Levels of ^{38}K: The ^{40}Ca(d, α), ^{40}Ca(d, $\alpha\gamma$), and ^{36}Ar(^{3}He,$p\gamma$) reactions*

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Precise level energies in ^{38}K have been measured up to the region of 6 MeV in excitation with our 100-cm broad-range magnetic spectrograph and the ^{40}Ca(d, α) reaction. With a Ge(Li) detector, γ-ray energies were measured in the ^{40}Ca(d, $\alpha\gamma$) and ^{36}Ar(^{3}He, $p\gamma$) reactions. Some 79 states have been identified in this region of excitation, approximately 30 of which have not previously been reported. Uncertainties in excitation energies are 1 to 3.5 keV. Branching ratios for levels up to 5.2 MeV were determined, and particle-γ angular correlations were measured with the ^{36}Ar(^{3}He, $p\gamma$) reaction. The mean lives of some levels in ^{38}K excited in the ^{40}Ca(d, $\alpha\gamma$) reaction at $E_d = 7.84$ MeV have been determined using the Doppler-shift attenuation method. The following mean lifetimes were deduced (excitation energy in keV, lifetime in fs): 3431, <170; 3615, 700^{+850}_{-310}; 3668, 95 ± 55; 3688, 400^{+160}_{-120}; 3702, >1100; and 4333, 350^{+700}_{-250}. The angular correlations, with the lifetimes and previous information, lead to the following assignments to the 3431-, 3615-, and 3688-keV levels, respectively: $J^\pi = (2)$, (3^- or 5^-), (3), where parentheses indicate assignments dependent upon unproven assignments to other levels from the literature. The observed decays further imply $J = (1, 2)$ for both the 3857- and 4214-keV levels. Clarifications of several ambiguous and erroneous level identifications in the literature are offered.

[NUCLEAR REACTIONS ^{40}Ca(d,α), E=7.84–16.0 MeV, ^{36}Ar(^{3}He,p), E=8.34 MeV; measured E_α, E_γ, $\alpha\gamma$, $\alpha\gamma(\theta)$, $p\gamma$, $p\gamma(\theta)$, γ branching, Doppler-shift attenuation. ^{38}K deduced levels, J, π, T, τ, δ.]

I. INTRODUCTION

The level structure of ^{38}K has previously been investigated by a variety of reactions such as (d, t), (^{3}He, α), (p, d), (d, α), and (^{3}He, $p\gamma$). Recent discoveries of low-lying high-spin states[1-3] have generated renewed interest in, and pointed out the need for, a more complete and precise level scheme. The neutron pickup reactions have produced much spectroscopic information but have not populated many of the states observed with the ^{40}Ca(d, α) reaction. Jänecke,[4] using the ^{40}Ca(d, α) reaction, reported on states in ^{38}K up to 4.8 MeV but the energy resolution in his experiment was about 25 keV and the precision for most of the levels reported is only ±20 keV. Subsequent studies of ^{38}K have shown that some of the low-lying levels observed by Jänecke[4] are actually doublets. We have undertaken a high-resolution study of the ^{40}Ca(d, α) reaction using the Notre Dame 100-cm broad-range magnetic spectrograph with a view to obtaining accurate excitation energies and a more complete level scheme, and have extended the region of investigation to 6 MeV in excitation. In conjunction with this work we have also studied particle-γ coincidences in the ^{36}Ar(^{3}He, $p\gamma$) reaction leading to excited states up to 5.2 MeV. In addition we have made lifetime measurements with the ^{40}Ca(d, $\alpha\gamma$) reaction using the Doppler-shift-attenuation method. From lifetimes and angular correlations could be deduced spins and parities of some excited states, restrictions on other assignments and mixing parameters for the deexciting γ rays. This work together with the spectrograph work has been useful in removing ambiguities in previous experiments and in obtaining a more complete level scheme of ^{38}K.

The experimental procedure and results of the spectrograph work are given in Sec. II. The γ-ray energies and the decay scheme are presented in Sec. III, the results of the Doppler-shift-attenuation measurements in Sec. IV, and the procedure and the results of the angular correlation studies on ^{36}Ar(^{3}He, $p\gamma$) are given in Sec. V. A discussion and comparison of the present results with previous experiments is presented in Sec. VI.

II. SPECTROGRAPH STUDY OF ^{40}Ca(d,α) REACTION

A. Experimental procedure

Deuteron and ^{3}He beams for the spectrograph and γ-ray experiments were produced with the University of Notre Dame FN tandem Van de Graaff accelerator, the nominal beam energy being determined by magnetic analysis. Targets for the spectrograph experiment were prepared by vacuum evaporation of natural Ca metal (97% ^{40}Ca) onto 20-μg/cm^2 commercial carbon foil backings. The carbon backing and oxidation of the target presented no particular problems for the spectrograph experiment because targets were set in the reflection position. The reaction α particles were momentum-analyzed with the 100-cm broad-range magnetic spectrograph. 50-μm Ilford KO nuclear track plates placed at the focal surface were used to detect and identify the α particles. Data were taken at the laboratory observation angles of 60, 90, and 120° with deuteron bombarding energies ranging from 10 to 16 MeV.

A typical α-particle spectrum at a bombarding energy of 12 MeV and observation angle of 120° is shown in Fig. 1. The data were collected for a charge accumulation of 40 mC with a target ≈10 keV thick to 5-MeV α particles. The contaminant peaks from ^{16}O and ^{13}C are clearly visible in the spectrum. The ^{12}C(d, α_0) group not shown is below the region of interest. The numbers above the groups are to identify them with the entries in Table I. Notice the large number of states above 6 MeV which were not analyzed. The nucleus ^{38}K becomes unbound to ^{37}Ar + p at 5.13 MeV excitation and thus many of the levels above this excitation may have natural widths comparable to or greater than our resolution. With the high level density it is difficult to distinguish close-lying doublets from levels with natural width. We terminated our analysis at 6 MeV although it is clear that there are many narrow states well beyond this region.

