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Levels in ^{45}K and ^{46}K excited by the β decay of ^{45}Ar and ^{46}Ar

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The nuclides ^{45}Ar and ^{46}Ar have been produced by spallation reactions on vanadium targets at $E_p = 600$ MeV. The subsequent β decays to ^{45}K and ^{46}K states have been studied. An intensity of $98.6 \pm 0.6\%$ was measured for the β transition to the 1.94 MeV state in ^{46}K. A decay scheme involving 13 β branches has been established for ^{45}Ar, and the corresponding log*ft* values have been deduced. Eleven states are reported for the first time in the β decay scheme of ^{45}Ar at 1.42, 1.47, 1.72, 2.52, 2.57, 2.75, 3.31, 3.99, 4.04, 4.36, and 4.57 MeV. From the lifetime, $\tau = 4.6 \pm 0.6$ ns, deduced from γ-γ delayed coincidences, the angular momentum of the 1081 keV level has been established as $7/2^-$ on the basis of the transition strength of its γ decay. A survey on the $1f_{7/2} \rightarrow 1d_{3/2}$ $M2$ transition in odd K nuclei is presented and the observed hindrance factors are discussed.

[RADIOACTIVITY ^{45,46}Ar [from ^{50,51}V(p, 6pxn)—natural target, mass separated] measured delayed E_γ, I_γ, prompt and delayed γ-γ coin., deduced decay schemes, $\log ft, J, \pi, T_{1/2}$.]

I. INTRODUCTION

The study of the ^{45}Ar β decay, first done by Tirsell *et al.*[1] and recently by Petry and coworkers,[2] through the ^{48}Ca(n, 2p 2n)^{45}Ar reaction has led to two decay schemes, the last one involving nine excited levels in ^{45}K. Up to now the investigation of the ^{46}Ar beta decay has shown a single beta branch with only one subsequent γ transition.[2,3] The high yields of argon isotopes available with the spallation reaction with 600 MeV protons at CERN, associated with the good experimental conditions given by the on-line mass separator Isolde have made possible a detailed study on the β decay of ^{43,44}Ar isotopes.[4] Using the same device and a higher intensity proton beam, it was possible to obtain reliable decay schemes for ^{45,46}Ar.

The present experiment was undertaken with the following motivations: We wanted first to remove, by γ-γ measurements and multimode analysis, the ambiguities presented in the previous studies of the ^{45}Ar decay. Secondly the measurement of the lifetime of the $\frac{7}{2}^-$ level in ^{45}K was desirable in order to compare the $M2$ strength with the values obtained for lighter potassium nuclei. Last, for ^{46}Ar, we intended to search for new β branches. The present results are more complete and supersede those presented earlier.[3]

The particle hole nature of low lying levels in odd K nuclei has been established up to $A = 43$ by the study of single nucleon transfer reactions[5] and has been investigated by the measurement of $M2$ transition strengths between the $1f_{7/2}$ and $1d_{3/2}$ orbits. For ^{45}K, the analysis of the (p, α) and the one proton pick up reactions (t, α) and (d, ^{3}He) gave limited information, and no precise location for the first $\frac{5}{2}^+$ and $\frac{7}{2}^-$ states was obtained.[6-8] From our data, the radiative decay properties of low lying levels in ^{45}K and ^{46}K can be discussed and in particular, the retardation of the $M2$ transition between the $1f_{7/2}$ and the $1d_{3/2}$ orbits can be evaluated for $A = 45$ and compared to the results obtained with scandium and lighter potassium nuclei for which a survey has been presented by Keinonen *et al.*[9]

II. EXPERIMENTAL PROCEDURE

The ^{45}Ar and ^{46}Ar isotopes have been produced by the spallation reaction ^{50,51}V(p, 6p xn) induced by the 600 MeV proton beam of the CERN synchrocyclotron on a vanadium carbide target.[10] Production rates were 10^4 s^{-1} for ^{45}Ar and roughly one order of magnitude less for ^{46}Ar with a 1 μA proton beam. As previously described[4] the mass selected atoms delivered by the Isolde facility are collected on a mylar tape associated with a transport system which allows for each isotope, β counting, and γ-ray spectrometry without noticeable build up of the daughter activity.

Multiscaling of the ^{45}Ar beta emission has been performed over 400 channels using a 400 ms counting time per channel, in order to determine

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its half-life with accuracy. With high efficiency GeLi detectors, singles γ-ray spectra were registered in a multianalysis mode (two counting periods of 20 seconds each), with two different gain conditions (0.75 keV/channel and 1.55 keV/channel) and γ-γ-t coincidence measurements were performed. Details on the data storing devices have been given in Ref. 4. Owing to the importance of a low energy transition reported between two levels at 1020 and 1081 keV (Ref. 2) special care was used in the collection of the data. The energy of the 61 keV ray has been determined by means of an intrinsic germanium detector with a beryllium window, a ^{133}Ba source providing energy calibration. The intensity of the 61 and 1020 keV γ rays in the spectrum has also been checked, using absorbers and various counting geometries, to insure that no sum effect accounted for the line observed at 1081 keV. The lifetime related to the 61 keV transition was inferred from γ-γ coincidence measurements between two NE102 A plastic scintillators optically coupled to two RTC XP 2230 B photomultiplier tubes. The rate of the delayed coincidences between the two counters is presented in Fig. 1. The long lived level ($\tau = 4.6 \pm 0.6$ ns) has been identified from γ-γ-t coincidence measurements between a Ge(Li) detector and a thin plastic scintillator counter selecting the low energy line. From the γ-ray spectra in coincidence with the prompt and the delayed part of the time spectrum (Fig. 2), evidence was given for the 1081 keV being the relevant state.

A new set of measurements was performed on the nucleus ^{46}Ar in order to search for low intensity β branches. The increase of the production rate and of the number of collections has improved the statistical quality of the data by a factor 30 with regard to the previous experiment.[3] Multiscaling of the β decay was registered (100×200 ms) and multispectra were taken in two different conditions (2×10 s over 2×4096 channels and 16×1.2 s over 16×512 channels). The ground state β transition has been deduced from simultaneous β and γ counting, after absolute efficiency calibration of the detectors by means of a ^{106}Rh source.

