PHYSICAL REVIEW C VOLUME 11, NUMBER 3 MARCH 1975

Lifetimes of levels in ^{136}Xe, ^{140}Cs, and ^{141}Cs populated in the decays of mass-separated ^{136}I, ^{140}Xe, and ^{141}Xe

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(Received 26 August 1974)

The decays of ^{141}Xe, ^{140}Xe, and ^{136}I were examined for the presence of energy levels in ^{141}Cs, ^{140}Cs, and ^{136}Xe, respectively, with measurable half-lives in the nsec range. Using a least-squares fitting procedure to analyze the delayed coincidence data taken with a planar Ge(Li)-plastic scintillator system, the half-lives of the following levels were measured: ^{141}Cs: 69.0 keV, 23.3 ± 0.7 nsec; 105.9 keV, 8.7 ± 0.2 nsec; ^{140}Cs: 13.9 keV, 471 ± 51 nsec; 64.7 keV, 3.7 ± 0.3 nsec; 103.1 keV, 7.3 ± 0.3 nsec (average of two measurements). In addition, upper limits for the half-lives of other levels in these two isotopes are also given, as well as for some levels in ^{136}Xe. Possible multipolarities of the transitions are discussed.

[RADIOACTIVITY ^{136}I, ^{140}Xe, ^{141}Xe from ^{235}U(n,f); measured delayed coin; deduced $T_{1/2}$ for levels in ^{136}Xe, ^{140}Cs, ^{141}Cs; Ge(Li) and scin detectors; mass-separated activities.]

I. INTRODUCTION

As a part of the experimental effort at the TRISTAN facility to study the decays of short-lived gaseous fission product nuclei, measurements have been made of some nuclear level lifetimes using a β-γ delayed coincidence technique. These measurements complement the information on nuclear structure provided by γ-ray decay scheme and internal conversion coefficient studies. For the measurements reported in this work, the γ-ray decay scheme studies at TRISTAN are in progress for the decays of ^{141}Xe and ^{136}I, and results have been reported for the decay of ^{140}Xe.[1,2] The experimental arrangement developed for this work will be used for future studies on other decays.

II. EXPERIMENTAL TECHNIQUE

The nuclei studied were obtained using the TRISTAN on-line isotope separator facility, located at the Ames Laboratory research reactor. A brief description of the system follows; more complete descriptions may be found in the literature.[3,4] A sample of uranium stearate, enriched in ^{235}U, is placed in a neutron beam external to the reactor. The gaseous fission products are carried through a transport tube to the ion source of the isotope separator. The ion beam of interest is selected by a slit at the focal plane of the separator, after which it continues through a switching magnet to a moving tape collector.[5] The detectors used for the delayed coincidence measurements were placed at opposite sides of the tape collector, viewing the point of ion beam deposit. The collection tape was moved periodically to prevent buildup of daughter activities during data collection.

The detectors used to measure the delayed coincidence time spectra were a plastic scintillator and a thin-window small-volume planar Ge(Li) detector. The scintillator is a 25-mm thick by 44-mm diam cylinder of NE102 plastic mounted on an Amperex PM2106 12-stage photomultiplier tube, operated at 2000 V. The Ge(Li) detector is an Ortec low energy photon spectrometer (LEPS), having a 1-cm^3 active volume with a depletion depth of 5.1 mm. The preamplifier used with the LEPS is an Ortec Model 117A.

Standard constant fraction discriminator timing was used with both detectors, as indicated in the block diagram of the equipment shown in Fig. 1. A pulse shape analyzer was used to eliminate signals from the Ge(Li) detector channel with rise times greater than about 70 nsec. These long rise time pulses produced noticeable tailing in the time spectra. The origin of these long rise time pulses and their effect on time spectra are discussed extensively in the literature.[6-9] Time calibration was taken from an Ortec 462 time calibrator.

The dual-parameter system, used with a 16 384-channel analyzer, stores a time-energy coincidence data array on magnetic tape. Normally for these studies this array is either 512 channels (time) by 2048 channels (energy), or 1024×2048 channels.

