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Nuclear Lifetimes of the 2815- and 3598-keV Levels of ^{39}K[†]

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The recoil-distance–Doppler-shift method has been used to measure the lifetimes of the 2815- and 3598-keV levels of ^{39}K. These excited states were populated by the reaction ^{6}Li(^{35}Cl,*d*)^{39}K using 68-MeV ^{35}Cl ions. The energies of the γ rays from these two levels were determined with a 55-cm^3 Ge(Li) detector to be 783(±1), 2815(±1), and 3598(±1) keV. The mean lifetime of the 2815-keV level was measured as 79(±8) psec, and that of the 3598-keV level as 59(±4) psec. The corresponding *E*3 strengths of 6.0(±0.1) and 25.5(±1.5) Weisskopf units are in very good agreement with the phonon-hole model calculations of Goode and Zambick.

I. INTRODUCTION

The inclusion of collective-model configurations in a description[1,2] of the structure of ^{39}K has met with some success, as summarized recently by Tapphorn, Kregar, and Seaman.[3] However, because of the fact that not all of the experimental lifetimes for the 2815-keV level were in agreement, and there was only a lower limit on the lifetime for the 3598-keV level, a critical comparison with theory could not be made for these levels. The limits on the lifetimes from the previous measurements, and the theoretical predictions, indicated that the lifetimes could be measured by the recoil-distance method[4] which has been used in this study.

In earlier work, the lifetime of the 2815-keV level has been given as >0.3,[5] >1,[3] >6,[6] ≤ 80,[7] ≤ 113,[8] and as 124 ± 24 psec.[9] The 3598-keV level's lifetime has been limited to >0.18[5] and >1 psec.[3] The branching from the 3598-keV level is known[10] to be 61% to the ground state and 39% to the 2815-keV level.

II. EXPERIMENTAL DETAILS

The Stanford University FN tandem Van de Graaff accelerator provided a 68-MeV beam of ^{35}Cl ions in the charge state +7, of which a typical current of 40 nA was used. The target was a 250-μg/cm^2 evaporated film of ^{6}LiF supported by a 400-μg/cm^2 nickel foil through which the beam passed before striking the LiF. The recoil ^{39}K ions produced by the reaction ^{6}Li(^{35}Cl, *d*)^{39}K were contained within a cone subtending a half angle of 6.2°. The target foil was cemented to a supporting ring prior to the evaporation process. No provision was made for additional stretching of the foil. However, the recoil distances were such that a possible small departure from flatness would only have broadened the Doppler-shifted γ-ray lines.

The γ-ray detector was a 55-cm^3 Ge(Li) crystal which was placed 85.3 mm from the target and at 0° relative to the beam axis. The recoil-ion stopper, made of aluminum, was movable relative to the target and to the detector.[11] The γ-ray detector subtended half angles varying from 13.58 to 14.30° as the stopper was moved. The detector resolution was 2.8 keV full width at half maximum at 1332 keV; the dispersion was 0.99 keV/channel. Through the use of γ rays whose energies are well known, in spectra taken at 90° relative to the beam with thick targets, it was possible to determine the energies of the ^{39}K transitions which are of interest, as illustrated by the energy level diagram in the inset in Fig. 2. They are 783(±1), 2815(±1), and 3598(±1) keV.

γ-ray spectra were acquired in 35 min per spectrum, at recoil distances from 0.38 to 2.75 mm. In order to increase the yield of the 3598-keV γ ray, additional data were taken in 1.5 h per spectrum at recoil distances from 0.33 to 1.48 mm. The "stopped" peak and the associated Doppler "shifted" peak in each γ-ray spectrum were well separated in energy with 137.6 and 177.2 keV between these peaks for the 2815- and the 3598-keV radiations, respectively. Typical spectra are shown in Fig. 1.

The stopped peak of the 783-keV γ ray which is due to the 3598 → 2815-keV transition was observed and the yield as a function of recoil distance was obtained, but its shifted peak was obscured by the broadened, shifted peak of the 788-keV γ ray from ^{36}Cl. In order to normalize these stopped peak yields, the yield I_n at each recoil distance of a completely shifted 518-keV line from ^{36}Cl was extracted from the spectra in lieu of the customary sum of the stopped intensity I_0 and the shifted intensity I_s.