III. RESULTS AND DISCUSSION

A. Argon 45

The half-life of ^{45}Ar has been determined to be $T_{1/2} = 21.48 \pm 0.15$ s. This value is close to those measured by Tirsell[1] ($T_{1/2} = 21 \pm 1$ s) and Petry[2] ($T_{1/2} = 20.8 \pm 0.5$ s) and is defined with less uncertainty. The singles γ-ray spectrum shown in Fig. 3 was obtained in the first counting period of the multianalysis measurement for 240 sources col-

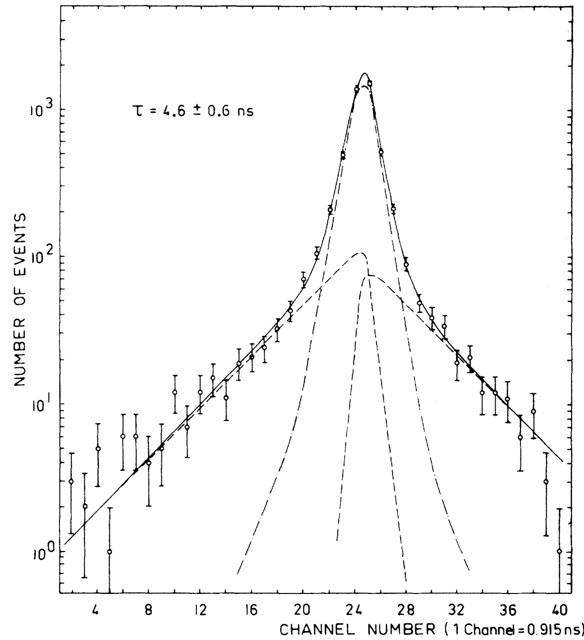

FIG. 1. Delayed coincidences taken in the decay of ^{45}Ar with two plastic scintillators. The experimental prompt curve, taken with a source of ^{22}Na, was slightly modified to include the change in resolution due to different single spectra. The multicomponent least squares fit shows the detection of the delayed radiations in both counters.

lected during 43 seconds each. As a Q_β value of 6890 ± 60 keV has been inferred from the ^{45}Ar mass measurement[11] the energy scale was extended up to 6.3 MeV but no γ ray with energy higher than 4.57 MeV was observed in our spectra. To be assigned to the β decay of ^{45}Ar, the lines had to satisfy at least one of the following conditions: to present the appropriate decay rate in the multianalysis measurement and/or to appear in coincidence with another well established transition. A list of the intensity and energy of the γ rays following the β decay of ^{45}Ar is given in Table I. Only tentative attributions are indicated for the 597.8 and 1209.5 keV lines. The sum of these two coincident radiations is equal to 1807.3 keV, an energy at which a γ ray is observed and assigned to the cross over transition $3.99 \rightarrow 2.19$ MeV; as there is no further evidence, the intermediate level can be at 3.40 or 2.78 MeV. The other few unattributed γ rays generally are of weak intensity. The branching ratios in ^{45}K deduced from our results are reported in Table II and the established deexcitation scheme is presented in Fig. 4. Seventeen excited states of ^{45}K are populated in the β decay of ^{45}Ar. Our coincidence measurements confirm the existence of the level at 1081 keV postulated by Petry *et al.*[2] The most striking dif-

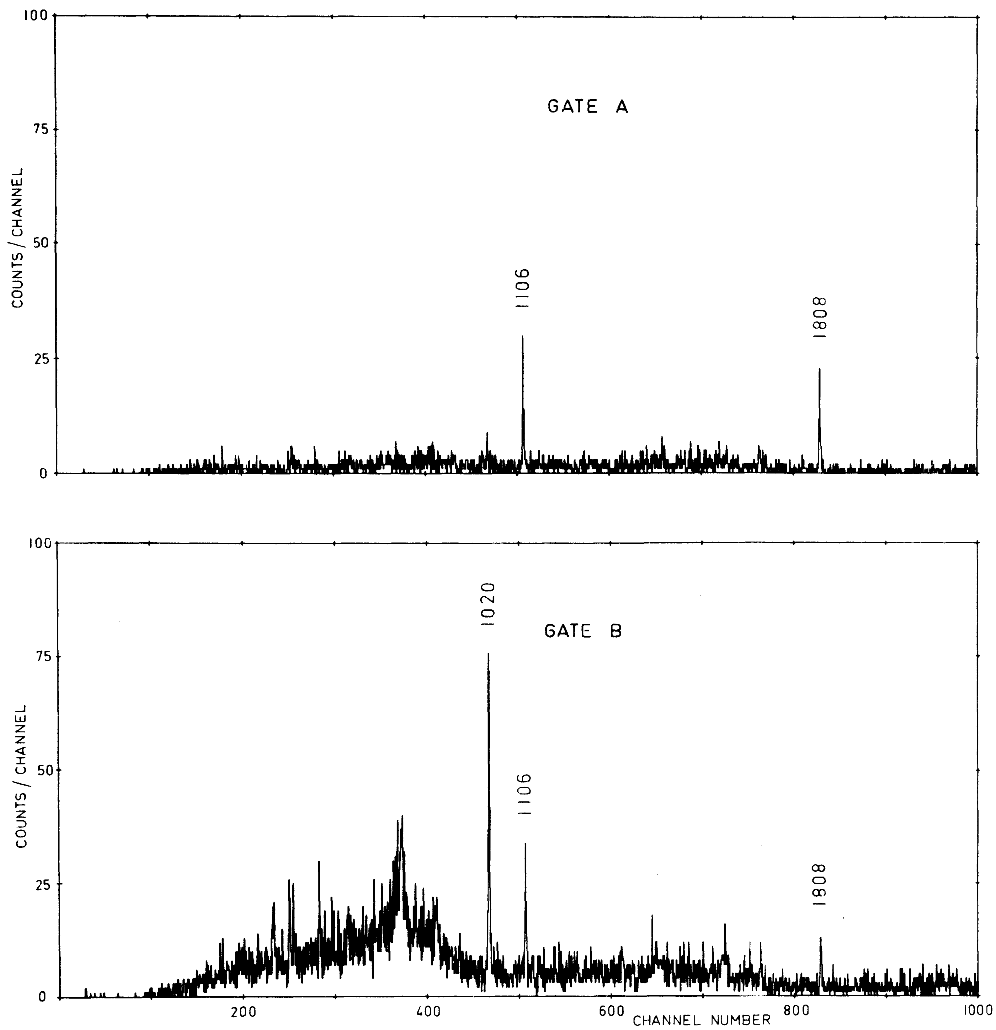

FIG. 2. Coincidence spectra resulting from γ-γ-t measurements between the 61 keV radiation detected with a plastic scintillator and the γ rays detected with a Ge(Li) counter. The upper spectrum has been obtained by taking into account the prompt part of the time distribution (Gate A). The lower spectrum corresponds to the delayed part of the time distribution (Gate B).

ference comes from the disproof of levels at 1808 and 2357 keV which played an important role in the previously reported[1,2] decay schemes. One should notice that most of the new levels we include in the decay scheme can be related as far as energy and spin are concerned, with those observed in particle transfer reactions.[12] The β branches and their relative intensity have been deduced from the gamma in out balance; they are reported in Table III with the corresponding logft values, calculated with the Gove and Martin log$f$ tables[13] for $T_{1/2}$ = 21.48 ± 0.15 s and Q_β = 6890 ± 60 keV.

