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Studies of the Low-Lying States of ^{41}K via the Reactions ^{41}Ar(β^-)^{41}K and ^{41}K($p,p'\gamma$)^{41}K[†]

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The 110-min β^- decay of the $\frac{7}{2}^-$ ground state of ^{41}Ar to excited states of ^{41}K was investigated by observation of the deexcitation ^{41}K γ rays with a Ge(Li) detector. In addition, both (p',γ) coincidence measurements and a magnetic spectrometer study were made of the reaction ^{41}K(p,p')^{41}K at proton energies between 5.3 and 5.8 MeV. The (p',γ) work gave γ-ray decay-mode information used in the analysis of the β^--decay studies. The magnetic spectrometer studies confirmed a new level of ^{41}K at 1594 ± 3 keV observed in the (p',γ) work. The β^- decay to the ^{41}K sixth excited state ($E_x = 1677.0 \pm 0.3$ keV) observed previously by Pratt was confirmed. The branch was found to be $(5.2 \pm 0.5) \times 10^{-2}\%$, corresponding to an allowed $\log f_0 t$ value of 7.68 ± 0.04. Rather severe upper limits were placed on any other branches to excited states except the major one to the $\frac{7}{2}^-$ state at 1294 keV.

I. INTRODUCTION

The available information on the excitation energies and spin-parity assignments for the low-lying levels of ^{41}K is collected in Fig. 1. Information from the present studies of the reactions ^{41}Ar(β^-)^{41}K and ^{41}K(p,p')^{41}K is incorporated. The main previous sources of information for this figure are the ^{40}K(n,γ)^{41}K work of Beckstrand and Shera,[1] results[2] from the reaction ^{41}K(p,p')^{41}K and studies[2,3] of the β^- decay of ^{41}Ar. Single-nucleon-transfer studies have been made via the reaction ^{42}Ca($d,{}^3$He)^{41}K,[4] the reaction, ^{42}Ca(t,α)^{41}K,[5] the reaction ^{40}Ar(^{3}He$,d$)^{41}K,[6] and the reaction ^{40}Ar(d,n)^{41}K.[7] These all suffer from inadequate energy resolution, and the only definite information not available previously is that giving a $J^\pi = \frac{1}{2}^+$ assignment to the first excited state. The reaction ^{41}K($n,n'\gamma$)^{41}K has also been studied.[8] However, little information was obtained from this work because the γ-ray energy resolution was inadequate. The work of Arnell and Persson[9] on the reaction ^{40}Ar(p,γ)^{41}K is a rich source of information on higher states of ^{41}K but, mainly because of inadequate γ-ray energy resolution, provides us with no new information on the low-lying states.

The motivation of the present work was to reinvestigate the β^- decay of ^{41}Ar to excited states of ^{41}K and specifically to search for weak branches by detecting delayed γ-ray emission. A previous study[3] of this type was made using NaI(Tl) γ-ray detectors. It was hoped that the increased sensitivity of Ge(Li) detectors would result in the acquisition of new information. The β^--decay studies are reported in Sec. II.

In the course of these studies it became evident that the interpretation of the β^--decay results would be greatly aided by ancilliary γ-ray branching ratio information. Accordingly, the reaction ^{41}K($p,p'\gamma$)^{41}K was utilized to investigate the γ-decay modes of the states shown in Fig. 1. The ^{40}K(n,γ)^{41}K results,[1] available after this work was analyzed, are more accurate in some cases than the present work and provide information quite valuable in the analysis of the β^--decay results. The γ-decay studies are described in Sec. III.

II. ^{41}Ar(β^-)^{41}K

The isotope ^{41}Ar, which has a half-life of 109.6 ± 0.4 min,[2] was produced via the reaction ^{40}Ar(d,p)^{41}Ar ($Q = 3.88$ MeV) with bombarding energies between 3 and 4 MeV. Natural Ar gas was contained at a pressure of ~0.6 atm in a cell with a nickel window 2.5×10^{-4} cm thick.

γ rays were detected with a 22-cm^3 Ge(Li) detector which had an energy resolution [full width at half maximum (FWHM)] of 3.8 keV for ^{60}Co γ rays. The relative efficiency for different γ-ray energies was determined experimentally.

