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Lifetimes of ^{39}K Excited States*

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The mean lifetimes of nine levels in ^{39}K up to 4.12 MeV in excitation have been measured by the Doppler-shift-attenuation method. The levels were populated by the ^{39}K$(p,p'\gamma)^{39}$K reaction at proton energies of 6.47 and 6.67 MeV. γ rays were detected in a 30-cm^3 coaxial Ge(Li) detector at 30 and 135° to the beam direction in coincidence with protons scattered between 164–174°. Transition strengths have been calculated for the first four excited states, and the results are compared with predictions of the weak-coupling model and a phonon-hole coupling model. The weak-coupling model is shown to underestimate $E2$, $M2$, and $E3$ strengths, while the phonon-hole coupling model predicts enhanced $E3$ strengths.

I. INTRODUCTION

The ground and first excited states in ^{39}K can be described in a simple shell-model picture as the $d_{3/2}$ and $s_{1/2}$ proton holes in the doubly magic ^{40}Ca nucleus, and the next two excited states can be described by promoting a $d_{3/2}$ proton to the $f_{7/2}$ and $p_{3/2}$ levels. However, the evidence of collective excitations in inelastic deuteron scattering[1] from ^{39}K and in electromagnetic transitions in ^{40}Ca[2,3] suggests that the appropriate model for ^{39}K should include collective effects.

Shell-model calculations employing effective interactions[4-7] in the A = 40 region have dealt primarily with energy-level predictions, with only limited success. Calculations by Sartoris and Zamick[8,9] using realistic interaction matrix elements derived from the Hamada-Johnston potential also predicted energy levels not in good agreement with experimental values. Of these shell-model calculations, the only transition rate calculated for ^{39}K is for the $M1$ decay of the 7.74-MeV level.[7]

Two approaches to the inclusion of collective effects are calculations in the weak-coupling model by Lewis, Roberson, and Tilley[10] and in a phonon-hole coupling model by Goode and Zamick.[11] In the weak-coupling model, $d_{3/2}$ and $s_{1/2}$ proton holes are coupled to the first 2^+, 3^-, and 5^- states in ^{40}Ca to obtain wave functions for calculations of transitions from all states up to 4.1 MeV in ^{39}Ca. In the phonon-hole model, the negative-parity states are considered as a $d_{3/2}$ hole coupled to the 3^- and 5^- states in ^{40}Ca.

This paper reports lifetime measurements of the excited states in ^{39}K up to 4.125 MeV in excitation. For the first four excited states, spins, branching ratios, and multipolarities are known, so that the various transition rates can be determined. These transition rates are compared with the predictions of the weak-coupling model of Lewis, Roberson, and Tilley[10] and the phonon-hole coupling model of Goode and Zamick.[11]

II. EXPERIMENTAL PROCEDURES

Lifetimes were measured by the Doppler-shift-attenuation method, in which the centroid shift of γ-ray energy measured at two different lab angles is related to the stopping time of the recoil ion in the target material. The method has been described extensively in the literature.[12-14] In this experiment, γ rays were detected at 30 and 135° to the beam direction, in coincidence with inelastically scattered protons detected at 164–174°. γ rays were detected in a 30-cm^3 Ge(Li) detector with better than 4-keV resolution for the ^{60}Co γ rays.

The coincidence requirement was necessary in order to define the initial velocity and direction of the recoiling ^{39}K ion, and to eliminate transitions from cascades from higher levels. Excitation functions were taken from 6.00–7.50 MeV in 20-keV steps with a target of 150-μg/cm^2 natural KI evaporated onto 20-μg/cm^2 carbon. The particular proton energies used were 6.47 and 6.67 MeV, which were the energies for maximum excitation of the levels of interest in the region of large cross-section variations due to Ericsson fluctuations.[15]

Coincidence measurements were made with a target of 6-mg/cm^2 natural KI evaporated onto 20-μg/cm^2 carbon. Beam currents of 1–3 nA on target were used for these measurements. With these beam intensities, 10–24 hours were required to obtain good statistics at each angle. An energy requirement was imposed on the scattered particles so that coincidences were measured only for recoil ions stopping within the target. A 5.1-mg/cm^2 aluminum foil was placed over the particle detector to absorb α particles from the ^{39}K(p,α) reaction. For excitation of the 3.018-

MeV level by 6.47-MeV protons, the recoil energy of the ^{39}K ion is 450 keV, and the range of this ion is about 160-μg/cm^2 in KI. The setting of the energy windows in the scattered proton spectrum was made to include several closely spaced levels so that several γ-ray transitions were recorded at the same time. The γ-ray energies were well separated in each case, so that there were no difficulties in measuring the centroid positions. Also, there were no γ-cascade transitions between levels within the windows used, so no difficulties were encountered with partial feeding from other levels.