The ^{45}K levels involved in the ^{45}Ar beta decay are discussed as follows:

Ground state. The spin and parity of the ^{45}K ground state has been established $J^\pi = \frac{3}{2}^+$ (Ref. 14) and the value $J^\pi = \frac{7}{2}^-$ is expected for the ^{45}Ar ground state from the shell model systematics. In that case the β_0 radiation is a first forbidden unique transition. Since no direct measurement of the ground state transition could be made, an upper limit of its intensity was estimated from the ^{45}K activity build up: $I_{\beta_0} < 25\%$. This result is not in contradiction with the prediction ($I_{\beta_0} \leq 6.5\%$) inferred from the review of the measured logf_1t in the $A = 40$ region where no value lower than 9.1 has been reported.[23]

474.5 keV level. Coincidence measurements clearly indicate that this level is populated by a 950 keV γ ray (1.42 → 0.47 MeV), which was not

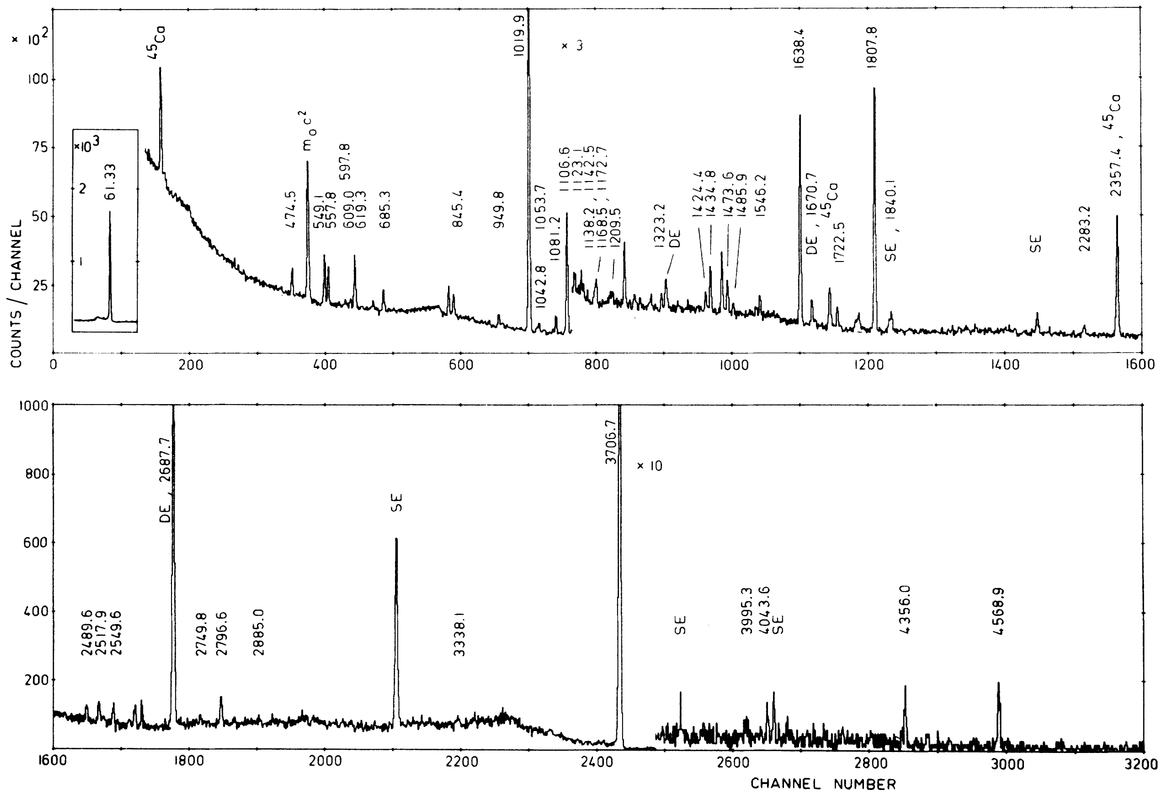

FIG. 3. Singles γ-ray spectrum following ^{45}Ar β decay, recorded during twenty seconds after collection. The single- and double-escape peaks are noted SE and DE, respectively. The insert shows the 61 keV line obtained in a separate high gain multianalysis measurement.

observed by Petry *et al.* An upper limit of the β branching has been set at 0.7%. Indeed, no direct β feeding is expected for that state since its spin and parity has been established from particle transfer reactions[12] as $J^\pi = \frac{1}{2}^+$.

1019.9 keV level. The feeding of this level by the 61 keV transition has been unambiguously deduced from the γ-γ coincidence measurements. Its decay takes place 100% to the ground state, the 1020 keV line being the main line of the spectrum, and an upper limit of 0.1% has been determined for the β branching. The lack of a 1.02 → 0.47 MeV transition suggests spin values higher than $\frac{3}{2}$. From the lifetime measurement, an upper limit of 1 ns can be set for this state, an $M2$ transition has to be rejected on the basis of the lower limit of the corresponding transition strength $[\Gamma_\gamma/\Gamma(M2) > 3$ Weisskopf units (W.u.)]. So, only $\frac{5}{2}^+$ and $\frac{7}{2}^+$ spin and parity assignments can be taken into consideration, since the $\frac{3}{2}^+$ value is inconsistent with the feeding of this level from the 1.08 MeV one.

