines of these energies are expected. The accuracy in the energy determination reduces the possibilities to make incorrect assignments. The Q-value for the $^{40}Ar(n,\gamma)^{41}Ar$ reaction was found to be 6 098.9 ±0.8 keV and for the $^{36}Ar(n,\gamma)^{37}Ar$ reaction it was found to be $Q = 8\,789.0 \pm 1.2$ keV. These values are in good agreement with literature values 6 100.6 ±4.9 and 8 790.8 ± 2.5 keV, respectively [3]. New values for a few excited states and the intensity balance for each level in ^{41}Ar and ^{37}Ar are shown in Table II.

4. Discussion

In a previous investigation presented in [1] gamma lines have been found of energies 1 750 and 1 960 keV. From the analysis of the present work it can be concluded that these lines must have been due to background conditions. The precision in the energy determinations has been improved considerably as compared to the previous investigation. The assignments that can be made on the basis of the new energy values are mainly in good agreement

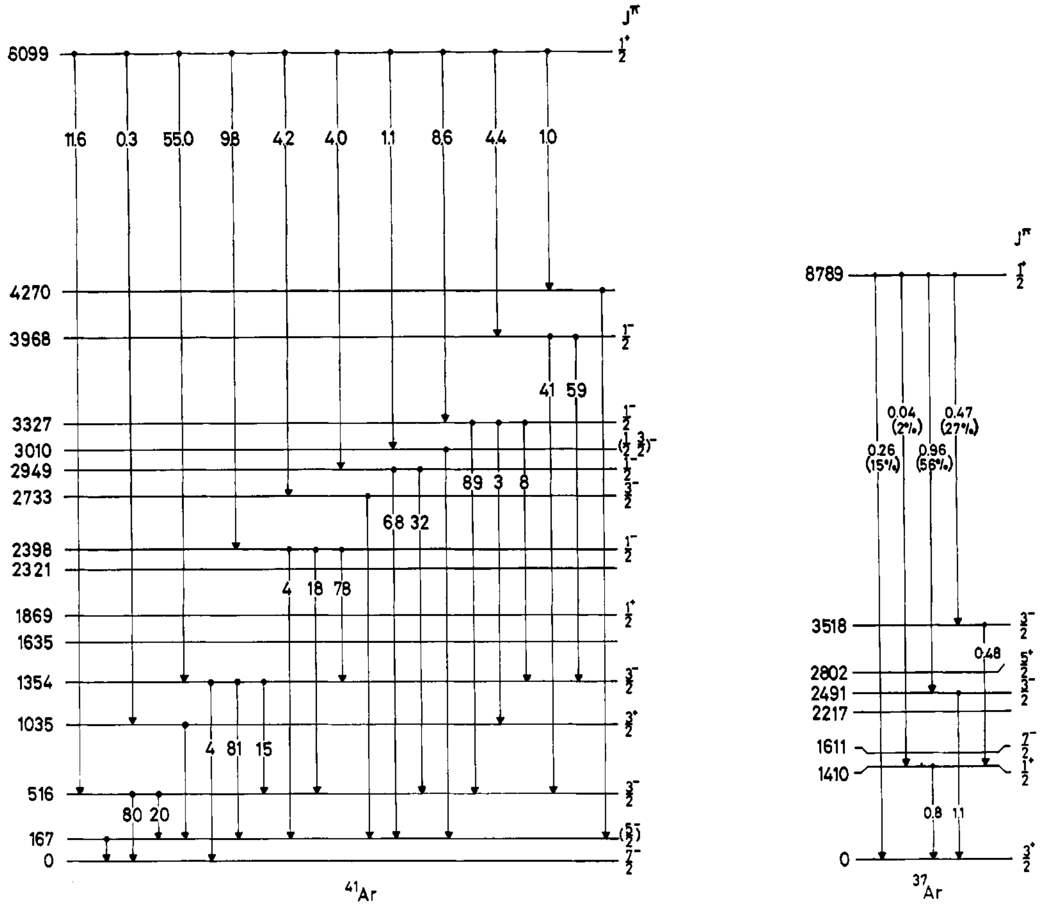

Fig. 4. Decay schemes of ^{41}Ar and ^{37}Ar. Primary transitions in ^{41}Ar are given in gamma rays per 100 neutron captures, whereas the de-excitation of other excited states is given in per cent. In the ^{37}Ar scheme the intensities of the transitions are referred to the ^{41}Ar intensities and are given in gamma rays per 100 neutron captures in ^{40}Ar.

with previous interpretations. A number of new transitions have, however, been found. Some of these are shown in the decay schemes in Fig. 4.

For the 2 398 keV level de-excitation lines to the $3/2^-$ states at 516 and 1 354 keV have been reported previously. The weak transition to the $5/2^-$ state at 167 keV observed in this work is not in disagreement with the $1/2^-$ assignment for the 2 398 keV level made in [4].

The 4 270 keV level has not been found to be excited in the (n,γ) reaction in previous works. The l_n-value for this level has been reported to be 1 [3]. The only de-excitation line observed proceeds to the $5/2^-$ level at 167 keV. A spin value of 3/2 thus seems to be more probable than 1/2.

The $1/2^-$ state at 3 327 keV is found to decay to the 1 354, 1 035 and 516 keV levels; only the transition to the 516 keV level has been observed previously. The 1 035 keV state is the only level with positive parity found to be excited. From spin and parity considerations it would not seem unexpected to find $E1$ transitions from several negative parity states to the $3/2^+$ state at 1 035 keV. The weak line from the 3 327 keV state is, however, the only $E1$ transition found in the decay scheme apart from primary transitions and the de-excitation line from the 1 035 keV state. Positive parity states in ^{41}Ar can be obtained by exciting one of the $d_{3/2}$ nucleons to a higher orbit. Levels in ^{41}Ar with negative parity are described as particle states of different configurations as discussed for instance by Shadmi and Talmi [14]. A transition between a particle and a hole state would be a two-step event, which is less probable than transitions between particle states.

The structure of the ^{43}Ca nucleus is very similar to that of ^{41}Ar and from a recent (n,γ) study of the ^{43}Ca level scheme [15] it is found that gamma transitions between particle and hole states are very rare. Similar effects are also found in ^{41}Ca [15].

In the decay scheme of ^{37}Ar shown in Fig. 4 a few more transitions were found than has been reported previously. A comparison between the intensities of the primary transitions in the ^{37}Ar and ^{41}Ar level schemes shows that the contribution to the gamma ray spectrum from ^{37}Ar is less than 2% of the part ascribed to ^{41}Ar whereas one would expect it to be 3.4%. This indicates that a few more transitions should be ascribed to neutron capture in ^{36}Ar.

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