The first studies were made with two gas target cells. One of these was bombarded for 3 h. It was then removed from the beam line and its γ-ray activity was examined after a wait of 1 h. In the meantime the other gas cell was being bombarded. Prominent γ rays immediately evident were the intense ground-state γ ray from the main (99.1%) branch of ^{41}Ar to the second excited state of ^{41}K at 1293.64 ± 0.04 keV[10] and the γ rays of 2167.61 ± 0.14 and 1642.3 ± 0.3 keV[11] from the β^- decay of ^{38}Cl. The ^{38}Cl activity is produced via the reaction ^{40}Ar-

$(d, \alpha)^{38}$Cl (Q = 5.48 MeV). It has a half-life of 37.2 min.

The intense ^{38}Cl activity made detection of weak ^{41}Ar activities difficult. Therefore the ^{38}Cl was separated out in a second set of measurements. This was done by transferring the target gas to a second reservoir through a dry-ice-alcohol cold trap (−72°C). Any Cl gas (freezing point = −34.6°C) was removed while the argon (freezing point = −185.7°C) was unaffected. A supplementary advantage of this method was the removal of activities induced in the nickel window and in the gas cell. In these studies the bombardment time was 110 min following by two counting intervals of 110 min each in which time 4096-channel γ-ray spectra were recorded. Portions of two such spectra are shown in Fig. 2. The 1294- and 1677-keV γ rays identified in Fig. 2 were observed to decay with half-lives of 109 ± 2 and 126 ± 21 min, respectively, in agreement with the ^{41}K half-life of 109.6 ± 0.4 min.[2] The energy of the 1677-keV γ ray was measured in the first series of measurements using ^{38}Cl γ rays for calibration as illustrated in Fig. 3. The result is 1677.0 ± 0.3 keV. This is in excellent agreement with the energy of 1677.5 ± 0.6 keV obtained for the excitation energy of the sixth excited state of ^{41}K by Beckstrand and Shera[1] in the reaction ^{40}K(n,γ)-^{41}K but in poor agreement with the result of 1664 ± 7 keV (for presumably the same ^{41}K γ ray) observed by Pratt[3] using a NaI(Tl) detector and the reaction ^{40}Ar$(n,\gamma)^{41}$Ar to form the ^{41}Ar activity. We obtain $(5.2 \pm 0.5) \times 10^{-4}$ for the intensity of the 1677-keV γ ray relative to the 1294-keV γ ray. This result is in excellent accord with the relative intensity of $(5 \pm 2) \times 10^{-4}$ obtained by Pratt.[3] No further γ rays were observed which could be assigned to ^{41}Ar$(\beta^-)^{41}$K. Before discussing the β^- decay of ^{41}K further, we turn to the experiment on the decay modes of the low-lying states of ^{41}K.

III. REACTION ^{41}K$(p,p'\gamma)^{41}$K

The target for this work consisted of 200 μg/cm^2 of KI enriched to 95% in ^{41}K evaporated on to a 20-μg/cm^2 carbon film. The proton detector was either an annular counter of 200-mm^2 area at 180° to the beam or, in certain cases, a 100-mm^2 counter at 135°.

The γ rays were detected in either a 22- or 54-cm^3 detector at 90° to the beam and 3 cm from the target. Conventional commercial fast-slow-coincidence units were used with time-to-pulse height conversion and a resolving time 2τ of 30 nsec. The measurements took a total of 50 h. The proton groups corresponding to the triplet at 1.56 to 1.59 MeV were not resolved, and neither were the next two doublets shown in Fig. 1; however, the energy resolution of the γ-ray detector was sufficient to resolve almost all the possible γ-ray transitions. The γ-ray spectrum observed in coincidence with a proton-energy interval corresponding to 1.50- to 1.60-MeV ^{41}K excitation energy is shown in Fig. 4. This figure shows the first evidence for a level at an excitation energy of 1594 keV in ^{41}K. All three members of the triplet are observed to decay to the ground state and the first excited state. The evidence for a 1594-keV level is provided not only by the 1594→ 980 and 1594→ 0 γ rays but also by the intensity of the 980-keV γ ray, which agrees with that expected from the sum of the three cas-