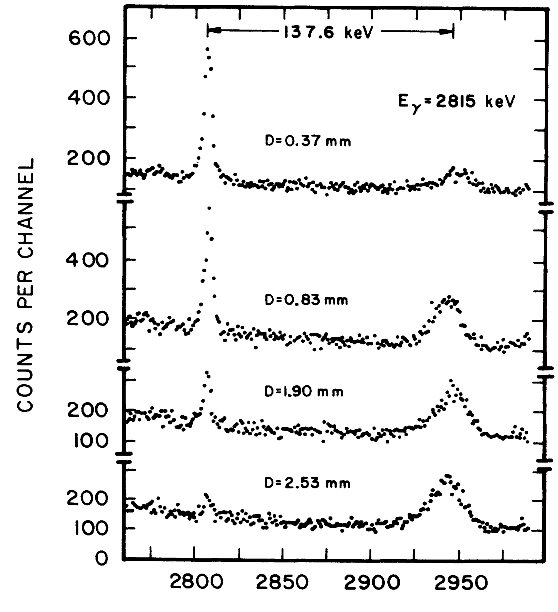

FIG. 1. Typical spectra of the "stopped" and "shifted" peaks of the 2815-keV γ ray of ^{39}K, as detected at 0° relative to the beam axis. The target-to-stopper distances were 0.37, 0.83, 1.90, and 2.53 mm.

The γ-ray yields were extracted by subtraction after fitting each stopped and shifted peak with a linear background based on off-the-peak counts in channels below and above the peak. Typical standard deviations in the yields were ±3% for the 2815-keV lines and ±9% for the 3598-keV lines.

The usual corrections[4,11] to the γ-ray yields were made. The shifted peak yield I_s was corrected relative to the lower-energy stopped peak yield I_0 through use of the ratio of previously measured detector efficiencies at the two energies. The shifted peak yield also was corrected for the change in solid angle subtended by the detector due to the conversion from the moving system of the ion to the laboratory system. The corrected shifted peak yield, I_s', was used to calculate the ratios, $I = I_0/(I_0+I_s')$, which are shown in Figs. 2 and 3. The alternative ratios I_0/I_n for the 783-keV γ ray are shown in Fig. 2.

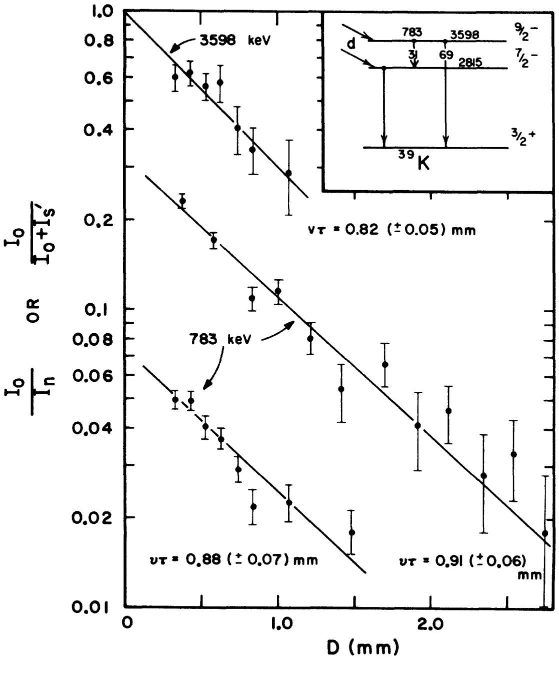

FIG. 2. The data and the fitted curves for the decay of the 3598-keV level. The data for the 3598-keV γ rays appear as the ratios $I_0/(I_0+I_s')$. The data for the 783-keV γ rays appear as the ratios I_0/I_n, where the I_n are the yields of the completely Doppler-shifted 518-keV γ rays of ^{36}Cl. The χ^2's were 1.1, 1.5, and 1.3, reading from the top down, corresponding to confidence levels of approximately 25%.

III. ANALYSIS OF DATA AND DISCUSSION OF RESULTS

The analytical equation which describes the ratios $I_0/(I_0+I_s')$ vs recoil distance for the 3598-keV radiation is given in Ref. 4. For the decay of the 2815-keV level, the equation is more complicated because the level is populated by γ decay from the 3598-keV level as well as directly by the reaction ${}^6\mathrm{Li}({}^{35}\mathrm{Cl}, d){}^{39}\mathrm{K}$, as shown in the inset of Fig. 2. The appropriate equation becomes

$$I=\left\{(1-F)\left(1+\frac{2D'}{R}\right)e^{-D'/D_2}+F\left(1+\frac{2D'}{R}\right)\left[e^{-D'/D_1}+\left(\frac{D_2}{D_1-D_2}\right)(e^{-D'/D_1}-e^{-D'/D_2})\right]\right\}\Bigg/$$
$$\left\{1+\frac{2D_2}{R}-(1-F)\left(\frac{2D_2}{R}\right)e^{-D'/D_2}+F\left[\frac{2D_1}{R}-\frac{2}{R}(D_1+D_2)e^{-D'/D_1}-\frac{2D_2^{\,2}}{R(D_1-D_2)}(e^{-D'/D_1}-e^{-D'/D_2})\right]\right\}. \qquad (1)$$