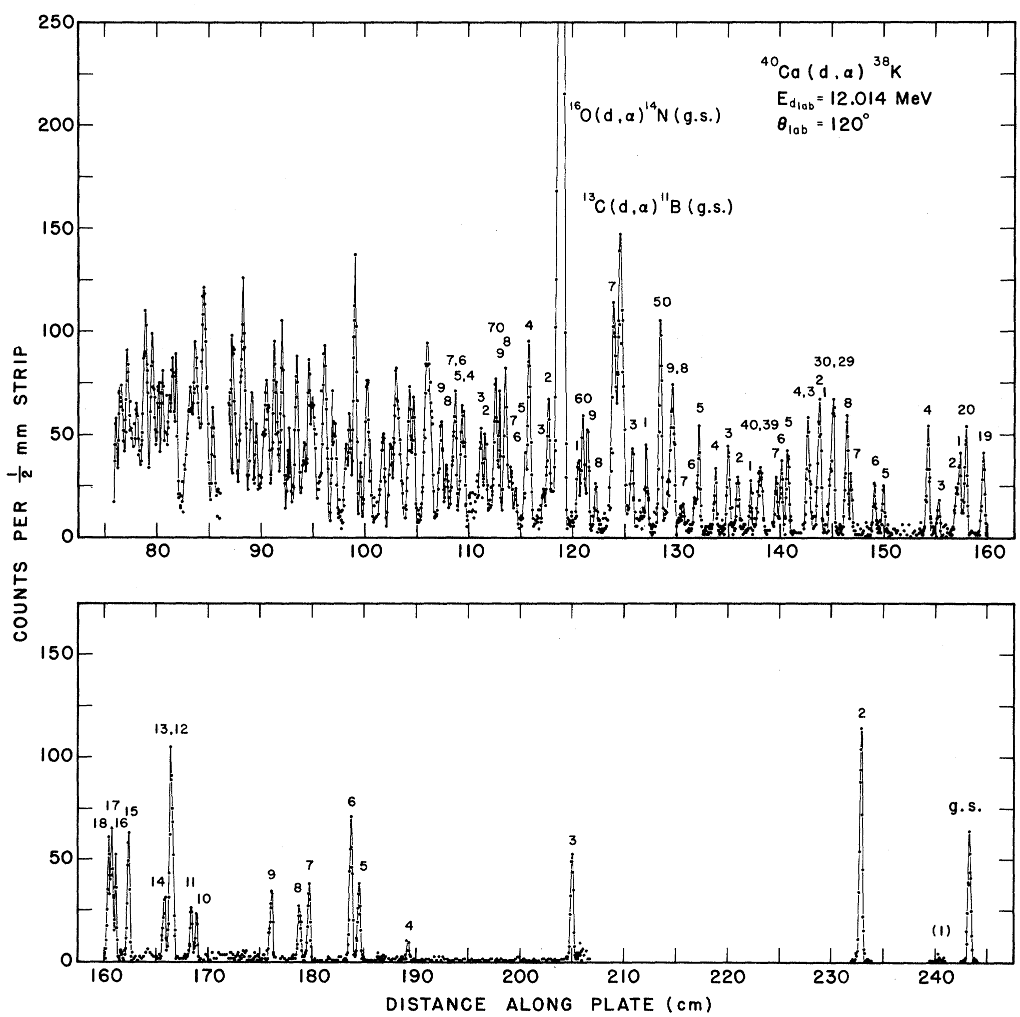

FIG. 1. Spectrum of α particles from the ^{40}Ca(d, α)^{38}K reaction recorded with the spectrograph. Groups leading to ^{38}K states are labeled with numbers corresponding to Table I. Groups from other reactions are labeled with the reaction.

TABLE I. Excitation energies of levels in ^{38}K.

Group number	Present work: Spectrograph ^{40}Ca(d, α) (keV)	Present work: Average of ^{40}Ca(d, $\alpha\gamma$) and ^{36}Ar(^{3}He, $p\gamma$) (keV)	Present work: Adopted energy (keV)	(d, α) Ref. 4 MeV± 20 keV	(d, $\alpha\gamma$) Ref. 6 (keV)	(p, d) Ref. 7 (keV)
1		131.8±1.0	131.8±1.0	0.119		130±1
2	459.0±0.8	459.4±1.1	459.1±0.7	0.43	458.8±1	459±1
3	1697.5±1.2	1699.0±1.0	1698.4±0.8	1.69	1698.2±1	1699±2
4	2402.4±1.5	2403.2±1.0	2403.0±0.8	2.41	2401.4±1	2404±2
5	2613.7±1.3	2612.4±1.1	2612.9±0.8	2.61	2612.9±0.4	2614±2
6	2646.5±1.3	2648.3±1.6	2647.2±1.0	2.63	2646.3±0.7	2648±2
7	2827.5±1.5	2828.7±1.1	2828.3±0.9	2.81	2829.0±1.2	2830±2
8	2869.9±1.5	2870.1±1.5	2870.0±1.1	2.84	2869.9±0.9	2871±2
9	2991.9±1.6	2991.8±2.4	2991.9±1.3	2.97	2993.2±1.1	
				3.05		
10	3317.0±1.5	3317.6±1.5	3317.3±1.1	3.33	3314.6±0.8	3317±2
11	3341.2±1.6	3342.5±1.6	3341.9±1.1		3341.5±1.3	3341±2
12	3421.5±1.6		3421.5±1.6	3.42	3418.9±2.1	
13	3431.0±1.5	3431.2±1.5	3431.1±1.1	3.44		3432±2
14	3458.4±1.6		3458.4±1.6	(3.47)		
15	3614.4±1.6	3615.3±1.7	3614.8±1.2	3.60		3617±2
16	3668.9±1.9	3668.0±1.2	3668.3±1.0	3.65	3668.3±1.6	
17	3688.2±1.8	3687.8±1.0	3687.9±0.9	3.67		
18	3701.3±1.9	3701.8±2.0	3701.5±1.4	3.70		3703±4
					3725.4±1.9 [a]	
19	3738.9±1.7	3738.8±1.5	3738.8±1.1			
				3.79		
20	3814.8±1.6	3815.4±1.1	3815.2±0.9	3.81		3819±3
21	3841.2±1.7	3839.7±3.2	3840.9±1.5	3.83		3842±4
					3848.5±2.1 [a]	
22	3856.6±2.0	3857.6±2.1	3857.0±1.4			3859±4
				3.91		
23	3935.4±1.8	3932.5±1.4	3933.6±1.1	3.94		3938±3
24	3978.6±1.7	3977.6±1.4	3978.0±1.1	(3.95)		3980±3
				(4.10)		
25	4173.8±2.0	4175.4±1.8	4174.7±1.3	4.14		4176±3
	(4196)			4.18		
26	4213.4±2.0	4215.3±1.8	4214.4±1.3	4.28		4217±3
27	4318.0±2.1	4316.9±3.0	4317.6±1.7	4.29		4321±4
28	4336.7±2.1	4331.0±1.5	4332.9±3.0 [b]			4338±4
				4.36		
29	4395.0±2.1	4394.3±2.4	4394.7±1.6			
30	4412.2±2.2	4409.2±1.3	4410.0±1.1	4.41		4405±4
31	4451.7±2.2		4451.7±2.2	4.46		
32	4459.9±2.3		4459.9±2.3			4459±4
33	4491.1±2.6		4491.1±2.6			
34	4504.9±2.3		4504.9±2.3			
				4.55		
35	4588.3±2.2	4587.4±3.0	4588.0±1.8	4.58		4598±3
36	4616.0±2.2		4616.0±2.2			
37	4639.0±2.2		4639.0±2.2	(4.63)		4646±4
38	4664.4±2.9		4664.4±2.9	4.67		4673±3
39	4702.3±2.7	4705.8±1.9	4704.6±1.2	4.71		4713±4
40	4718.3±2.9	4724.4±1.9	4722.6±3.0 [b]			
41	4749.7±2.5		4749.7±2.5			
				4.78		
42	4806.1±2.8		4806.1±2.8			
43	4845.3±2.8		4845.3±2.8			4853±4
44	4901.4±2.8	4901.2±1.3	4901.2±1.2			
45	4970.6±3.0		4970.6±3.0			
46	4989.5±3.2	4988.7±1.5	4988.8±1.4			4998±4