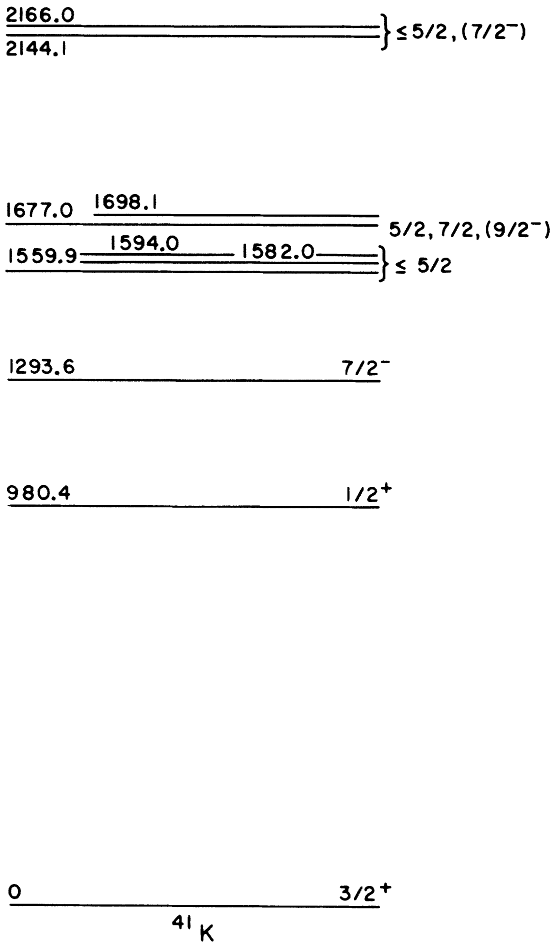

FIG. 1 Summary of excitation energies and spin-parity assignments for the energy levels of ^{41}K. The present results are incorporated. The excitation energies are from Ref. 1 except for the 1293.6-keV level (Ref. 10) and the levels at 980.42 ± 0.10, 1594 ± 3, and 1677.0 ± 0.3 keV (present work). The spin-parity assignments for the ground state and first two excited states are from Refs. 2 and 4–7. The limitations on the spin-parity assignments of the higher-lying states are discussed in Sec. IV. The 1594-keV level, not previously reported, was observed in the present work.

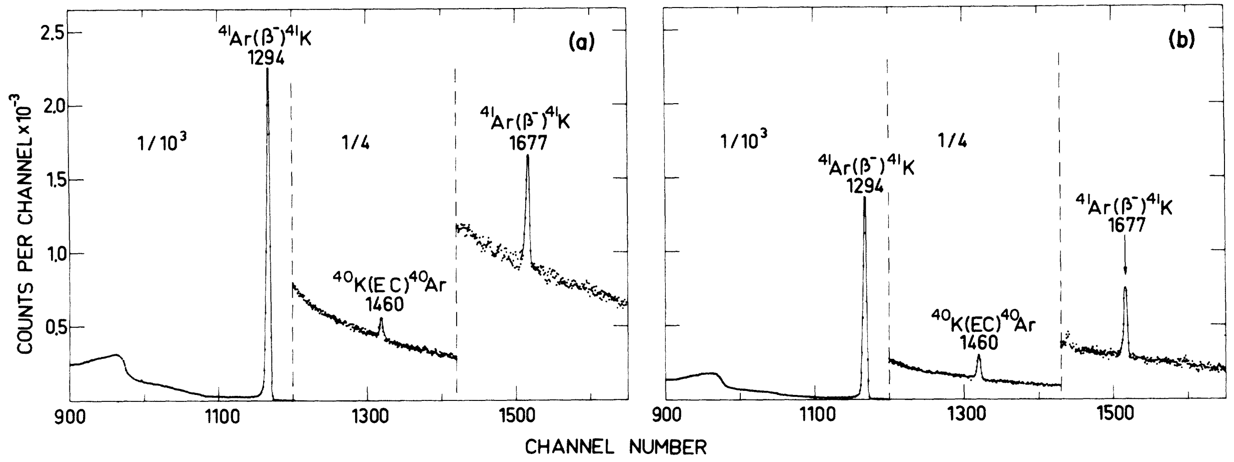

FIG. 2. Portions of γ-ray spectra taken after separation of the ^{41}Ar and ^{38}Cl activities. The spectra (a) and (b) are for successive 110-min intervals after a 110-min bombardment. The γ-ray energies are given in keV. The ^{40}K activity is from room background.

cade intensities. The branching ratio measurements are subject to an unknown uncertainty due to possible proton-γ angular correlations. For the third, fourth, and fifth levels it was possible to observe the two primary γ rays in singles and so independently verify the (p,γ) branching-ratio results. For the 2144- and 2166-keV levels no such check was possible, as is reflected in the uncertainties assigned to the branching ratios for these two levels. The information on γ-ray decay modes obtained in the present work is collected in Table I, which also gives the results of Beckstrand and Shera[1] and our adopted synthesis of the two results.