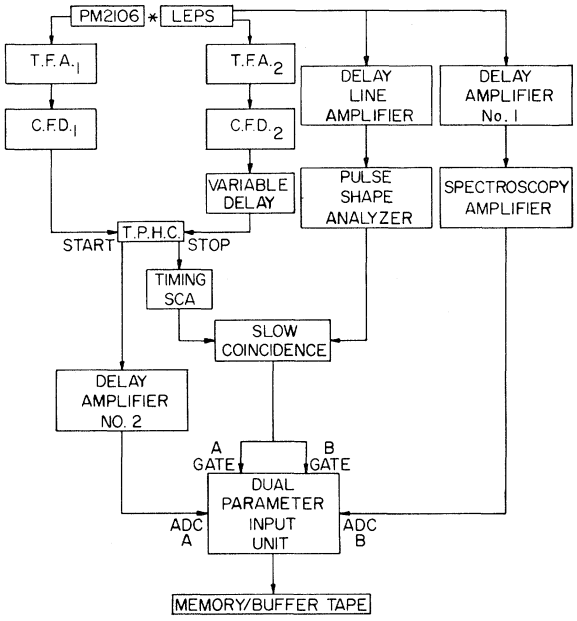

FIG. 1. Block diagram of the circuitry used in the lifetime measurement system.

III. DATA ANALYSIS

The data collected on magnetic tape were sorted into delayed coincidence time spectra by setting gates on the energy spectrum of the nucleus being studied. A gate was set on each of the transition peaks in the spectrum, as well as on the background distribution above each peak. The background gate was set within 5 keV of the energy peak, and the resulting background time spectrum was subtracted from the time spectrum obtained by gating on the peak.

As long as the prompt response (i.e., the time spectrum resulting from an essentially instantaneous transition) of the system, $P(t)$, spans a much smaller time than the response to a delayed transition $F(t)$, the normal linear slope technique[10] can be used to determine the half-life of the transition. In all but one case studied here, however, the presence of some tailing on the late side of the prompt response peak caused a small decrease in the slope of the delayed time distribution. To improve the accuracy of the lifetime measurements, a fitting technique was used which accounts for the response of the system to a prompt transition.

The prompt response of the system was taken to be the time spectrum obtained by setting a gate on the background just above each energy peak. The response to a delayed transition was taken to be

$$F(t_i) = C \sum_j e^{-\lambda t_j} P(t_i - t_j),$$

where C is a normalization constant to be fitted and λ is the transition probability. To this was added the chance coincidence background terms. Though this background normally was constant, the terms used were $(Dt_i + E)$, which allowed for the presence of a slope. One more term, $GP(t_i)$, where G is a constant to be fitted, was added. It was found that in some cases the subtraction of the time spectrum gated on the energy background above the peak did not entirely remove the prompt contribution to the delayed spectrum.

Using initial estimates of the five parameters λ, C, D, E, and G taken from graphs of the data, a standard least squares fit was performed.

The fitting technique was verified using the 80.98-keV transition in ^{133}Cs, which has a reported half-life of 6.30 ± 0.02 nsec.[11] The measured value using the system and fitting technique described here was 6.2 ± 0.2 nsec.

The uncertainties associated with the measured lifetimes come from two sources. One is the statistical uncertainty of the least-squares fit, taken from the diagonal element of the error matrix calculated during the fitting procedure. The second contribution comes from the fact that the choice of the prompt spectrum, since its shape varies with energy, has an effect on the value of the mean life determined by the program. To estimate this effect, the time spectrum for each transition was fitted using prompt spectra taken from energies both higher and lower than the energy corresponding to the peak being fitted.

For each transition that had a measurable half-life reported in this work, the prompt spectra were taken from energies approximately 15 keV away, both above and below, from the transition energy being studied. Using the values of the half-lives obtained this way, plus the original value that was calculated, the effect of the prompt spectrum choice on the half-life could be estimated over an energy range of about 30 keV. Since the actual prompt spectrum used for each fit reported here was taken from approximately 5 keV above the

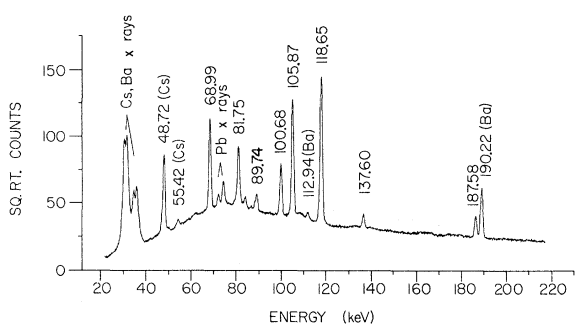

FIG. 2. Energy profile for the decay of ^{141}Xe.