In this equation F is the fraction of the events which populate the 2815-keV level through γ-ray emission from the 3598-keV level of lifetime τ_1, τ_2 is the lifetime of the 2815-keV level, D_1 and D_2 are characteristic distances $v_1\tau_1$ and $v_2\tau_2$ where v_1 and v_2 are the respective average axial recoil-ion velocities, D' equals $D-D_0$ where D is the experimental recoil distance from target to stopper and D_0 is a small correction to the reference position from which D is measured, and R is the fixed distance from the target to the detector. This equation contains a correction for the change in solid angle subtended by the detector which occurs as the stopper is moved.

Since it is the product $v\tau$ which is obtained from the data, v is required. The average axial component of the velocity of the recoil ions was determined from the energy differences between the stopped peaks and the shifted peaks. The Doppler shifts for each of the spectra were determined and averaged; for the 2815-keV level the energy shift was 137.6(±2.6 rms) keV; for the 3598-keV level, the energy shift was 177.2(±2.7 rms) keV. To obtain the velocity v, the relativistic equation with second-order approximation[11] was used, and the necessary correction for the averaging effect of the solid angle subtended by the detector was made. The resulting average axial velocities were 0.0485(±0.0015)c for the 2815-keV level, and 0.0489(±0.0015)c for the 3598-keV level.

Equation (1), with F set equal to zero, and with a trivial change of subscripts from 2 to 1, is suitable for describing the simple one-stage decay of the 3598-keV level. This equation was fitted to the data ratios I by use of a nonlinear least-squares-fitting program with D_1 and D_0 as adjustable parameters. The uncertainties in the parameters were computed at the 0.1% confidence level. The result for $D_1=v_1\tau_1$ was 0.82(±0.05) mm. D_0 was −0.13 mm. The 783-keV data in the form of the ratios I_0/I_n were fitted by a similar equation in which D_0 becomes an unimportant scale-dependent parameter. From the two sets of 783-keV data $v_1\tau_1$ was found to be 0.91(±0.06) and 0.88-(±0.07) mm. The fitted data are shown in Fig. 2. The weighted average was 0.87(±0.06) mm from which the mean lifetime was determined to be

$$\tau(3598\text{-keV level})=59(\pm 4)\ \text{psec}.$$

The 2815-keV γ-ray data were fitted with Eq. (1) using the above value of $D_1=v_1\tau_1$, with F and $D_2=v_2\tau_2$ as variable parameters and with the same D_0 as above. The χ^2 for the fitting was not very sensitive to changes in the parameters, and pairs of F and D_2 produced acceptable fittings for D_2 from 1.0 to 1.3 mm. The observed intensities of

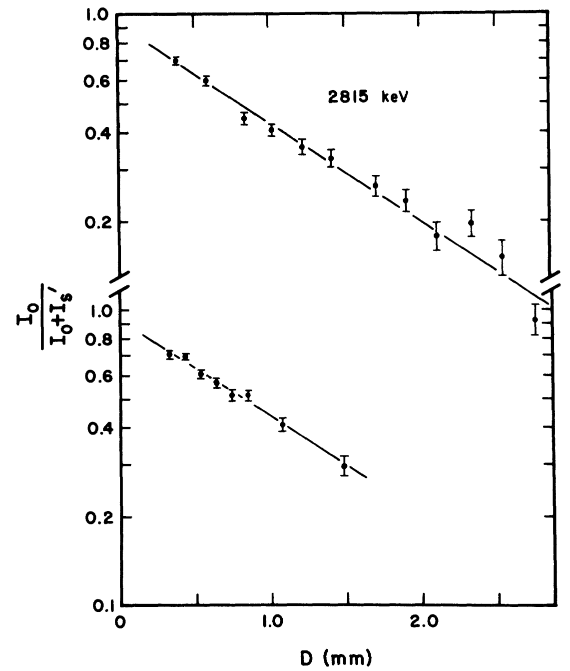

FIG. 3. The data and the fitted curves for the decay of the 2815-keV level of ^{39}K. The data appear as the ratios $I_0/(I_0+I_s')$. The fitting was made according to Eq. (1). The χ^2's were approximately 3 in each case, corresponding to confidence levels just below 0.1%.