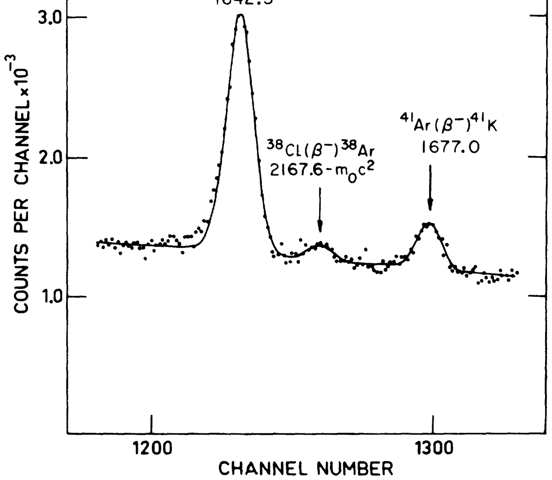

FIG. 3. The 1677-keV region in a γ-ray spectrum obtained following bombardment of a natural argon target with 3.0-MeV deuterons. The ^{38}Cl γ rays were used to provide an energy calibration for the ^{41}Ar γ ray.

An incidental result of the ^{41}K$(p,p')^{41}$K work was a measurement from the γ-ray singles of some γ-ray energies. From these measurements we obtained ^{41}K excitation energies of 980.42 ± 0.10, 1559.5 ± 1.0, 1582.7 ± 1.0, and 1698.0 ± 1.0 keV for the first, third, fourth, and seventh states of Fig. 1. These results are in excellent accord with the ^{40}K$(n,\gamma)^{41}$K results of Beckstrand and Shera.[1]

As a check on the ^{41}K$(p,p')^{41}$K results, especially the discovery of a new ^{41}K level at 1594 keV, a magnetic spectrograph of the Buechner type[12] was used to record proton spectra from the reaction ^{41}K$(p,p')^{41}$K at 90 and 130° to the beam. The target was 100 μg/cm^2 of enriched KI on 20-μg/cm^2 carbon. Beam energies of 5.3, 5.5, and 5.8 MeV were used at both angles. The duration of the exposure of the photographic plates was about 24 h. The best energy resolution (FWHM) was 6 keV. The spectrum of protons obtained at E_p = 5.5 MeV, and θ_p = 90° is shown in Fig. 5. The evidence for a proton group corresponding to a level at 1594-keV excitation in ^{41}K is clear. The spectra obtained at E_p = 5.5 MeV, θ_p = 130° and E_p = 5.8 MeV, θ_p = 90° showed similar evidence for the 1584-keV level; while the remaining three spectra, of worse energy resolution, gave indication of an unresolved doublet at 1.59 MeV. Thus the magnetic spectrograph results gave definite confirmation of a ^{41}K level at 1594 ± 3 keV. There was no evidence for a level at 1517 keV in any of the ^{41}K$(p,p')^{41}$K studies. We conclude that the observed level of this energy suggested by the ^{40}K$(n,\gamma)^{41}$K studies[1] probably does not exist.