1081.2 keV level. The decay of this level proceeds 95% through the 1.02 MeV level and 5% to the ground state. The logft value (6.4 ± 0.1) determined from the β branching (13%) limits the spin assignment to $\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$. The value we have measured for the lifetime of the 1.08 MeV state is $\tau = 4.6 \pm 0.6$ ns. Therefore the 1.08 MeV → 0 transition can be analyzed only in terms of an $M2$ or $M2/E3$ emission. An $M2$ transition presents a strength of 0.03 ± 0.01 W.u. which is comparable to the strength of the $\frac{7}{2}^- \rightarrow \frac{3}{2}^+$ transitions in other potassium nuclei. An $E1$ emission would be unusually weak and a pure $E3$ transition unrealistically enhanced. From the lifetime, the 61 keV radiation (1.08 → 1.02 MeV) can be interpreted only as an $M1$ [$(2.8 \pm 0.9) \times 10^{-2}$ W.u.] or an $E1$ [$(0.7 \pm 0.2) \times 10^{-3}$ W.u.] emission. It is of interest to note that a spin value of $\frac{7}{2}^-$ for the 1081 keV level is consistent with the indication of an $l = 3$ transfer momentum to the state at the same energy (1080 ± 10 keV) in the ^{46}Ca(t, α) ^{45}K reaction.[7]

1424.4 keV level. This level decays 40% to the ground state ($\frac{3}{2}^+$) and 60% to the 474 keV level ($\frac{1}{2}^+$). An upper limit of 0.7% was found for its β branching. The lack of direct β feeding and the γ decay favor the identification of this level with the one observed in the (t, α) reaction[7] at 1417 ± 10 keV to which $J^\pi = \frac{1}{2}^+$ was assigned.

1473.6 keV level. Indication for the existence of

TABLE I. Energy and relative intensity of γ rays following β decay of ^{45}Ar.

E_γ (keV)	I_γ	Coincident transitions (keV) [a]	E_i (MeV)	E_f (MeV)
61.33 ± 0.05	715.2	558, 685, 1020, 1054, 1107, 1435, 1808, (2357)	1.08	1.02
474.5 ± 0.2	69.8	950, 1323	0.47	0
549.1 ± 0.1	79.1	558, 619, 685, 1020, 1638, 1808	2.19	1.64
557.8 ± 0.1	64.0	61, 549, 1020, 1081, 1808, 2357	1.64	1.08
597.8 ± 0.5	9.6	(549), 1209, (1638)	(3.99 (2.78	3.40) 2.19)
609.0 ± 0.1	9.1	none		
619.3 ± 0.2	87.0	549, 685, 2357	1.64	1.02
685.3 ± 0.2	35.3	61, 549, (1020), 1123	3.99	3.31
845.4 ± 1.0 [b]	8.7		2.57	1.72
949.8 ± 0.3	28.0	474, (1323)	1.42	0.47
1019.9 ± 0.1	1000	61, 549, 558, 619, 1107, 1435, 1546 1808, (1840), 2357, (2550), (2797), (3338)	1.02	0
1042.8 ± 0.3	25.3	1474	2.52	1.47
1053.7 ± 0.5	11.1			
1081.2 ± 0.2	36.9	1107, 1435, 1808	1.08	0
1106.6 ± 0.1	310.0	61, 685, 1020, 1081, 1123, 1808	2.19	1.08
1123.1 ± 0.5	38.8	549, 558, 619, 685, 1020, 1107, 1638	3.31	2.19
1138.2 ± 0.5	19.3	845, 1054, 1546	3.70	2.57
1142.5 ± 1.2	10.7	(549)		
1168.5 ± 0.5	10.2	(1107)		
1172.7 ± 0.3	23.9			
1209.5 ± 0.4	14.7	549, 598, 1107	(3.99 (3.40	2.78) 2.19)
1323.2 ± 0.6	11.2	474, 950, 1424	2.74	1.42
1424.4 ± 0.5	18.3	none	1.42	0
1434.8 ± 1.0	27.3	(61), (1020), (1080)	2.15	1.08
1473.6 ± 0.3	41.2	1043, (2885)	1.47	0
1485.9 ± 0.7	9.7			
1546.2 ± 0.7	25.2	1020, (1138)	2.57	1.02
1638.4 ± 0.1	273.0	549, 1808, 2357	1.64	0
1670.7 ± 0.8	10.2	685, 1638	3.31	1.64
1722.5 ± 0.3	33.8	845, 1138	1.72	0
1807.8 ± 0.1	382.4	61, 549, 1020, 1080, 1107, 1638	3.99	2.19
1840.1 ± 0.5	21.6	1435	4.36	2.52
2283.2 ± 0.7	24.8	474, 950, 1424	3.71	1.42
2357.4 ± 0.2 [b]	227.5	61, 558, 619, 1020, 1080, 1638	3.99	1.64
2489.6 ± 0.9	16.7			
2517.9 ± 0.5	24.2	none	2.52	0
2549.6 ± 0.9	18.6	(1020)		
2687.7 ± 0.5	179.4	511, 1020	3.71	1.02
2749.8 ± 1.5	16.5		2.75	0
2796.6 ± 0.5	34.4	(1020)		
2885.0 ± 2.0	8.0		4.36	1.47
3338.1 ± 1	14.4		4.36	1.02
3706.7 ± 0.2	963.5		3.71	0
3995.3 ± 1.5	8.1		3.99	0
4043.6 ± 1.0	7.8		4.04	0
4356.0 ± 1.0	12.6		4.36	0
4568.9 ± 1.0	15.4		4.57	0

[a] γ rays for which no coincidence information is given are not present in the γ–γ coincidence data. Parentheses denote possible coincidences.

[b] In. Fig. 3 the lines corresponding to these γ rays are contaminated by background activities.

TABLE II. γ-ray branching ratios in ^{45}K.