TABLE I *(Continued)*

Group number	Present work Spectrograph ^{40}Ca(d, α) (keV)	Average of ^{40}Ca(d, $\alpha\gamma$) and ^{36}Ar(^{3}He, $p\gamma$) (keV)	Adopted energy (keV)	(d, α) Ref. 4 MeV± 20 keV	(d, $\alpha\gamma$) Ref. 6 (keV)	(p, d) Ref. 7 (keV)
47	5048.9± 3.0	5047.5± 1.4	5047.8± 1.3			5058± 4
	(5076)					
48	5085.8± 3.0		5085.8± 2.9			
49	5103.8± 3.0		5103.8± 3.0			
50	5131.3± 2.3	5133.8± 1.5	5133.1± 1.3			
51	5191.9± 3.0		5191.9± 3.0			
52	(5212)	5216.4± 1.6	5216.4± 1.6			
	(5224)					
	(5243)					5249± 5
53	5256.9± 3.0		5256.9± 3.0			
54	5286.0± 3.0		5286.0± 3.0			
55	5296.2± 3.2		5296.2± 3.2			
56	5307.1± 3.2		5307.1± 3.2			
57	5330.2± 3.1		5330.2± 3.1			5341± 5
58	5406.5± 3.1		5406.5± 3.1			
59	5439.2± 3.1		5439.2± 3.1			5449± 4
60	5458.9± 3.1		5458.9± 3.1			
61	5479.8± 3.1		5479.8± 3.1			
	(5537)					5549± 6
	(5553)					
	(5562)					
62	5601.4± 3.2		5601.4± 3.2			
63	5616.5± 3.4		5616.6± 3.4			5626± 4
64	5676.3± 3.3		5676.3± 3.3			5680± 5
65	5692.6± 3.4		5692.6± 3.4			
66	5729.7± 3.3		5729.7± 3.3			5737± 4
67	5749.1± 3.3		5749.1± 3.3			
68	5768.6± 3.3		5768.6± 3.3			5778± 6
69	5794.8± 3.4		5794.8± 3.4			
70	5809.8± 3.4		5809.8± 3.4			5809± 6
71	5828.0± 3.4		5828.0± 3.4			
72	5850.8± 3.4		5850.8± 3.4			5856± 5
73	5869.0± 3.4		5869.0± 3.4			5891± 5
74	5934.3± 3.4		5934.3± 3.4			
						5944± 5
75	5944.2± 3.5		5944.2± 3.5			
76	5969.7± 3.4		5969.7± 3.4			5976± 5
77	5982.6± 3.5		5982.6± 3.5			
78	6001.8± 3.4		6001.8± 3.4			5991± 5
79	6021.7± 3.5		6021.7± 3.5			

[a] The excitation energy should probably be raised by 131 keV. See text.
[b] The possibility may exist that these are different levels and should not be averaged.

B. Results

According to the isospin selection rule, the ^{40}Ca(d, α) reaction should populate only $T=0$ states; however, Jänecke[4] in his study of this reaction at a bombarding energy of 7.7 MeV observed a large violation of the rule for the 0^+, $T=1$ analog of the ground state of ^{38}Ar. In the present experiment the reaction conditions were such that this state was only populated weakly and we were not able to obtain an accurate excitation for it. The second $T=1$ state at 2403 keV was populated a little more strongly. A summary of the levels observed in the spectrograph experiment is given in column 2 of Table I. The excitation energies are averages of from three to eight measurements. Unless an α-particle group was observed under at least three different reaction conditions, the corresponding level was considered only a possible level of ^{38}K and is listed in the table in parentheses. The uncertainties in column 2 are calculated according to the procedures described in Ref. 5. The uncertainties include estimates of both random and systematic contributions to the following quantities: the position of a group on the plate, beam spot position, reaction angle, input energy, spectrograph field, and spectrograph calibration curve. The number assigned to each α-particle group in Fig. 1 and given in column 1 should not be interpreted as a level number, since we have probably not observed all levels. In column 3 are the excitation energies and uncertainties of levels determined from our γ-ray measurements. The adopted energy, which is the weighted average of the spectrograph and γ-ray results, is given in column 4. The remaining columns are comparisons with other work[6,7] to be discussed in Sec. VI.

III. γ-RAY ENERGIES AND BRANCHING RATIOS

A. Procedures

Measurements of ^{38}K γ rays were made with the ^{40}Ca(d, $\alpha\gamma$) reaction at $E_d = 8.0$ MeV and also with ^{36}Ar(^{3}He, $p\gamma$) at $E_{3He} = 8.34$ MeV. In both cases, all γ-ray measurements were carried out in coincidence with particles detected in an annular silicon surface-barrier detector at 180° to the beam direction. The Ge(Li) γ-ray detector had nominally 40-cm^3 active volume and was located 7 cm from the target. Its energy resolution varied from 2.4

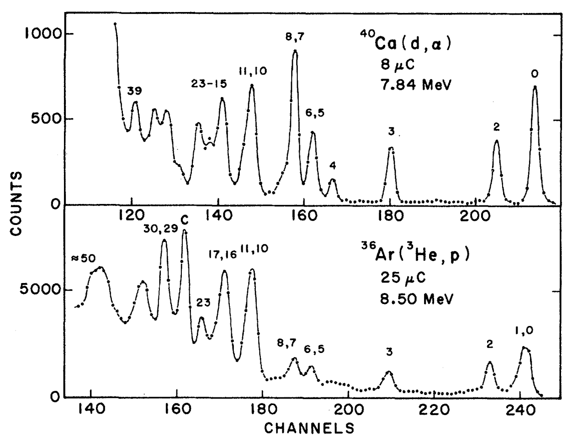

FIG. 2. Particle spectra measured with annular silicon surface-barrier detectors at 180°. The upper spectrum, from the ^{40}Ca(d, α) reaction, was taken with a 100-μg/cm^2 Ca target on a 1-mg/cm^2 Ag backing as used in the Doppler-shift attenuation experiment. The Ca target for the work described in Sec. III was a thicker layer of Ca but was self-supporting. The lower spectrum was taken with a 0.2-cm atm gas target as described in the text, with protons detected through a 76-μm Mylar foil. Yields of individual levels in this reaction exhibit large fluctuations. Peaks in both spectra are numbered according to Table I.