IV. DISCUSSION

A. Possible Spin-Parity Assignments

It can be seen from Table I that all of the nine definitely established levels below 2.2-MeV excitation have γ-ray branches to the ground state. As summarized in Table II, limits on the intensities of these ground-state branches were used in setting limits on the β^- branching ratios to seven of the nine excited states. The γ-ray intensity limits were obtained from the spectra described in Sec. II. The relative β^- branching ratios to the ground and second excited states were taken from previous work,[2] as were the β^- end-point energies.[2] The $\log f_0 t$ values include all the usual corrections except radiative ones. The β^- transition to the 1294-keV level is allowed, in support of the $\frac{7}{2}^-$ assignments to it and the ^{41}Ar ground state.[2] The β^- transition to the ground state is actually unique first forbidden with $\log f_1 t = 9.69 \pm 0.04$.[13] If the β^- decay to the 1677-keV level were unique first forbidden, it would have $\log f_1 t = 8.11 \pm 0.04$. This corresponds to a matrix element about a factor of 10 larger than any known unique first-forbidden decay in the region $A \leqslant 50$[13, 14]; and even though this result would be permissable on theoretical grounds, we consider it to be highly improbable and thus consider only the allowed and nonunique first-forbidden possibilities for this β^- branch. The $\log f_0 t$ value is considerably larger than the bulk of known allowed

TABLE I. γ-ray branching ratios for the low-lying levels of ^{41}K.

Level No.	E_i (keV)	E_f (keV)	E_γ (keV)	Branching ratios (%) Previous[a]	Present	Adopted
2	1293.64	0	1293.6	100	100	100
		980.4	313.2	<2	···	<2
3	1559.9	0	1559.9	80 ± 4	87 ± 4	84 ± 3
		980.4	579.5	20 ± 4	13 ± 3	16 ± 3
		1293.6	266.3	<0.4	<2	<0.4
4	1582.0	0	1582.0	76 ± 4	90 ± 4	83 ± 5
		980.4	601.6	24 ± 4	10 ± 2	17 ± 5
		1293.6	288.4	<0.7	<2	<0.7
5	1594.0	0	1594.0	···	61 ± 8	61 ± 8
		980.4	613.6	···	39 ± 8	39 ± 8
		1293.6	300.4	···	<17	<17
6	1677.1	0	1677.1	99.1 ± 0.6	100	99.1 ± 0.6
		980.4	696.7	≤0.5	<5	≤0.5
		1293.6	383.5	0.9 ± 0.6	≤10	0.9 ± 0.6
7	1698.1	0	1698.1	100	100	100
		980.4	717.7	<2	<10	<2
		1293.6	404.5	<0.7	<9	<0.7
8	2144.1	0	2144.1	57 ± 7	46 ± 7	54 ± 7
		980.4	1163.7	18 ± 4	14 ± 4	16 ± 4
		1293.6	850.5	···	<12	<12
		(1516.8)	627.3	···	<12	<12
		1559.9	584.2	21 ± 5	26 ± 6	24 ± 5
		1582.0	562.1	···	<15	<15
		1594.0	550.1	···	<12	<12
		1677.0	467.1	···	<13	<13
		1698.1	446.0	4 ± 1	14 ± 6	6 ± 2
9	2166.0	0	2166.0	30 ± 8	26 ± 8	30 ± 8
		980.4	1185.6	43 ± 8	34 ± 7	43 ± 8
		1293.6	872.4	···	<25	<25
		(1516.8)	649.2	···	<25	<25
		1559.9	606.1	···	<25	<25
		1582.0	584.0	27 ± 8	~16	27 ± 8
		1594.0	572.0	≤8	≲24	≤8
		1677.0	489.0	···	<25	<25
		1698.1	467.9	···	<25	<25

[a] D. F. Beckstrand and E. B. Shera, Phys. Rev. C **2**, 208 (1971); E. B. Shera, private communication.