TABLE I. Radiative transition widths for the 2815- and 3598-keV levels, and a comparison with two model calculations. Under the phonon-hole coupling model, the two values refer to $d_{3/2}$-$f_{7/2}$ energy gaps of 7.2 and 5.4 MeV, respectively.

Transition (keV)	$J_i^\pi \to J_f^\pi$	Branching [a] (%)	Multipole mixing ratio, [a] δ	$\sigma\lambda$	Partial width (10^{-6} eV)	$\|M(\sigma\lambda)\|^2$ (W.u.)		
						Expt. [b]	Phonon-hole coupling model [c]	Core-coupling model [d]
2815 → 0	$\frac{7}{2}^- \to \frac{3}{2}^+$	100	$\frac{E3}{M2}$: -0.19 ± 0.10	$M2$	8.04	0.26(±0.03) [e]		9×10^{-6}
				$E3$	0.29	6.04(±0.06) [e]	2.5; 9	0.25
3598 → 0	$\frac{9}{2}^- \to \frac{3}{2}^+$	61	$\frac{M4}{E3}$: $\|\delta\| > 2.7$ or $\|\delta\| < 0.36$	$E3$	6.80 [f]	25.5(±1.5) [f]	16; 23	0.29
				$M4$	···	···		0.012
3598 → 2815	$\frac{9}{2}^- \to \frac{7}{2}^-$	39	$\frac{E2}{M1}$: $-1.2 < \delta < 0.5$	$M1$	3.88 [g]	$3.8(\pm 0.4) \times 10^{-4}$		
				$E2$	0.47 [g]	0.24(±0.02) [g]		

[a] From Ref. 10.

[b] Present work. The uncertainties were propagated from the errors in the lifetimes.

[c] From Ref. 2.

[d] From Ref. 3.

[e] The uncertainty in the δ increases these errors to ${}^{+0.007}_{-0.012}$ and ${}^{+7.50}_{-2.50}$.

[f] Calculated using $|\delta| = 0$.

[g] Calculated using the middle value, $\delta = -0.35$.

the 2815- and 3598-keV γ rays and the use of the known branching ratio of the 3598-keV level led to $F = 0.15(\pm 0.02)$, which was used to obtain corresponding D_2's of 1.16(±0.02) and 1.17(±0.02) mm, respectively, for the two sets of data. The fitted data are shown in Fig. 3. A similar analysis of the I_0/I_n ratios gave similar results. Because of the lack of knowledge of the angular distributions of the γ rays, the uncertainty in the average D_2 was increased to 4 standard deviations, giving $D_2 = 1.16(\pm 0.08)$ mm and

$$\tau(2815\text{-keV level}) = 79(\pm 8)\ \text{psec}\,.$$

A comparison of the experimental and the theoretical transition strengths is made in Table I. The spin assignments, branching ratios, and the multipole mixing ratios were reported by Lopes *et al.*[10] For the 2815-keV level, the $M2$ and $E3$ transition strengths are normal,[12] and the $E3$ strength as calculated on the phonon-hole coupling model[2] is in better agreement with the experimental value than is that calculated[3] with the weak-coupling model.[1] For the 3598-keV level transition to the ground state, the multipole mixing ratio $\delta(M4/E3) = 0$ has been chosen since a nonzero value required an abnormally large $M4$ strength, as, for example, 2.4×10^6 Weisskopf units (W.u.) at $\delta = 0.36$. Thus, it is assumed that the transition is effectively a pure $E3$ transition whose strength is 25.5 W.u. For the 3598-keV level transition to the 2815-keV level, the upper limit on the $E2$ strength calculated with $\delta = -1.2$ indicates a retarded $E2$ transition. If $\delta = 0$ were assumed, then the assumed pure $M1$ transition would have a strength of 4.4×10^{-4} W.u. For this level, too, the phonon-hole coupling model gives the better agreement with the data.

Note added in proof. Robertson,[13] has shown that a relatively small collective octopole admixture in the 2815-keV-level's wave function as given in Ref. 10 produces an $E3$ width of 0.080×10^{-6} eV in reasonable agreement with the experimental result. Also, he has used the wave function of Maripuu and Hokken,[14] to calculate this $E3$ width as 0.035×10^{-6} eV. It is to be noted that the 2815-keV-level's experimental $E3$ width is critically dependent on the experimental value of the multipole mixing ratio δ.

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