TABLE II. γ-ray transition energies corrected for Doppler shift and recoil. Most of the (^{3}He, $p\gamma$) energies which are just differences between two excitations in column 3 of Table I are omitted from this table.

^{40}Ca(d, $\alpha\gamma$) (keV)	^{36}Ar(^{3}He, $p\gamma$) (keV)	Identification (keV)
327.7 ± 0.4	327.4 ± 0.5	459 → 132
1568.3 ± 0.5	1566.4 ± 0.6	1698 → 132
1943.3 ± 1.0	1942.6 ± 1.0	2403 → 459
	2270.3 ± 1.5	2403 → 132
2698.7 ± 1.2	2696.5 ± 1.2	2828 → 132
425.6 ± 0.8	424.4 ± 1.3	2828 → 2403
2871.0 ± 2.0	2868.9 ± 1.5	2870 → 0
2412.0 ± 2.0	2410.8 ± 1.7	2870 → 459
1171.9 ± 0.7	1170.6 ± 1.3	2870 → 1698
467.6 ± 0.6	465.3 ± 1.0	2870 → 2403
3319.6 ± 3.8	3316.3 ± 1.5	3317 → 0
915.9 ± 0.4	913.8 ± 0.8	3317 → 2403
3431.1 ± 3.8	3430.2 ± 1.5	3431 → 0
1029.1 ± 0.7	1026.8 ± 0.7	3431 → 2403
	3689.8 ± 3.0	3688 → 0
	1073.3 ± 0.7	3688 → 2613
	1039.6 ± 0.7	3688 → 2648
	3815.2 ± 1.5	3815 → 0
	1412.3 ± 1.3	3815 → 2403
	3847.6 ± 1.9	3978 → 132
	3516.4 ± 1.4	3978 → 459
	4085.9 ± 2.1	4214 → 132
	1809.6 ± 2.7	4214 → 2403

to more than 4.0 keV during the course of these experiments. The particle-energy resolution was about 200 keV in the ^{40}Ca(d, $\alpha\gamma$) experiment and 150 keV for ^{36}Ar(^{3}He, $p\gamma$). This was usually adequate to identify the level of origin of each γ ray although adjacent levels frequently were not resolved by the particle detector. Here the spectrograph data have been quite helpful in the identification of levels. Particle spectra from the two reactions are shown in Fig. 2.

For the first reaction, self-supporting Ca targets were transported to the target chamber in a dry nitrogen atmosphere. The particle detector's sensitive depth was 100 μm so that protons and elastically scattered deuterons could not deposit more than about 4 MeV in it. Only one coincidence spectrum was taken of this reaction, with the γ-ray detector at 90°. The calibration energies extended up to the 2614-keV line of a natural Th source; the energy scale was continued upward by linear extrapolation of calibration points between 1173 and 2614 keV.

The ^{36}Ar gas target was contained in a thin-walled stainless-steel cell in the form of a cylinder 5 mm in diameter and 10 mm long, coaxial with the beam. Entrance and exit windows were 0.5-μm Ni foils cemented to the ends of the cylinder.

TABLE III. Branching ratios of excited ^{38}K levels.

Initial level (keV)	Final level (keV) 0	132	459	2403	2613	2647	other (keV)
459		100					
1698		100					
2403		6 ± 2	94 ± 2				
2613	(100)						
2647	(100)						
2828		90 ± 3		10 ± 3			
2870	38 ± 5		25 ± 7	22 ± 5			15 ± 4 to 1698
2992			(100)				
3317	41 ± 4			59 ± 4			
3342		(100)					
3431	40 ± 3			60 ± 3			
3615						(100)	
3668				(100)			
3688	22 ± 6				52 ± 5	26 ± 5	
3702				(100)			
3739	(100)						
3815	49 ± 6			51 ± 6			
3841						(100)	
3857		(100)					
3934					(100)		
3978		74 ± 7	26 ± 7				
4175			(100)				
4214		72 ± 6		28 ± 6			
4318	(100)						
4333							(100) to 3934
4395	(100)						
4410							(100) to 1698
4588	(100)						
4705							(100) to 3615
4723							(100) to 3342
4901				(100)			
4989				(100)			
5048					(100)		
5133				(100)			
5216							(100) to 1698

A pressure of 0.2 atm of Ar enriched to 99.7% in ^{36}Ar was maintained in the cell. In this case a particle detector 1.5 mm thick was selected; it was covered with 76 μm of Mylar foil to screen out ^{3}He ions scattered principally from the cell windows. γ-rays were detected at 90, 113.5, 125, 134, and 144° in separate experiments, in random order. γ-ray calibration points ranging from 265 to 3548 keV from sources of ^{75}Se, ^{137}Cs, ^{60}Co, and ^{56}Co were taken after each coincidence spectrum. Since attenuation of the Doppler shift in this low-pressure gas cell is negligible for lifetimes shorter than 1 ns, all of the γ-ray energies were corrected for the full Doppler shift as well as for recoil. The resulting five determinations of transition energies from ^{36}Ar(^{3}He, $p\gamma$) were averaged.

For the determination of branching ratios, the angular distribution of each transition observed in the ^{36}Ar(^{3}He, $p\gamma$) spectra was fitted to a series of even Legendre polynomials and the resulting coefficient A_0 of the zero-order term was taken as the measure of intensity. These values were corrected for the energy dependence of the detector efficiency.

B. Results

The transition energies determined from the ^{40}Ca(d, $\alpha\gamma$) spectrum and some of those from the ^{36}Ar(^{3}He, $p\gamma$) spectra are listed in Table II. The excitation energies of most low-lying states of ^{38}K are related to two or more transition energies. In particular, there is no γ-ray transition from the first excited state, so its excitation-energy determination depends on sums and differences of several transition energies connecting the first excited state and the ground state to higher levels.

From the (d, $\alpha\gamma$) data a self-consistent set of excitation energies for the low-lying levels was obtained by least-squares adjustment[8] of the level energies to the transition energies. The same was done with the (^{3}He, $p\gamma$) data, and the two sets of energies were averaged to produce the results in column 3 of Table I. For many of the higher levels, the entries in column 3 are (^{3}He, $p\gamma$) results only.

Hereinafter, levels will be identified by the adopted energy in column 4 of Table I.

The branching ratios determined from the (^{3}He, $p\gamma$) experiments are given in Table III, with uncertainties compounded from those in counting statistics, the relative-efficiency determination, and the angular distribution coefficients. As is conventional, the uncertainties do not include allowance for possible unobserved branches.