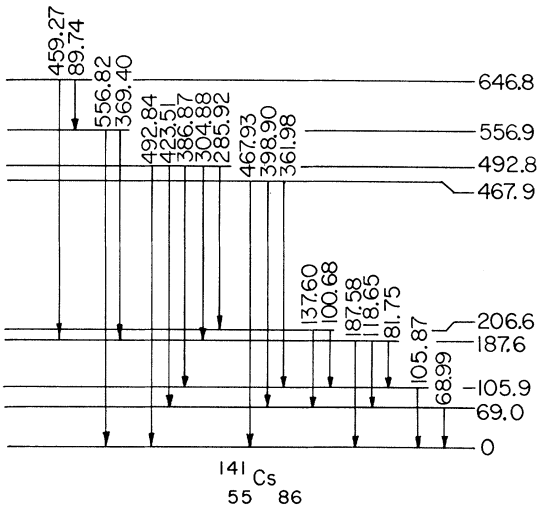

FIG. 3. Low-energy level scheme for ^{141}Cs.

transition energy peak, a correction was then made to the half-life value on the basis of the above estimate. For the worst case, the 69.0-keV transition in ^{141}Cs, this amounted to a reduction of the half-life value by 0.3 nsec. For the other reported half-lives, the corrections were smaller.

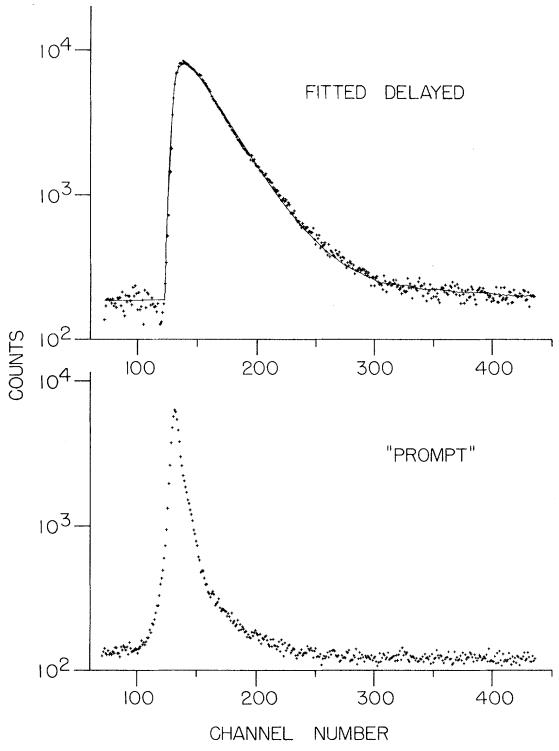

FIG. 4. Delayed coincidence time spectrum and fitted function for the decay of the 105.87-keV level of ^{141}Cs (top), and the prompt spectrum used in the fitting program (bottom).

TABLE I. Half-lives of levels in ^{141}Cs and ^{141}Ba.

Transition energy (keV)	Initial level (keV)	Half-life (nsec)
48.72 [a]		<3.4
55.42 [a]		<3.2
68.99	69.0	23.3 ± 0.7
81.75	187.6	<2.4
89.74	646.8	<2.4
100.68	206.6	<2.3
105.87	105.9	8.7 ± 0.2
118.65	187.6	<2.1
137.60	206.6	<2.1
187.58	187.6	<1.9

[a] Transitions in ^{141}Ba.

The half-lives listed in the tables of results are the values found by the fitting program, corrected for an apparent increase in half-life caused by the choice of the prompt spectrum. The associated uncertainties listed are the statistical uncertainties (one standard deviation) taken from the error matrix.

IV. RESULTS AND DISCUSSION

A. Levels of ^{141}Cs

The energy profile of the decay of ^{141}Xe is shown in Fig. 2. Two strong peaks from the decay of ^{141}Cs and two from the decay of ^{141}Ba are also present in the energy spectrum. For reference, the low-energy part of the ^{141}Cs level scheme is presented in Fig. 3. The γ-ray energies and the decay scheme are from a study by Cook and Talbert,[12] and from a compilation by Auble.[13]

Of the transitions studied, the 68.99-keV level was found to have a half-life of 23.3 ± 0.7 nsec. The 105.87-keV ground-state transition half-life was measured as 8.7 ± 0.2 nsec. The delayed coincidence time spectrum for this transition, along with the fitted function, is shown in Fig. 4 as an exam-

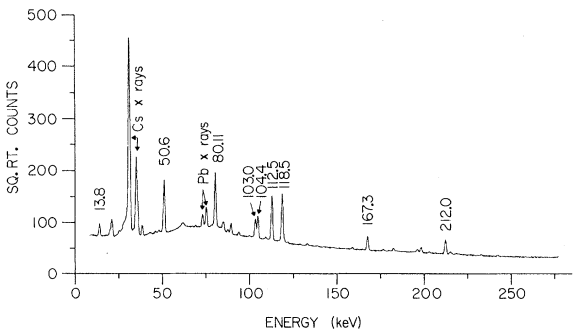

FIG. 5. Energy profile for the decay of ^{140}Xe.