E_i (MeV)	E_f (MeV)	Branching ratio
0.47	0	100
1.02	0	100
1.08	0	4.9 ± 2.4
	1.02	95.1 ± 2.4
1.42	0	39.5 ± 0.7
	0.47	60.5 ± 0.7
1.47	0	100
1.64	0	64.4 ± 2.2
	1.02	20.5 ± 1.7
	1.08	15.1 ± 1.5
1.72	0	100
2.19	1.08	79.7 ± 1.8
	1.64	20.3 ± 1.8
2.51	0	31.5 ± 5.7
	1.08	35.6 ± 7.5
	1.47	32.9 ± 5.3
2.57	1.02	74.3 ± 4.4
	1.72	25.7 ± 4.4
2.75	0	59.5 ± 9.3
	1.42	40.5 ± 9.3
3.31	1.64	20.1 ± 3.3
	2.19	79.9 ± 3.3
3.71	0	75.5 ± 2.1
	1.02	21.1 ± 2.0
	1.42	1.9 ± 0.5
	2.57	1.5 ± 0.4
3.99	0	1.2 ± 0.3
	1.64	34.8 ± 0.6
	2.19	58.5 ± 2.2
	3.31	5.4 ± 0.7
4.04	0	100
4.36	0	22.2 ± 4.5
	1.02	25.4 ± 9
	1.47	14.3 ± 5.5
	2.51	38.1 ± 6.8
4.57	0	100

this level is given from the coincidence of the 1474 keV ray with the 2885 and 1043 keV lines. From the upper limit of the lifetime of this state deduced from our experiment ($\tau \leq 1$ ns), an $E3$ transition to the ground state has to be rejected $[\Gamma_\gamma/\Gamma(E3) \geq 100$ W.u.$]$ excluding spin values higher than $\frac{7}{2}$.

1638.7 keV level. The γ decay of this level reported by Petry *et al.* is confirmed by our measurements. Angular momenta higher than $\frac{7}{2}$ would be inconsistent with the observed ground state transition (64%).

1722.5 keV level. A γ ray of 1722.5 keV gives indication for the location of a level at this energy. From γ-γ coincidence measurements this state is partly populated by the γ deexcitation of the 2.57 MeV level and by a weak direct β feeding. If this level can be identified with the one quoted at 1714 ± 10 keV in the ^{46}Ca(t, α) work,[7] with a transfer momentum $l = (0, 2)$, our $\log f_1 t$ value (9.15 ± 0.1) would restrict the spin value to $\frac{3}{2}^+$ or $\frac{5}{2}^+$.

2187.8 keV level. The existence of this level has been postulated by Petry *et al.* and is confirmed by γ-γ coincidences involving the 549, 1106, 1123, and 1808 keV γ rays. Our measurements allow us to attribute unambiguously the 549 keV line to the decay of the 2.19 MeV level. Owing to the feeding of this state by the intense 1808 keV γ transition, a lower limit of $\log ft$ has been set at 8.3 for the β branch, which rules out spin and parity restrictions introduced in Ref. 2 on the basis of a $\log ft$ value close to 6.

2517.4 and 2566.7 keV levels. Our γ-γ measurements can be interpreted by the existence of two states located at these energies. For the 2.52 MeV state the $\log ft$ value (6.6 ± 0.1) allows us to restrict the possible spins to $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$.

2748.3 keV level. A level at 2750 keV has been observed in the (p, α) reaction[6] with $l > 3$. As the level we report deexcites to the ground state $(\frac{3}{2}^+)$ and to the 1424 keV state $(\frac{1}{2}^+)$, no identification can be made between these two 2.75 levels on the basis of their angular momentum.

3310.5 keV level. This level is established from γ-γ coincidence involving the 685, 1123, and 1671 keV lines. From its decay mode it may be the one observed in the (p, α) reaction[6] at 3290 ± 30 keV with an $l \geq 3$ transfer momentum.

3707.1 keV level. Four γ transitions are found to deexcite this level, populated by the most intense β branch of the ^{45}Ar decay. The negative parity of this state is inferred from the low $\log ft$ value (4.6 ± 0.1) while the γ transition to the $J^\pi = \frac{1}{2}^+$, 1424 keV level excludes the $\frac{9}{2}^-$ value for the angular momentum. With the remaining possibilities, $J^\pi = \frac{7}{2}^-$, $\frac{5}{2}^-$, the 3.71 → 1.42 MeV transition can be interpreted either as an $M2$ or an $E3$ emission.

3995.8 keV level. In our decay scheme, this level is the second in importance, from the point of view of its β feeding. Its deexcitation proceeds through 4 γ transitions, in particular, the 1808 and 2357 keV transitions which were previously interpreted as two ground state transitions from assumed states in ^{45}K. The $\log ft$ value (4.7 ± 0.1) implies negative parity and limits the angular momentum to $\frac{5}{2}$, $\frac{7}{2}$, $\frac{9}{2}$. Due to the existence of a 1.2% ground state transition the values $\frac{5}{2}^-$, $\frac{7}{2}^-$ would be preferred. This level could be the same that the one reported in the (p, α) study[6] at 3970 ± 30 keV, with $l \geq 3$.

4043.8 keV level. A γ ray of this energy, presenting the suitable decay rate in the multianalysis experiment, gives indication for the existence of a state at that energy, since no other γ ray has been found in coincidence.