The calculation of the Doppler-shift-attenuation as a function of lifetime was made with the stopping-power theory of Lindhard, Scharff, and Schiott.[16] Nuclear scattering and the accounting for stopping in the compound were carried out according to the procedures given by Blaugrund.[17] Numerical integrations over the stopping powers and nuclear scattering expressions were carried out with the nuclear stopping power expression[18]:

$$d\epsilon/d\rho_n = \epsilon^{1/2}/(0.67+2.07\epsilon+0.03\epsilon^2),$$

where ϵ and ρ are the dimensionless energy and length parameters defined by Lindhard, Scharff, and Schiott. The electronic stopping was taken from Lindhard. Although there are experimental deviations from the Lindhard values (e.g., Ref. 19), these are more pronounced in the lighter nuclei. Further, at the low initial recoil velocities used here, only half of the stopping power is electronic, and of course much less than half as the ion slows down. Thus, electronic stopping-power uncertainties do not contribute greatly to the lifetime errors.

III. RESULTS

The measured attenuation factors $F(\tau)$ and the mean lifetimes for the levels studied are given in Table I. $F(\tau)$ is the ratio of the Doppler shift in the γ-ray energy for recoiling nuclei slowing down in the target material to the Doppler shift that would be obtained for nuclei recoiling into the vacuum. $F(\tau)$ is given by[18]

$$F(\tau)=\frac{\Delta E}{E_0\langle v_i/c\rangle[\cos\theta_1-\cos\theta_2]},$$

TABLE I. Lifetimes of excited states in ^{39}K.

E_γ (MeV)	J^π	$F(\tau)$	τ	Other τ values	Ref.
2.521	$\frac{1}{2}^+$	0.84 ± 0.03	88^{+17}_{-18} fsec	>80 fsec	20
				105 ± 32 fsec	23
				32 ± 12 fsec	25
				>50 fsec	26
2.813	$\frac{7}{2}^-$	0.02 ± 0.02	>1 psec	>0.3 psec	20
				>6 psec	23
				≤113 psec	21
				≤80 psec	22
				124 ± 24 psec	24
3.018	$\frac{3}{2}^-$	0.92 ± 0.04	40^{+22}_{-20} fsec	37 ± 13 fsec	20
				<54 fsec	23
				21 ± 6 fsec	25
				15 ± 6 fsec	26
3.596	$\frac{9}{2}^-$	0.01 ± 0.03	>1 psec	>0.18 psec	20
3.884	$(\frac{3}{2},\frac{5}{2})$	0.94 ± 0.04	28^{+20}_{-19} fsec	21 ± 6 fsec [a]	20
3.941	$(\frac{5}{2},\frac{7}{2})$	0.80 ± 0.05	103^{+30}_{-28} fsec		
4.082	$(\frac{1}{2}^+,\leq\frac{3}{2}^-)$	0.84 ± 0.07	78^{+39}_{-36} fsec	19^{+37}_{-36} fsec	26
4.092		0.78 ± 0.10	110^{+65}_{-52} fsec		
4.125	$>\frac{5}{2}^-$	0.80 ± 0.07	100^{+42}_{-37} fsec		

[a]Assuming $J=\frac{5}{2}$.