IV. LIFETIME MEASUREMENTS

For Doppler-shift attenuation measurements the ^{40}Ca(d, α) reaction at 7.84 MeV was selected. Approximately 100 μg/cm^2 of natural Ca was evaporated onto 1-mg/cm^2 Ag backings. The targets were transported in vacuum to the scattering chamber. Target and backing thicknesses were verified by low-energy proton elastic scattering from the same targets after completion of the coincidence experiments.

Doppler-shift data consisted of two two-parameter $\alpha\gamma$ coincidence spectra taken with the annular particle detector at 180°, as described previously, but with the Ge(Li) detector at angles of 90 or 144°. Six 24-h runs at 20-nA beam current were made, alternating between the two angles in order to minimize systematic errors. In addition to uncertainties due to small numbers of counts and the increasing line width of the deteriorating Ge(Li) detector, a rate-dependent baseline shift introduced an additional 0.25 keV uncertainty in the Doppler shifts. Experimental shifts were determined from the centroids of the peaks. A few of the peaks are illustrated in Fig. 3.

The attenuation curve was calculated using the method of Blaugrund.[9] Correction factors to the theoretical electronic and nuclear stopping powers of Lindhard and Scharff[10] were determined as described by Schulz *et al.*[11] The deviation of the correction factors from unity was taken as a measure of the uncertainty in the $F(\tau)$ curve. The effect of stopping in the Ca target material itself was included, with the approximation that all reactions took place at the midplane of the Ca layer.

Results of the Doppler-shift attenuation experiment are listed in Table IV. Both the uncertainties in the experimental $F(\tau)$ and in computation of the $F(\tau)$ curve are incorporated. Generally the results for the lower levels are in agreement with, but less accurate than, values from the literature.[6,13] The lifetimes or lifetime limits for the 3431-, 3615-, 3668-, 3688-, 3702-, and 4333-keV levels are new or improved values. The mean value in the last column of Table IV is the one used in estimating transition rates in subsequent sections of this paper.

V. DIRECTIONAL CORRELATIONS

A. Procedures

The five ^{36}Ar(^{3}He, $p\gamma$) two-parameter spectra provided the data for angular correlations of the various transitions in axially symmetric geometry with substate populations limited to $M_J = 0, \pm 1$. The five points were taken in separate experiments, between which the apparatus had to be dismantled. To normalize the intensity measurements there were available the collected charge, the numbers

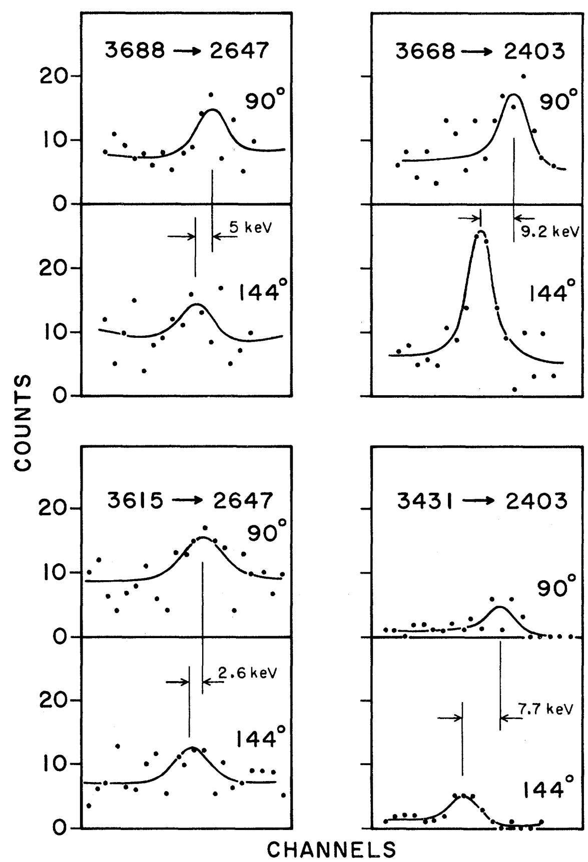

FIG. 3. Projections of the $\alpha\gamma$ coincidence spectra along the γ-ray axis, showing the attenuated Doppler shifts of certain transitions, labeled in keV. The peaks drawn in are not fits to the points; energy shifts were determined from centroid shifts.

TABLE IV. Observed attenuation factors $F(\tau)$ of γ rays and deduced mean lifetimes of initial levels in ^{38}K.

Transition (keV)	$F(\tau)$	τ (fs) Present	Ref. 6	Ref. 13	Mean
1698 → 132	0.85 ± 0.05	82 ± 35	65 ± 17	54 ± 25	64 ± 13
2403 → 459	0.86 ± 0.07	76 ± 50	90 ± 25	54 ± 25	74 ± 16
2403 → 132			90^{+60}_{-90}		
2613 → 0	0.02 ± 0.07	>2600	$9^{+7}_{-2}\times 10^3$		
2647 → 0	0.01 ± 0.07	>3400	>12 000		
2828 → 132	0.66 ± 0.07	205^{+65}_{-55}	280 ± 70		240 ± 50
2870 → 2403	0.14 ± 0.22	>550			
2870 → 1698	0.10 ± 0.11	>1000			
2870 → 459			>2800		
2870 → 0	0.07 ± 0.07	>1700	4500 ± 1200		
3342 → 132	0.89 ± 0.08	<105	<55		
3431 → 2403	0.85 ± 0.13	<170			
3615 → 2647	0.31 ± 0.14	700^{+850}_{-310}			
3668 → 2403	0.83 ± 0.08	95 ± 55	<150		
3688 → 2647	0.55 ± 0.13	300^{+200}_{-120}			400^{+160}_{-120}
3688 → 2613	0.40 ± 0.11	480^{+300}_{-160}			
3702 → 2403	0.09 ± 0.11	>1100			
4333 → 3934	0.50 ± 0.27	350^{+700}_{-250}			

of counts in selected peaks in the proton singles spectra as determined with single-channel analyzers, and the number of coincidences from the 1698-keV level measured at a fixed angle with a NaI detector. These did not consistently agree with one another, but the variations among them were not greater than ±10% for any one angle. In part the inconsistency is attributed to difficulty in reproducing the experimental setup exactly each time. A major factor also is the extreme energy dependence of the ^{36}Ar(^{3}He, p) reaction differential cross section, which imples also a large energy dependence of the alignments of the excited states. This problem was compounded by significant variations in energy loss in the different entrance foils used from time to time in the gas cell. In order to reproduce the beam energy in the cell within ±5 keV, the intensity ratios of some isolated proton peaks were checked and the accelerator energy adjusted accordingly prior to each coincidence run.