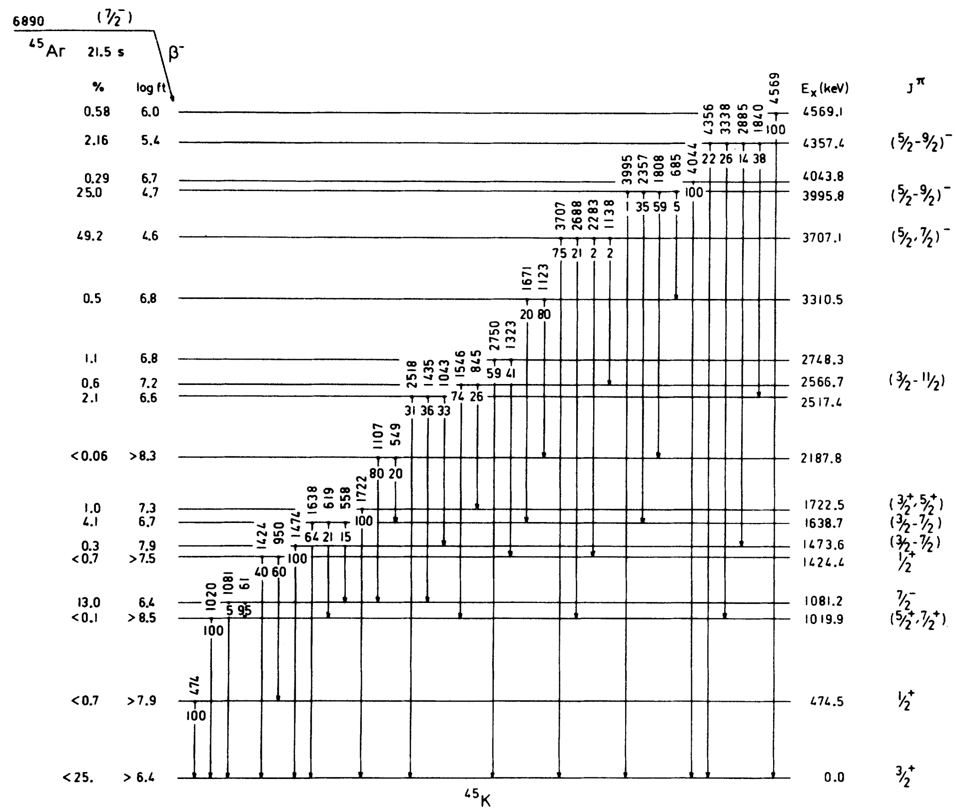

FIG. 4. Proposed decay scheme for ^{45}Ar. Empirical rules (Ref. 26) for spin and parity assignments from log*ft* values have been used. Spin values are from Ref. 12 and this work. For the levels without quoted angular momentum, $J=\frac{5}{2}, \frac{7}{2}$, or $\frac{9}{2}$, according to their log*ft* value.

4357.4 keV level. Four γ transitions can be interpreted on the basis of the existence of this level, for which the β feeding (log$ft = 5.4 \pm 0.1$) restricts the spin and parity to $\frac{5}{2}^-, \frac{7}{2}^-, \frac{9}{2}^-$.

4569.1 keV level. This level is observed through its ground state transition and its excitation energy is almost the same as the one of the state reported in the (p, α) experiment[6] at 4570 ± 30 keV, with $l \geq 3$.

The decay scheme we have established accounts for nearly all the observed γ rays subsequent to the ^{45}Ar beta decay. It involves 11 levels of ^{45}K which are reported for the first time in the radioactivity of ^{45}Ar at 1.42, 1.47, 1.72, 2.52, 2.57, 2.75, 3.31, 3.99, 4.04, 4.36, and 4.57 MeV. Additionally there are indications that the states at 1.42, 1.72, 3.31, 3.99, and 4.57 MeV are the same as those reported in particle transfer reactions.[12]

The comparison of the ^{45}K and ^{41}K level schemes has been made by Petry *et al.*[2] as these two nuclei with one proton hole in the *s-d* shell and two neutron particles or holes in the $f_{7/2}$ shell are expected to have similar level structure. It is of interest to note that the similarities between the two nuclei appear more clearly with the revised level scheme presented in Fig. 4. In particular for both ^{41}K and ^{45}K, eight states can now be identified below 1.75 MeV and for both nuclei there is a 0.45 MeV energy gap above 1.7 MeV in the level diagram.

B. Argon 46

The half-life has been measured equal to 7.8 ± 0.8 s. In addition to the strong γ ray depopulating the level at 1.94 MeV reported previously[2,3] and now located at 1944.3 ± 0.1 keV, three much weaker lines—each with an intensity less than 1% relative to the prominent ray (Table IV)—were observed at 288.1, 584.7, and 1020.3 keV and could be attributed to the decay of ^{46}Ar on the basis of their decay rate in the multispectra (Fig. 5). The low branching ratio precluded the measurement of γ-γ coincidences. Therefore a tentative interpretation of the γ rays as transitions in ^{46}K could only be inferred by comparison with the level diagram resulting from particle transfer reactions.[15] The observed γ rays do not match energy differences between the levels known below 1.94 MeV. Furthermore, in that energy region, only negative parity states with $J \geq 2$ are reported, so that one would

TABLE III. β branching and logft values in the ^{45}Ar decay.

Final state in ^{45}K (keV)	I_β (%)	logft
0	<25	>6.4
474.5 ± 0.2	<0.7	>7.9
1019.9 ± 0.1	<0.1	>8.5
1081.2 ± 0.1	13.0 ± 2.1	6.4 ± 0.1
1424.4 ± 0.2	<0.7	>7.5
1473.6 ± 0.3	0.3 ± 0.2	$7.9^{+0.6}_{-0.2}$
1638.7 ± 0.3	4.1 ± 1.1	6.7 ± 0.2
1722.5 ± 0.3	1.0 ± 0.2	7.3 ± 0.1
2187.8 ± 0.1	<0.06	>8.3
2517.4 ± 0.5	2.1 ± 0.4	6.6 ± 0.1
2566.7 ± 1.2	0.6 ± 0.3	$7.2^{+0.3}_{-0.2}$
2748.3 ± 1.3	1.1 ± 0.2	6.8 ± 0.1
3310.5 ± 1.0	0.5 ± 0.3	$6.8^{+0.3}_{-0.2}$
3707.1 ± 0.3	49.2 ± 2.0	4.6 ± 0.1
3995.8 ± 0.1	25.0 ± 1.3	4.7 ± 0.1
4043.8 ± 1.0	0.29 ± 0.04	6.7 ± 0.1
4357.4 ± 0.6	2.16 ± 0.33	5.4 ± 0.1
4569.1 ± 1.0	0.58 ± 0.10	6.0 ± 0.1

expect new β branches to populate higher lying states of positive parity. Most probably, the 1.94 MeV level is populated by the 0.28 MeV line originating from a 2232.6 keV level which is close to the 2222 ± 5 keV state[15] reported with $J^\pi = 0^+$. For the two other lines no interpretation can be proposed on the basis of the presently known levels in ^{46}K. An attempt to measure the intensity of the ground state transition yields an upper limit ($\leq 5\%$) for which $\log f_1 t \geq 8.3$ which would be consistent with a first forbidden unique transition ($0^+ \to 2^-$) in so far as the ground state of ^{46}K has $J^\pi = 2^-$.

As only a lower limit of the β branching to the 1.94 MeV state could be set in the former experiment,[3] we have been able to define here, despite the uncertainties of the decay scheme, an intensity of $(98.6 \pm 0.6)\%$ for that branch if we assume no β_0 transition. The corresponding logft value, 4.2 ± 0.1, is in agreement with the 1^+ spin and parity assignment for the 1.94 MeV state.

TABLE IV. Energy and relative intensity of γ rays following β decay of ^{46}Ar.