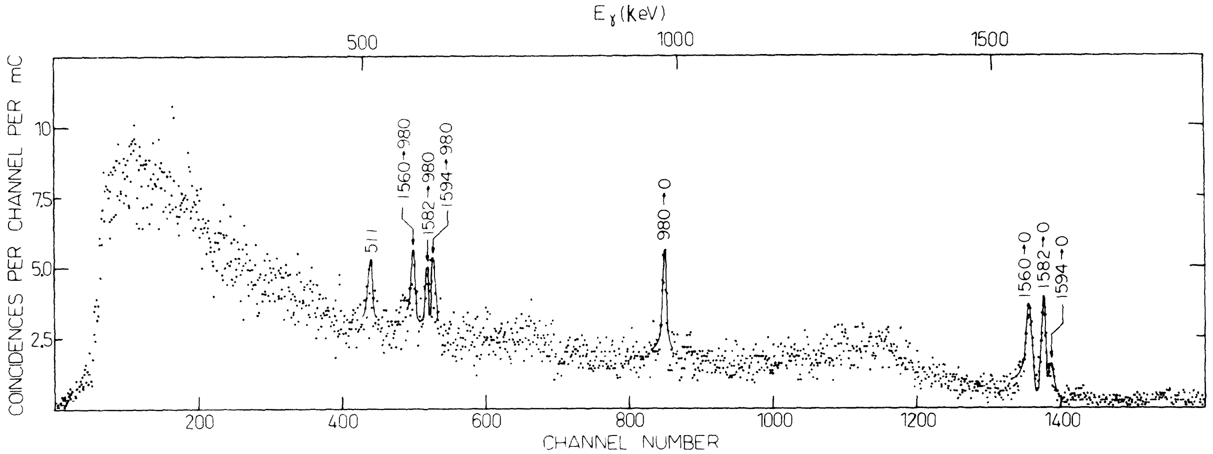

FIG. 4. γ-ray spectrum obtained in the reaction ^{41}K$(p,p'\gamma)^{41}$K at 90° to the beam and in coincidence with protons detected in a 180° annular silicon detector. The slow-coincidence gate was set on the region of the proton spectrum corresponding to 1.50- to 1.60-MeV excitation. The ^{41}K γ rays are identified by the transitions (in keV) to which they are assigned.

transitions; however, we do not rule out the allowed possibility, since, even though there may always be theoretical upper limits to the size of β^- and γ-decay matrix elements, there are never any rigorous limits on how small they can be. Thus we conclude from the β decay that the 1677-keV level has $J=\frac{5}{2}, \frac{7}{2}$, or $\frac{9}{2}$ with either parity.

From the (p,γ) coincidence studies, we can ascertain that the mean lifetimes of the third through ninth excited states are short compared to a loosely defined value of the order of the experimental resolving time of $\sim 3\times10^{-8}$ sec. We use this qualitative limit to determine the spin-parity restrictions of Fig. 1 for the levels above 1.5 MeV. Firstly, the 1560-, 1582-, and 1594-keV levels all decay to the $\frac{1}{2}^+$ 980-keV level and since the $E3$ Weisskopf single-particle estimates[15] are 78×10^{-5}, 60×10^{-5}, and 52×10^{-5} sec, respectively, for the three cascade transitions in question, we can safely eliminate the possibility of spins of $\frac{7}{2}$ or higher for all three levels. The 2144- and 2166-keV levels also decay partially via the $\frac{1}{2}^+$ 980-keV level and so a similar