The Ge(Li) detector deteriorated in resolution during the course of the experiments. The efficiency at 1332 keV but not at higher γ-ray energies was measured from time to time. Because of the difficulties just described and of the small numbers of counts, the angular correlation data provide reliable information only in special cases, particularly where there is a large anisotropy. In these cases, alternative methods of normalization do not materially affect the inferences drawn from the data. The correlation data were interpreted with conventional χ^2 analysis based on direct comparison of calculated distributions to the data.

B. Results

The 3342-keV level was found to decay solely to the first excited state. Since the latter has $J=0$ and the lifetime of the 3342-keV level is short (Table IV), only initial spins of 1 and 2, and no multipole mixing, need be considered in the angular-correlation analysis. The present data indicate $J=1$ at 25% confidence with $J=2$ rejected at a confidence level well below 10^{-5}.

The lifetime limit for the 3431-keV level (Table IV), together with the 60% branch to the 2403-keV, 2^+, $T=1$ level, limit its possible spin to 1, 2, or 3 since the $E2$ strength of this transition would exceed 300 W.u. (Weisskopf unit) for a 0^+ or 4^+ assignment. Its parity is known to be positive.[7] With the transition strength limits proposed by Endt and van der Leun,[14] the $E2/M1$ mixing ratio of the 3431 → 2403 keV transition is limited to $|\delta|<0.1$ if $T=0$ or $|\delta|<0.7$ if $T=1$. It is improbable that $T=1$ if $J^\pi=1$ or 3^+, as there is no corresponding state known in ^{38}Ar. Figure 4 shows the χ^2 analysis of the angular correlation of the

$3431 \rightarrow 2403$ keV radiation with these restrictions. While the $J=2$ curve is the only one to exceed 0.1% confidence, it reaches only 12% at best, reflecting the experimental difficulties mentioned above. We consider the $J=2$ assignment only probable.

The 3615-keV level decays to the 2647-keV level, which is probably[2,3] a 4^-, $T=0$ state. From the directional correlation, a spin of 4 or 6 for the initial level can be eliminated at the 0.1% confidence level. The χ^2 analysis for other spin possibilities is shown in Fig. 5. For the hypothesis $J^\pi=2^+$, the measured lifetime implies a $M2$ strength in excess of 2000 W.u., while for 2^- the large $M3$ mixing required would be even more prohibitive. Similarly, 3^+ or 5^+ assignments would require excessive $M2$ strengths, since a significant quadrupole admixture is required in both cases. For either of the remaining possibilities, 3^- or 5^-, the $E2$ strength, about 20 W.u. calculated for $\delta=0.1$ favors a $\Delta T=0$ transition and thus for the 3615-keV level $J^\pi=3^-$ or 5^-, $T=(0)$ if for the 2647-keV level $J^\pi=4^-$, $T=0$ as assumed.

The 3688-keV level also decays to the 2647-keV level. The angular correlation of this radiation indicates $J=3$ or 5 for the initial level with $J=4$ rejected beyond the 0.1% confidence level, if the final level has spin 4.

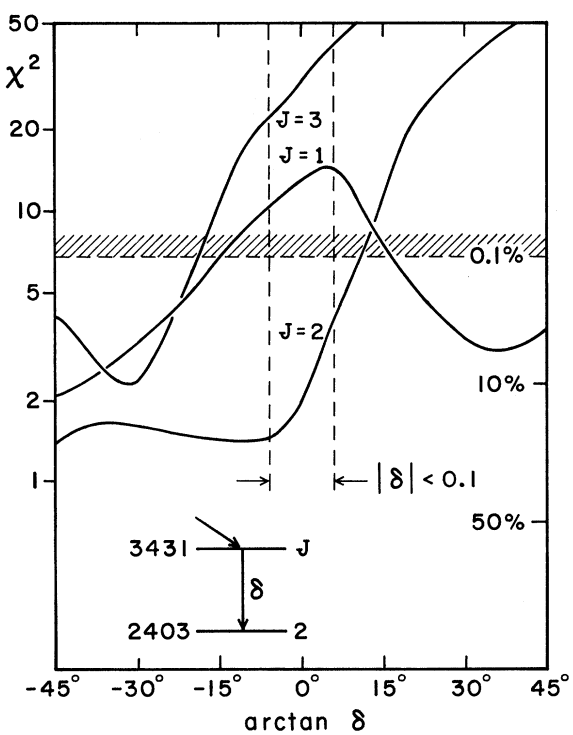

FIG. 4. The goodness-of-fit index χ^2 as a function of multipole mixing ratio δ for the directional correlation of the $3431 \rightarrow 2403$ keV γ ray. Confidence levels are indicated at the right. The vertical lines enclose the region $|\delta| < 0.1$ to which $T=0$ initial levels are restricted through the measured lifetime.

VI. DISCUSSION

The consistency between magnetic-spectrograph and Ge(Li) detector energy determinations in this work makes it possible to clarify some of the literature on ^{38}K excited levels. Figure 6 is the level scheme with known spin-parity assignments and mean lifetimes. From the γ-ray decay it appears that the 2647-keV level is the one assigned[2] $T=0$ and probably $J^\pi=4^-$ in recent studies[2,3] of the 3458-keV isomer. In neutron pickup experiments on ^{39}K in which the 2613- and 2647-keV levels were unresolved, angular distributions with $l=1$ (Refs. 15 and 16) and mixed $l=1+3$ (Ref. 17) have been reported. If the 2647-keV level has $J=4$, any $l=1$ component must pertain to the 2613-keV level. From this and the observed γ-ray decay the 2613-keV would be restricted to 2^- or 3^-. But Wildenthal, Rice, and Preedom[7] report only $l=3$ pickup for both members of the 2613-2647-keV doublet, which were resolved in their work. The absence of a $l=1$ component does not support the spin restriction just mentioned.

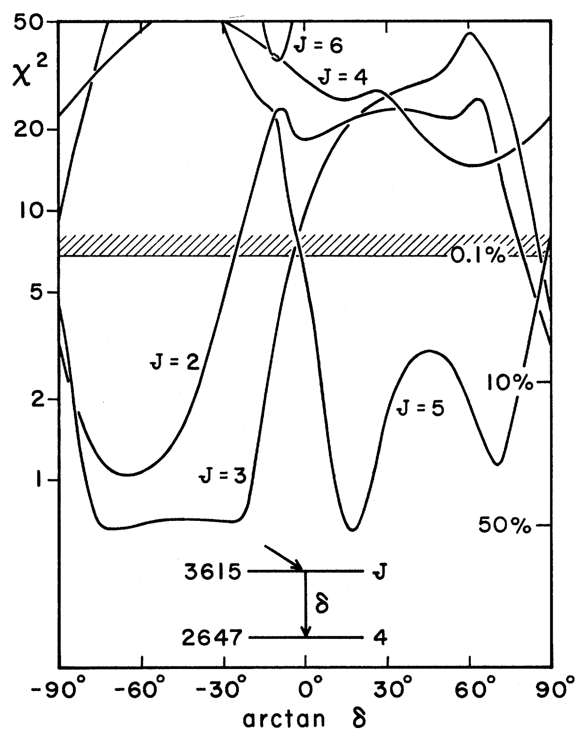

FIG. 5. The goodness-of-fit index χ^2 as a function of multipole mixing ratio δ for the $3615 \rightarrow 2647$ keV transition. Confidence levels are indicated at the right.