E_γ (keV)	I_γ	E_i (MeV)	E_f (MeV)
288.1 ± 0.7	7 ± 2	(2.23	1.94)
584.7 ± 1.5	4 ± 1		
1020.3 ± 1.2	8 ± 3		
1944.3 ± 0.1	1000	1.94	0

C. The $f_{7/2} \to d_{3/2}$ $M2$ transitions in odd potassium nuclei

Single proton hole states appear at low energy in the odd potassium spectra where the ground state and the first excited state are primarily $d_{3/2}$ and $s_{1/2}$ proton holes. It has been shown also that if the $1d_{3/2}$ and $1s_{1/2}$ strengths are concentrated in one state, for increasing distance from the Fermi surface a large distribution of the hole strength[5] is found. This is the case for the $1d_{5/2}$ hole and from the preceding discussion of ^{45}K it appears that the level at 1020 keV might belong to the $1d_{5/2}$ hole strength distribution. For the level at 1081 keV, the spin value $J^\pi = \frac{7}{2}^-$ can be related to a two-hole configuration, namely $|f^7(\frac{7}{2}, \frac{5}{2})d^6(0,1)|_{7/2, 7/2}$, where each coupling is labeled by its J and T.

The energy of the narrow $1d_{3/2}$ and $2s_{1/2}$ hole states shows a linear dependence on the mass of the potassium isotopes[16] which is well reproduced with the single particle-hole interaction proposed by Bansal and French[17] and Zamick[18] (BFZ). With the same interaction the lowest energy for the $\frac{7}{2}^-$ particle-hole states related to the $(sd)^{-2}(f)^n$ configurations can be predicted (see Appendix). As the calculated energies for $J^\pi = \frac{3}{2}^+$ and $J^\pi = \frac{7}{2}^-$ in ^{41,43,45}K reproduce reasonably well the experimental values, it was of interest to compare the experimental $M2$ strength measured in ^{45}K for the $\frac{7}{2}^- \to \frac{3}{2}^+$ transition with the weak coupling estimate. The reduced transition probability $B_{\rm BFZ}(M2)$ has been calculated using the expression given by Keinonen *et al.*[9] who have discussed the systematics of the $M2$ transitions between the $1f_{7/2}$ and the $1d_{3/2}$ shell in $33 \leq A \leq 47$ nuclei. According to these authors, we have considered the extreme weak coupling picture (lowest seniority) for the reduced matrix element of the transition:

$$[f^{m+1}(I_f, T_f)d^n(I_d, T_d)]_{IT} \to [f^m(I'_f, T'_f)d^{n+1}(I'_d, T'_d)]_{I'T}$$

where for ^{45}K we have $m=6$, $n=6$, $I_f = I = \frac{7}{2}$, $I'_f = I_d = 0$, $I'_d = I' = \frac{3}{2}$. For the calculation we have used the free nucleon g factors, the isoscalar and isovector coupling constants G_s^0 and G_s^1 defined in Ref. 9 and respectively equal to -1.09 and -8.75.

The experimental values $B_{\rm exp}(M2)$ and the ratios $B_{\rm BFZ}/B_{\rm exp}$ are given in Table V for $1f_{7/2} \to 1d_{3/2}$ transitions in potassium and scandium nuclei. It should be noted that for all the transitions reported, the isospin factor in the expression of the reduced matrix element, defined as

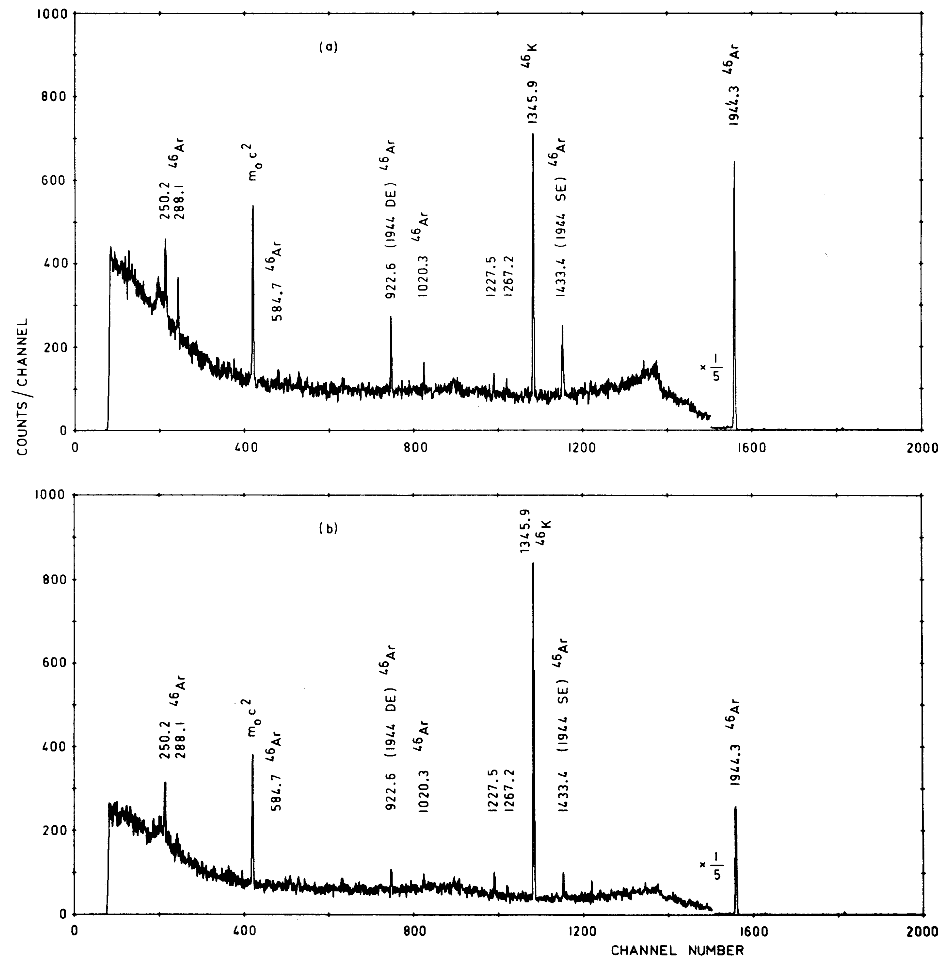

FIG. 5. Delayed gamma spectra following ^{46}Ar β decay, recorded in coincidence with a 4π-β counter. The spectrum (a) was accumulated during a 10 s time period initiated immediately after each collection; the spectrum (b) was accumulated during the same time period initiated 10 s after each collection. Isotope labels refer to parent nuclei. Unassigned peaks may result from unreported transitions in the ^{46}K to ^{46}Ca decay.