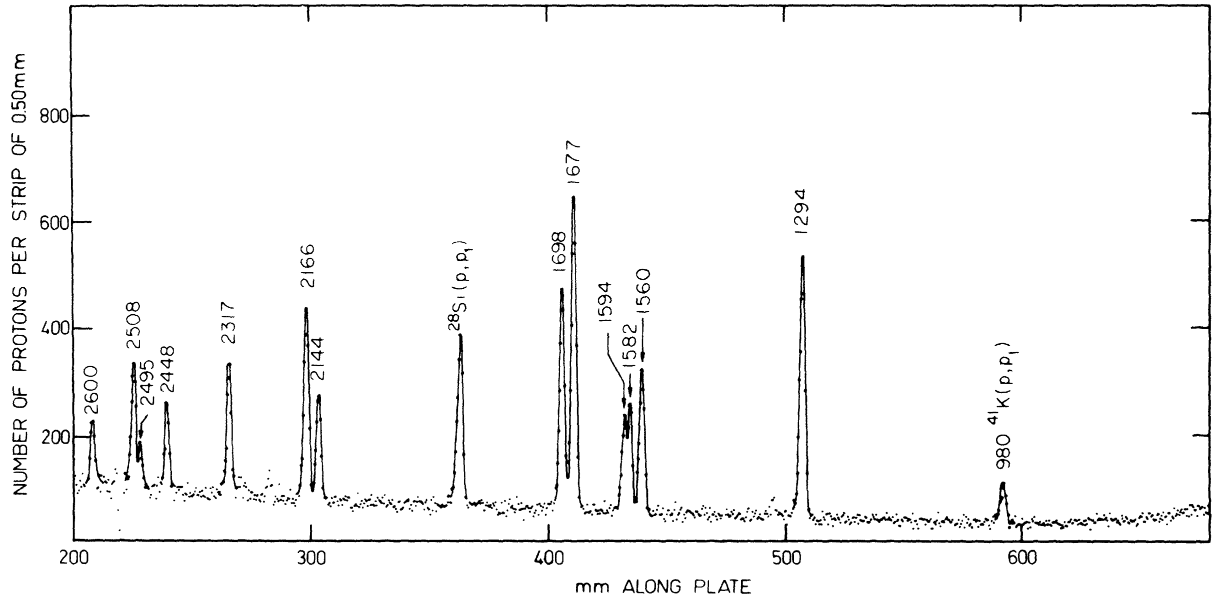

FIG. 5. Proton spectrum obtained in a broad-range magnetic spectrograph in the reaction ^{41}K$(p,p')^{41}$K at $E_p=5.5$ MeV and $\theta_{p'}=90°$. The ^{41}K proton peaks are labeled by the excitation energies (in keV) of the levels to which they correspond. These excitation energies are nominal from Ref. 1 and/or Fig.1.

TABLE II. Results from $^{41}Ar(\beta^-)^{41}K$.

Level No.	^{41}K level (Ref. a) (keV)	Ground-state γ branch (Ref. b) (%)	β^- end-point energy (Ref. c) (keV)	β^- intensity (Ref. d) (%)	$\log f_0 t$
0	0	...	2491.9	0.83 ± 0.08[e]	8.44 ± 0.04
1	980.42	100	1511.5	$<2.5 \times 10^{-2}$	>9.0
2	1293.64	100	1198.3 ± 1.1	99.12 ± 0.08[e]	5.046 ± 0.002
3	1559.9	>81	932.0	$<3.8 \times 10^{-3}$	>9.0
4	1582.0	>78	909.9	$<4.0 \times 10^{-3}$	>9.0
5	1594.0	>53	897.9	$<5.8 \times 10^{-3}$	>8.8
6	1677.0	99.1	814.9	$(5.2 \pm 0.5) \times 10^{-2}$	7.68 ± 0.04
7	1698.1	100	793.8	$<3.0 \times 10^{-3}$	>8.9
8	2144.1	>47	347.8	$<5.4 \times 10^{-3}$	>7.3
9	2166.0	>22	325.9	$<1.2 \times 10^{-2}$	>6.9

[a] From Ref. 1 except for level 2 (Ref. 10) and levels 1, 5, and 6 (present work).

[b] Based on the adopted branching ratios of Table I. The limits correspond to 1 standard deviation.

[c] Based on the end-point energy given for the second excited state (Ref. 2) and the excitation energies of column 2.

[d] Obtained from the intensity of the ground-state γ-ray transition and the branching ratios of column 3. The limits correspond to 2 standard deviations from the statistical yield for the γ ray in question.

[e] From Refs. 2 and 13.

argument gives the limitations of Fig. 1 for these two levels. Finally, the $\frac{9}{2}^+$ alternative for the 1677-keV level is eliminated and the possibility of a $\frac{9}{2}^-$assignment is rendered remote from consideration of the decay of this level.

In the $^{40}Ar(n,\gamma)^{41}Ar$ studies of Beckstrand and Shera[1] it was found that the levels at 1294, 1582, 1677, 1698, and 2144 keV were directly fed from the $\frac{7}{2}^-$, $\frac{9}{2}^-$ capturing states of ^{41}K. Beckstrand and Shera conclude, since the primary transitions are almost certainly dipole, that these states therefore have $J \geqslant \frac{5}{2}$. Although this is not a rigorous argument, it has a high likelihood of being correct. It would suggest, in particular, that the 1582-keV level has $J = \frac{5}{2}$ and the 2144-keV level is $\frac{5}{2}^{\pm}$ or (less probably) $\frac{7}{2}^-$.

B. Comparison to Shell-Model Expectations

In zeroth order, the low-lying even-parity states of ^{41}K belong to the shell-model configuration $(d_{3/2})^{-1}(f_{7/2})^2$. Beckstrand and Shera[1] reviewed previous calculations in this configuration space and performed one themselves using interaction energies derived from the binding energies of the four lowest levels of ^{40}K. In this calculation, as well as earlier ones,[16,17] the ground state and first excited state are predicted to be $\frac{3}{2}^+$ and $\frac{1}{2}^+$, and three further levels of $\frac{7}{2}^+$, $\frac{5}{2}^+$, and $\frac{3}{2}^+$ are predicted within 2.2 MeV of the ground state. Thus, as seen from Fig. 1, there are four surplus levels between excitation energies of 1.5 and 2.2 MeV in ^{41}K and, unless these are all of odd parity, the shell-model space $(d_{3/2})^{-1}(f_{7/2})^2$ is too restricted to explain all the observed even-parity states below 2.2-MeV excitation.