From its mode of decay and spin assignment we identify the 3342-keV level with the 3337-keV level, $J^\pi = 1^+$, $T=(0)$ reported by Gallmann *et al.*[18] in ^{38}Ca $\beta-$decay and with the 3338-keV, probably 1^+, level of Hasper, Smith, and Smulders.[19] The parity is confirmed by the angular distribution results of Wildenthal *et al.*[7]

The region near 3.4 MeV in excitation is of particular interest. Kouzes and Sherr[1] have reported a (7^+) level at 3.445 ± 0.015 MeV. They used the ^{36}Ar(α, d) ^{38}K reaction which should strongly populate a state with configuration $(1f_{7/2})^2$ coupled to $J^\pi = 7^+$. Fortune, Puttaswamy, and Yntema[16] using the ^{39}K(d, t) ^{38}K reaction have reported that a level at 3.441 ± 0.015 MeV is probably a 2^+ state. This assignment is in agreement with the 2^+ assignment for a state at 3.42 ± 0.010 MeV made by Fenton *et al.*[15] in their study of the ^{39}K$(^3$He$, \alpha)$ ^{38}K reaction. van Driel *et al.*[2] in a study of the ^{24}Mg$(^{16}$O$, p n \gamma)$ ^{38}K reaction report a (7^+) level at 3458.0 ± 0.2 keV and a (6^-) level at 3420.0 ± 0.2 keV. Yates *et al.*[3] obtained very similar results.

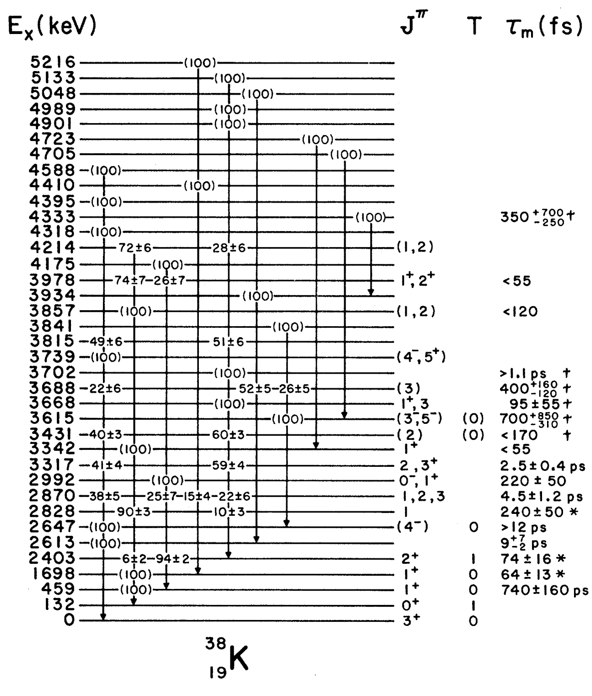

FIG. 6. A partial level scheme of ^{38}K, including only those levels among which γ-ray transitions have been observed in the present work. All excitation energies and all branching ratios are present results. The spin assignments are taken from Refs. 1–3, 12, 18, and 19 except those to the 3431-, 3615-, 3688-, 3857-, and 4214-keV levels which are discussed in the text. Lifetimes indicated by an asterisk (*) are averages including present results while a dagger (†) indicates the present results alone. Other lifetimes are taken from Refs. 2, 3, 6, 12, and 13.

In the present spectrograph measurements levels are seen at 3421.5, 3431.1, and 3458.4 keV. Figure 7 shows these groups for two separate runs. The levels at 3431 and 3422 keV have been unfolded from the data by use of the group shape of a single level such as the 3458-keV level.

In the γ-ray coincidence spectra we observed only the center member of the triplet, at 3431 keV. The measured lifetime upper limit of 170 fs, as well as the decay scheme, clearly distinguish this level from the 3422- and 3458-keV levels. From its γ-ray branch to the 2403-keV level we identify the 3443-keV level of Hasper *et al.*[19] with the present 3431-keV level. Presumably they did not resolve the ground state branch of this level from the $3422 \to 0$ keV decay. The 3431-keV level, with $J=(2)$ from the present angular-correlation analysis, is probably the one observed in neutron pick-up reactions[7,15–17] and identified tentatively in each work with the 2^+, $T=0$ level predicted to lie near this excitation energy in shell-model calculations. A summary of the present results along with previous investigations is shown in Fig. 8.

Some of the γ-rays reported by Hasper *et al.*[19] and Hasper and Smith[6] as proceeding from the 3668-keV level come instead from the 3688-keV level (see Fig. 6.). Our measurement of the lifetime of the 3688-keV level (Table IV) is based on the transitions to the 2613- and 2647-keV levels. If these final states have spin-parity 3^- and 4^-, the spin of the 3688-keV level is limited to 3 or 4 from the lifetime alone with only a miniscule possibility of 5^- with an $E2$ strength larger than 50 W.u. Spin 4 has been eliminated by the angular

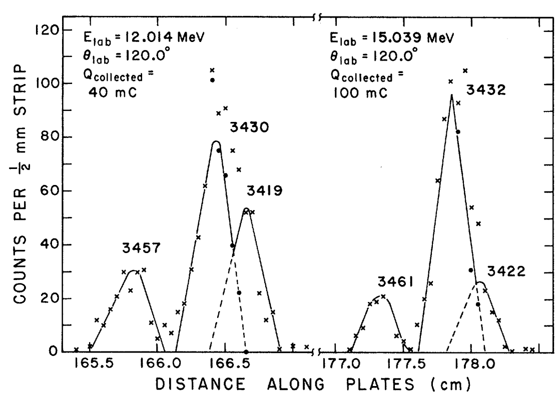

FIG. 7. Portions of two spectra from the ^{40}Ca$(d, \alpha)^{38}$K reaction recorded with the spectrograph. Bombarding energies, observation angles, and collected charge are shown in the figure. The ×'s show the number of counts and the circles are deduced by unfolding the overlapped groups using the group shape of isolated groups. Labels shown energies from these particular runs. The values based on all runs are given in Table I.

correlation analysis. Neither the present 3688- nor the 3702-keV level can be the 3689-keV level which Hasper *et al.*[19] and Hasper and Smith[6] observed to decay to the 0^+, 132-keV level, and to which they assigned $J^\pi = 1^+$, $2^\pm$ from the angular correlation of this transition. No 3688 → 132 keV transition was observed in the present work.