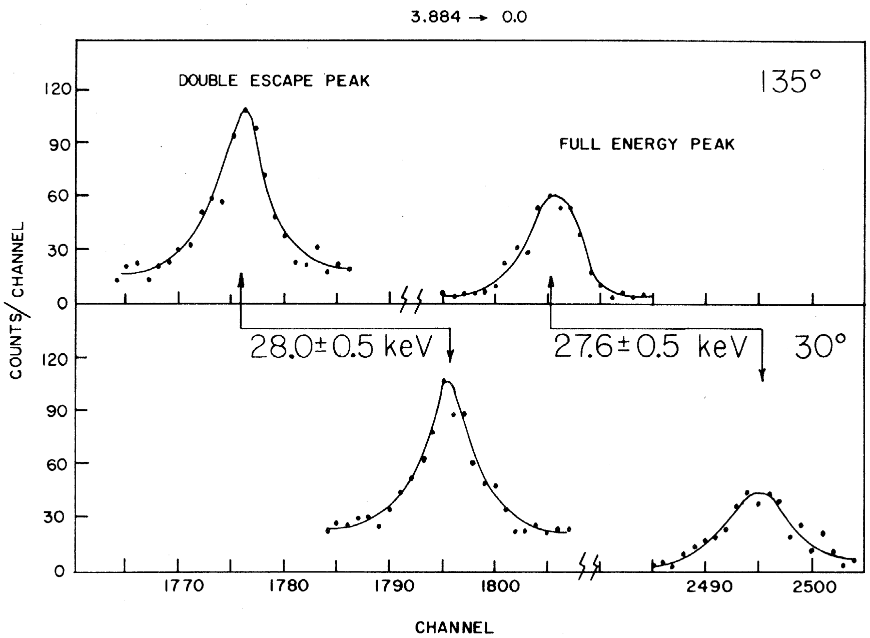

FIG. 1. γ-ray coincidence spectrum for the 3.889-MeV level decay to the ground state at detector angles of 30 and 135°.

where ΔE is the centroid shift from angles θ_1 to θ_2, $\langle v_i \rangle$ is the average initial recoil velocity, and E_0 is the unshifted γ-ray energy. The lifetimes measured in other work are also given. The errors given for the attenuation factors are primarily from the statistical error from the centroid position determination, and a ±15% error to

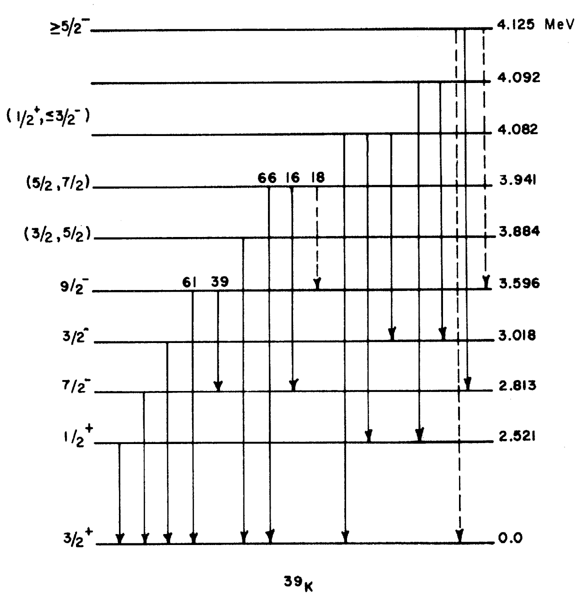

FIG. 2. γ-ray transitions in ^{39}K, taken from Ref. 27. Dashed lines indicate transitions not observed in this work. Numbers above the transitions indicate percentage decay.

account for possible deviations in the stopping-power values used. The uncertainties in initial recoil velocity and detector position contribute only slightly to the total error. The energies of the levels are determined to ±1 keV.

In other work the most extensive measurements on lifetimes are from the nuclear resonance scattering data of Booth and Wright,[20] and good agreement with the results reported here is obtained in all cases. Two direct timing measurements[21,22] of the lifetime for the 2.813-MeV ($\frac{7}{2}^-$) state determined upper limits on the lifetime. Another Doppler-shift-attenuation measurement by Robertson *et al.*[23] for the first three excited states with the ^{39}K ion stopping in KI agrees well with our results.

Several more recent measurements of a few of the lifetimes are inconsistent with the work reported here and with that of Refs. 21–23. The lifetime of the 2.813-MeV state by a direct timing measurement is reported by Alexander *et al.*[24] This value is somewhat greater than the upper limit of Holland and Lynch.[22] Doppler-shift-attenuation measurements[25,26] of the 2.521-, 2.813-, and 4.082-MeV states are somewhat lower than our values. All lifetime values are listed in Table I.