In zeroth order, the low-lying odd-parity states of ^{41}K arise from $(d_{3/2})^{-2}(f_{7/2})^3$. From the ^{38}Ar spectrum, we can see that the $(d_{3/2})^{-2}$ component should have $J^\pi = 0^+$ with $J^\pi = 2^+$ about 2.2 MeV higher. Thus the low-lying odd-parity spectrum of ^{41}K should resemble a $(f_{7/2})^3$ spectrum, i.e., that of ^{43}Ca. We expect, then, $\frac{5}{2}^-$ and $\frac{3}{2}^-$ states within 700 keV or so above the 1294-keV level of ^{41}K. We would also expect this from a comparison with the low-lying levels of ^{41}Ar which also belong to the $(d_{3/2})^{-2}(f_{7/2})^3$ configuration in zeroth order. Since the $\frac{5}{2}^-$ level is certainly expected below 2.2 MeV and is not expected to decay to the $\frac{1}{2}^+$ 980-keV level and since β^- decay to it would be allowed, the most likely candidate for the $\frac{5}{2}^-$ state is the 1677-keV level.

If we assume $(d_{3/2})^{-2}{}_{0^+}(f_{7/2})^3{}_J$ for the lowest $T = \frac{3}{2}$, $\frac{7}{2}^-$, and $\frac{5}{2}^-$ states of ^{41}K, $(d_{3/2})^{-2}{}_{0^+}(f_{7/2})^3{}_{7/2}$ for the ^{41}Ar ground state, and $(f_{7/2})^3{}_J$ for the similar ^{43}Ca and ^{43}Sc states, then we can quite simply predict the relative β^- decay rates of ^{41}Ar and ^{43}Sc to the $\frac{7}{2}^-$ and $\frac{5}{2}^-$ states of ^{41}K and ^{43}Ca. For mass 41, the effect of the $(d_{3/2})^{-2}{}_{0^+}$ core is felt only in the antisymmetrization, and this effect is to decrease the mass-41 rates by $\frac{2}{5}$ relative to the mass-43 rates.[18] From the data given by Endt and Van der-Leun[2] we calculate $\log f_0 t$ values of 5.00 ± 0.03 and 4.87 ± 0.08 for the decay of ^{43}Sc to the ^{43}Ca $\frac{7}{2}^-$ and $\frac{5}{2}^-$ states, respectively. Thus we predict $\log f_0 t$ values of 5.4 and 5.3 for the decay of ^{41}Ar to the $\frac{7}{2}^-$ and $\frac{5}{2}^-$ states of ^{41}K. The result for the $\frac{7}{2}^-$

state is in fair agreement with the experimental value of 5.05; but if, in actual fact, the $\frac{5}{2}^-$ state is the one at 1677 keV, as we tentatively suggest, then there is considerable unexplained retardation of the β^- decay to this state. Of course, it remains to be seen whether or not the $\frac{5}{2}^-$ state in question is actually below 2.2-MeV excitation, as expected.

We would like to thank E. B. Shera for discussions concerning his work on the reaction $^{40}\mathrm{K}(n,\gamma)$-$^{41}\mathrm{K}$.

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[18] These decays were considered previously by W. G. Grayson and L. W. Nordheim [Phys. Rev. 102, 1093 (1956)]. These authors found that the ^{43}Sc decay to the ^{43}Ca $\frac{7}{2}^-$ ground state has a matrix element in the good seniority model corresponding to log$ft = 3.886$. Thus the experimental rate is retarded by a factor of 13 relative to this simple scheme. For the $^{41}\mathrm{Ar}(\beta^-)^{41}\mathrm{K}$ $\frac{7}{2}^- \rightarrow \frac{7}{2}^-$ decay they found the same rate as the mass-43 case instead of $\frac{2}{5}$ slower as we would predict. The difference is that they did not fully antisymmetrize their wave functions.