TABLE V. Comparison between the reduced transition probability, $B_{\mathrm{BFZ}}(M2)$, calculated with the formalism proposed by Keinonen (Ref. 9) for weak coupling estimates and the experimental value $B_{\mathrm{exp}}(M2)$, for the $1f_{7/2}\to 1d_{3/2}$ transitions in potassium and scandium nuclei.

Nucleus	Initial state E_x (MeV), I	Final state E_x (MeV), I'	$B_{\mathrm{exp}}(M2)$ [a] ($\mu 0^2$ fm^2)	$B_{\mathrm{BFZ}}/B_{\mathrm{exp}}$	$\lvert G_{\mathrm{eff}}\rvert$
^{41}K	1.29, $\frac{7}{2}^-$	0, $\frac{3}{2}^+$	1.94 ± 0.06	18.9 ± 1.0	2.26 ± 0.06
^{43}K	0.74, $\frac{7}{2}^-$	0, $\frac{3}{2}^+$	1.21 ± 0.05	36.4 ± 1.5 [c]	1.63 ± 0.04
^{45}K	1.08, $\frac{7}{2}^-$	0, $\frac{3}{2}^+$	0.63 ± 0.2 [b]	77.5 ± 25.0	1.12 ± 0.2
^{43}Sc	0.15, $\frac{3}{2}^+$	0, $\frac{7}{2}^-$	1.41 ± 0.02	33.6 ± 0.5	1.69 ± 0.02
^{45}Sc	0.013, $\frac{3}{2}^+$	0, $\frac{7}{2}^-$	1.36 ± 0.06	37.4 ± 1.8 [c]	1.61 ± 0.04
^{47}Sc	0.76, $\frac{3}{2}^+$	0, $\frac{7}{2}^-$	0.72 ± 0.11	73.0 ± 12.0	1.15 ± 0.1
^{49}Sc	2.37, $\frac{3}{2}^+$	0, $\frac{7}{2}^-$	0.48 ± 0.03	111 ± 7	0.93 ± 0.03

[a] $B_{\mathrm{exp}}(M2)$ are deduced from the lifetimes reported in Refs. 12, 23, and 24 unless otherwise quoted.
[b] Present work.
[c] These values are in agreement with the revised value of Keinonen (Ref. 25).

$$f_T = \frac{T_3}{T(T+1)}\,[T_d'(T_d'+1) - T_d(T_d+1) + T_f(T_f+1) - T_f'(T_f'+1)]$$

has the same value, $f_T = -1$, corresponding to single proton transitions.

As Keinonen *et al.*[9] have done, we have introduced the effective $M2$ coupling constant G_{eff}:

$$G_{\text{eff}} = G_s[B_{\text{exp}}(M2)/B_{\text{BFZ}}(M2)]^{1/2},$$

where G_s has been defined as $G_s = G_s^0 - f_T G_s^1$.

The values of $|G_{\text{eff}}|$ are given in the last column. From the comparison of the values reported in Table V two conclusions can be drawn:

(a) Hindrance of the $M2$ transitions is found to be of the same order for potassium and scandium isotopes and to increase with the mass number.

(b) Retardation of the $M2$ transition is more pronounced for potassium and scandium nuclei than for the lighter ones reported in the systematics of Keinonen *et al.* For the fourteen $M2$ transitions with $|f_T| = 1$ listed by these authors, one finds $|G_{\text{eff}}/G_s| = 0.24 \pm 0.06$ in good agreement with $|G_{\text{eff}}/G_s| = 0.25$ deduced by Ejiri *et al.*[19] for the $1h_{11/2} \to 1g_{7/2}$ quasiparticle $M2$ transitions. A retardation factor of the same order has also been reported recently[20] for $1g_{9/2} \to 1f_{5/2}$ single quasiparticle transitions. The seven values listed in Table V for $^{41-45}$K and $^{43-49}$Sc yield $|G_{\text{eff}}/G_s| = 0.15 \pm 0.03$.

The hindrance factor observed in the case of the $\frac{3}{2}^+ \to \frac{7}{2}^-$ $M2$ transition in the Sc isotopes have been discussed by Lawson and Macfarlane[21] who have showed that the deformation of the effective single particle potential implies an important core excitation probability in the wave function of the $d_{3/2}$ hole state. Taking into account these core excitation probabilities, hindrance factors of the correct order of magnitude are obtained for the $M2$ decays. According to the similarity of the experimental values, a quantitative understanding of the $M2$ transition strength in K nuclei requires an estimation of the amount of core excitation in these nuclei.

TABLE VI. Comparison between the experimental and calculated values of the two-proton separation energy, $R_{2\pi}$, for the lowest $J^\pi = \frac{7}{2}^-$ state in ^{41,43,45}K.

Nucleus	E_x exp. (MeV)	J^π	$R_{2\pi}$ exp. (MeV)	$R_{2\pi}$ calc. (MeV)
^{41}K	1.293	$\frac{7}{2}^-$	16.49	16.54
^{43}K	0.738	$\frac{7}{2}^-$	19.80	19.88
^{45}K	1.081	$\frac{7}{2}^-$	23.38	23.24

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APPENDIX

The agreement between experimental and calculated excitation energies for the first $J^\pi = \frac{7}{2}^-$ level of the odd potassium isotopes using the weak coupling estimate is illustrated by the Table VI. We have reported values for the two-proton separation energy $R_{2\pi}(A,Z)$ corresponding to the energy required to remove two protons from a nucleus to reach $M^*(A, T_z)$. Calculated values have been obtained from the relation

$$R_{2\pi}(A,Z) = R_{2\pi}(^{38}\text{Ar}) - (2a - b/2)(A - 38) - (b - 2c)(Z - 18)$$

using $(a - b/4) = 0.837$ MeV and $(b/2 - c) = 1.597$ MeV.

In a previous paper[4] we have compared the excitation energy for the first $J^\pi = \frac{7}{2}^-$ in ^{39}K ($E_x = 2.813$ MeV, $R_{2\pi} = 12.23$ MeV) with the value obtained with the model ($R_{2\pi} = 13.20$ MeV). It has been pointed out however by Sherr[22] that this level is not a member of the same series limited to $T_> = T_p + T_h$ states and that the $T_< = T_p + T_h - 1$ value accounts for the 1 MeV disagreement obtained in that case.

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