The γ-ray coincidence spectrum for the ground-state transition from the 3.884-MeV state is shown in Fig. 1. In this transition and most of the others studied the γ-ray energy is high enough so that there are both a full-energy peak and a double-escape peak, thus giving two measurements of the centroid shift. The double-escape and full-energy centroid shifts were averaged and an attenuation factor was calculated from this average shift. For levels which decayed with more than one γ-ray energy, the attenuation factors for each of the branches were averaged together to obtain a final value.

The energy-level diagram for ^{39}K is shown in Fig. 2. The dashed lines on Fig. 2 indicate transitions not observed in this work. The spin assignments and branching-ratio data are from the work of Lopes *et al.*[27] The spin assignments and mixing ratios are known for only a few of the levels at this time. These data are summarized in Table II, along with the experimental values of transition probabilities Γ expressed as the enhancement over single-particle values.

IV. DISCUSSION

Collective excitations in the ^{39}K nucleus can be treated by coupling a proton hole to the ^{40}Ca nucleus. Lewis, Roberson, and Tilley[10] have employed the weak-coupling model suggested by Lawson and Uretsky[28] and developed by de-Shalit[29] to describe electromagnetic transitions in ^{39}Ca in terms of ^{40}Ca transitions, and obtained quantitative agreement with their mixing ratios. Similar calculations have been carried out in this work for ^{39}K, with amplitudes for the various configurations from Lewis, Roberson, and Tilley. The transition strengths obtained are shown in Table III expressed in terms of enhancement over single-particle units defined by Wilkinson.[30] The transition probabilities for the ^{40}Ca core states were taken from the work of MacDonald *et al.*[2] as corrected by Anderson *et al.*[3] The core-coupling configurations were made up of $d_{3/2}$ and $s_{1/2}$ holes coupled to the 0^+ ground state and 3^-, 2^+, and 5^- excited states of ^{40}Ca. An inhibition factor of 100 was assumed for the $E1$ and $M2$ transition strengths of ^{40}Ca as these are $\Delta T = 0$ transitions in a self-conjugate nucleus. One single-particle unit was assumed for the ^{40}Ca $M1$ transition strength in order to obtain some estimate for the $M1$ decay of the 2.521-MeV level in ^{39}K. An estimate of one single-particle unit was also used for the $M4$ decay of the ^{40}Ca core state.

The comparison of the experimental results to the weak-coupling model estimates is made in Table III. Since the mixing ratio for the decay of the first excited state at 2.521 MeV is unknown, the experimental transition probability has been given as completely $E2$ or completely $M1$. The

TABLE II. Summary of electromagnetic decay properties for ^{39}K.

E_{ex}	J^π	Branching ratio	τ	Multipolarity	δ	$\|M\|^2$ (W.u.) Exp. values for ^{39}K
2.521	$\frac{1}{2}^+$	100% to g.s.	88^{+17}_{-18} fsec	$E2$	Unknown	$11.3^{+2.9}_{-1.8}$ [a]
				$M1$		$0.022^{+0.006}_{-0.004}$ [a]
2.813	$\frac{7}{2}^-$	100% to g.s.	>6, ≤113 psec	$E3$	-0.19 ± 0.10	$<1.1\times10^{3}$ [b]
						<175 [c]
						>0.96 [d]
				$M2$		<21 [b]
						<3.6 [c]
						>0.18 [d]
3.018	$\frac{3}{2}^-$	100% to g.s.	40^{+22}_{-20}	$M2$	-0.03 ± 0.15	$0.34^{+24.3}_{-0.34}$
				$E1$		$7.7^{+7.6}_{-2.6}\times10^{-4}$
3.596	$\frac{9}{2}^-$	61 ± 7% to g.s.	>1 psec	$M4$	$\|\delta\|>2.7$ or $\|\delta\|<0.36$	$<1\times10^{9}$ [b]
				$E3$		$<1.5\times10^{3}$
		39 ± 7% to 2.813		$E2$	$-1.2<\delta<0.5$	<91.3
				$M1$		<0.024

[a] For pure $M1$ and pure $E2$.
[b] One standard deviation included in the mixing and branching ratios.
[c] With τ from Ref. 23.
[d] With τ from Ref. 21.

model prediction underestimates the $E2$ value, but is in fair agreement if the transition were primarily $M1$. For the decay of the 2.813-MeV state only upper and lower limits are placed upon the $E3$ and $M2$ transition probabilities. However, both of the model estimates are too low. In the decay of the 3.018-MeV state, the $E1$ value from the model is quite close to the experimental value, while the $M2$ value is much lower. For the 3.596-MeV state decay, the model predictions are well below the experimentally determined upper limits.