The isobaric analog of the 3377-keV, 0^+ state in ^{38}Ar is expected to be in the vicinity of 3500 keV in ^{38}K. Of the known levels in the vicinity, the γ-ray data rule out all but that at 3702 keV, which decays to the 2^+, $T=1$ level at 2403 keV. This would be a T-allowed $E2$ transition of ≤25 W.u. in strength. The angular correlation of γ rays from the same transition in the present data is indistinguishable from isotropic, which would be consistent with an initial spin of 0. Factors opposing the identification of the 3702-keV level as 0^+, $T=1$ are the 200-keV discrepancy in excitation energy, which is fairly large for a bound state, and the large cross section for the ^{40}Ca(d, α) reaction to this level (group 18 in Fig. 1), which can only proceed by violation of the isospin selection rule.

On the basis of the ^{36}Ar(α, d) reaction cross section, Kouzes and Sherr[1] have proposed an assignment of 4^- or 5^+ for a level which they observed at approximately 3737 keV. The γ-ray decay of the present 3739-keV level to the 3^+ ground state is entirely compatible with this assignment.

The 3726-keV γ ray from the 3857-keV level to the first excited state is probably the one which Hasper and Smith[6] interpreted as a 3725 → 0 keV transition. There is no evidence for a 3725-keV state. Accordingly, the lifetime limit of <120 fs reported in Ref. 6 should be associated with the 3857-keV level.

Similarly, the same authors measured the energy and Doppler-shift attenuation of a 3848.5-keV γ ray which they took to be a ground-state decay. In the present work, both 3847.6- and 3516.4-keV γ rays were observed at an excitation near 3978 keV. These are interpreted as decays to the first and second excited levels from the 3978-keV level, and the 3848-keV level of Ref. 6 is believed to be spurious. The lifetime value $\tau < 55$ fs applies to the 3978-keV level.

From the existence of radiative transitions to the 0^+ first excited state, the spins of both the 3857- and 4214-keV levels can be restricted to 1 or 2 with very high probability.

From 4315 keV upward, only one γ-ray decay of each level was observed, if any. It is quite likely that other branches have been missed due to decreasing Ge(Li) detector efficiency, diminishing cross sections and increasing background in the particle spectrum. As examples, the 4705 → 3615 and especially the 4333 → 3934 keV transitions are favorable for detection because of the relatively high Ge(Li) detector efficiency for low γ-ray energies, but it would be imprudent to assume that these initial levels do not also decay to lower-lying ones.

A comparison of the present spectrograph ^{40}Ca(d, α) work with that of Jänecke[4] is given in Table I. Except for the first excited state, the reported uncertainties in Ref. 4 are 20 keV and groups above 4.18 MeV may possibly be doublets or triplets. Since we have resolved so many more states in this region, a meaningful comparison is difficult. Below 4 MeV agreement is quite good.

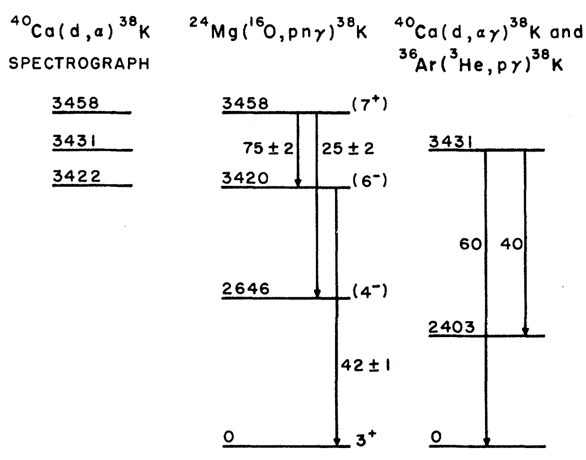

FIG. 8. Levels of ^{38}K near 3.4 MeV in excitation. The present spectrograph results and the present (d, $\alpha\gamma$) and (^{3}He, $p\gamma$) results are shown. The (^{16}O, $pn\gamma$) results are from Refs. 2 and 3.

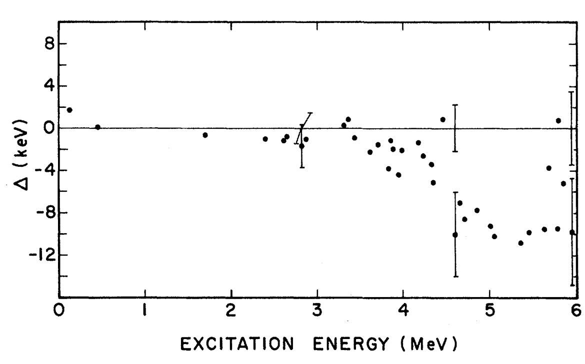

FIG. 9. The difference Δ is defined as the present excitation energy minus that from Ref. 7. Representative uncertainties of the present work are shown on the zero line. Representative uncertainties of Ref. 7 are shown on the points. Only those levels for which there is a clear correspondence between the two measurements were used in this comparison.

We do not observe the level at 3.05 MeV and no γ-ray decay has been observed from this level. If this is a $T=1$ level it is possible that our reaction conditions were such that it was not populated appreciably, as is the case for the first excited state. This would not explain why it was not observed in the (^{3}He, $p\gamma$) reaction.

For comparison, the excitation energies reported in the ^{40}Ca(d, $\alpha\gamma$) work of Hasper and Smith[6] are also given in Table I. Here agreement is excellent with the exception of the 3725- and 3848-keV states already discussed. When those values are increased by 131 keV they too are in excellent agreement with the present excitation energies of the 3857- and 3978-keV levels, respectively.

Excitation energies from the recent (p, d) work of Wildenthal *et al.*[7] are also given in Table I. We have been able to verify many of the new levels reported by these authors but a comparison of energies above 4.3 MeV in excitation is made difficult by the great density of levels. For example, Wildenthal *et al.* report a level at 4405 ± 4 keV. This energy is about the average of the levels at 4395 and 4410 keV. Their experimental resolution of 10 keV should have been sufficient to resolve these two, so it may be that only one of these was populated. It is not clear with which state their value should be compared. A plot of the difference between our two results versus excitation energy is shown in Fig. 9. One can see that the agreement below 4.5 MeV is well within the stated uncertainties. Above 4.5 MeV although the two sets of numbers differ by only slightly more than the uncertainties there appears to be a systematic shift. For the lower states Wildenthal *et al.*[7] have used some of the preliminary excitation energies of Collins *et al.*[20] in obtaining a calibration to their spectrograph. Thus we can expect good agreement in the lower region but it is not clear why there is a break at 4.5 MeV.

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