The weak-coupling model appears to be inadequate for describing the decay properties of ^{39}K, because it underestimates the $E2$, $E3$, and $M2$ transition strengths by at least an order of magnitude. Presumably this is because higher-order particle-hole correlations have not been included. Also, transitions to the first excited 0^+ state in ^{40}Ca have been disregarded because of a lack of experimental information. The branching ratio for the decay of the 3.90-MeV (2^+) to the 3.37-MeV (0^+) state has recently been measured[31] to be $8.7 \pm 1.4 \times 10^{-4}$. The ratio of transition energies is 6×10^{-5}, so that the $B(E2)$ value for the decay to the excited 0^+ state is about 15 times that to the ground state. The core-coupling model might also be improved by including some octupole strength in the interaction. This would account for the enhanced $E3$ transition strengths.

A phonon-hole coupling model has been employed by Goode and Zamick[11] to describe the low-lying nonnormal-parity states of ^{41}Ca and ^{39}K. For ^{39}K a $d_{3/2}$ hole is coupled to the 3^- or 5^- phonon state of ^{40}Ca. They have extended the random-phase-approximation technique from the doubly-closed-shell ^{40}Ca nucleus to the closed shell plus a particle or hole nucleus, and thus can include many-particle many-hole configurations in the ^{40}Ca states. Two $d_{3/2}$-$f_{7/2}$ single-particle energy gaps of 5.4 and 7.2 MeV were used, with the result that the best fit to the energy of the negative-parity levels undoubtedly would occur for some intermediate value. The predicted transition rates for ^{39}K are given in Table III.

The transition rates in the phonon-hole coupling model are given only for the $E1$ and $E3$ decays of the second, third, and fourth excited states. As is seen in Table III, the $E1$ transition rate prediction is about twice the experimental value or the weak-coupling model estimate. The $E3$ transition rates are much larger than the weak-coupling estimates, presumably because of including higher-order particle-hole correlations in the wave functions as well as more octupole strength in the form of configuration mixing of the 3^- and 5^- phonon states.

The available data indicate the existence of collective strengths in $E2$, $M2$, and $E3$ transi-

TABLE III. Comparison of experimental and theoretical transition strengths for ^{39}K.

Transition (MeV)	Multipolarity	$\|M\|^2$ (W.u.) Experimental	$\|M\|^2$ (W.u.) Core-coupling model (Ref. 10)	$\|M\|^2$ (W.u.) Phonon-hole coupling model (Ref. 11)
2.521 → 0.0	$E2$	$11.3^{+2.9}_{-1.8}$ [a]	0.38	
	$M1$	$0.022^{+0.006}_{-0.004}$ [a]	0.032	
2.813 → 0.0	$E3$	$<1.1 \times 10^3$ [b]		
		<175 [c]	0.25	2.5
		>0.96 [d]		
	$M2$	<21 [b]		
		<3.6 [c]	9.3×10^{-6}	
		>0.18 [d]		
3.018 → 0.0	$M2$	$0.34^{+24.7}_{-0.34}$	1.2×10^{-3}	
	$E1$	$7.7^{+7.6}_{-2.5} \times 10^{-4}$	6.1×10^{-4}	15×10^{-4}
3.596 → 0.0	$M4$	$<1 \times 10^9$ [b]	1.2×10^{-2}	
	$E3$	$<1.5 \times 10^3$ [b]	0.29	16

[a] Pure $E2$ and $M1$ transitions.
[b] One standard deviation included in the mixing and branching ratios.
[c] With τ from Ref. 23.
[d] With τ from Ref. 21.

tions from low-lying states in ^{39}K. The weak-coupling model underestimates these strengths, while the phonon-hole coupling model predicts larger $E3$ transition rates that are consistent with the data. The phonon-hole model also predicts a larger $E1$ transition rate for the 3.018-MeV level because it explicitly includes transitions from $(d_{3/2}^{-2}, f_{7/2})$ to $(d_{3/2}^{-1})$ configurations. More experimental information concerning the decay of the higher excited states in ^{39}K is needed in order to make a more extensive test of these collective models.

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