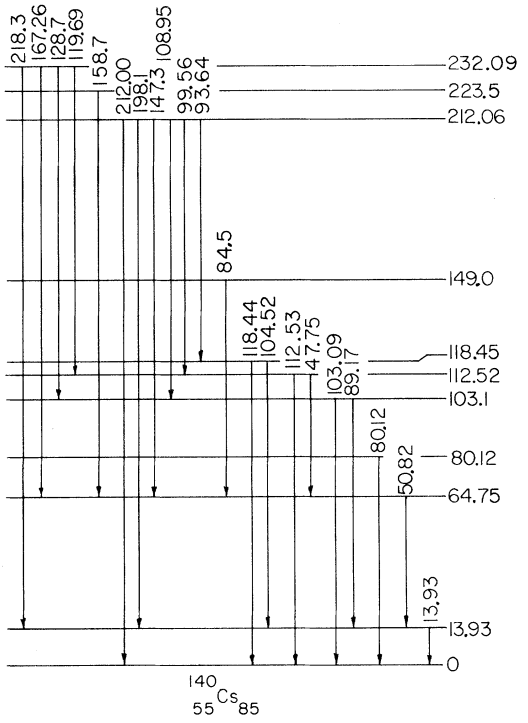

FIG. 6. Low-energy level scheme for ^{140}Cs.

ple of the results of the fitting technique. Also shown in Fig. 4 is the prompt spectrum used in the fit. The time calibration is 0.468 nsec/channel.

Table I summarizes these values along with the upper limits of the half-lives for the other transitions studied.

B. Levels of ^{140}Cs

The energy profile for the decay of ^{140}Xe is shown in Fig. 5. Figure 6 shows the low-energy part of the level scheme for ^{140}Cs, taken from a study by

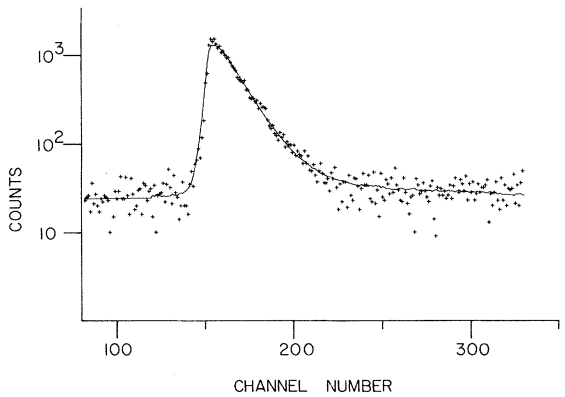

FIG. 7. Delayed coincidence time spectrum and fitted function for the decay of the 103.1-keV level of ^{140}Cs.

TABLE II. Half-lives of levels in ^{140}Cs.

Transition energy (keV)	Initial level (keV)	Half-life (nsec)
13.93	13.93	471 ±51
50.82	64.75	3.6± 0.3
80.12	80.12	<2.7
84.5	149.0	<2.7
89.17	103.1	7.0± 0.4
93.64	212.06	<2.6
103.1	103.1	7.5± 0.3
104.52	118.45	<2.4
112.53	112.52	<2.3
118.44	118.45	<2.0
167.26	232.09	<1.9

Adams *et al.*[2]

Values for the half-lives of four transitions in ^{140}Cs were measured. The 13.93-keV ground-state transition has a measured half-life of 471± 51 nsec. This value was obtained by fitting a straight line to the slope of the time distribution.

The decay of the 64.75-keV level via the 50.82-keV γ ray was measured as having a half-life of 3.7± 0.3 nsec. The 89.17-keV transition from the 103.1-keV level has a measured half-life of 7.0 ± 0.4 nsec. The 103.1-keV ground-state transition half-life was also measured, giving a value of 7.5 ± 0.3 nsec. The average value for the half-life of the 103.1-keV level is then 7.3± 0.3 nsec.

Figure 7 shows the time distribution from the decay of the 103.1-keV level via the 89.17-keV γ ray. The time calibration is 0.954 nsec/channel. The four half-lives determined and the upper limits of some other transitions are listed in Table II.

C. Levels of ^{136}Xe

Figure 8 shows the energy profile of the decay of ^{136}I. Since the yield of iodine activity from the TRISTAN facility is much less than that of the noble gas fission products, the statistics are poorer than in the other studies. The low-energy part of the ^{136}Xe level scheme, from a study now in progress by Western,[14] is shown in Fig. 9.

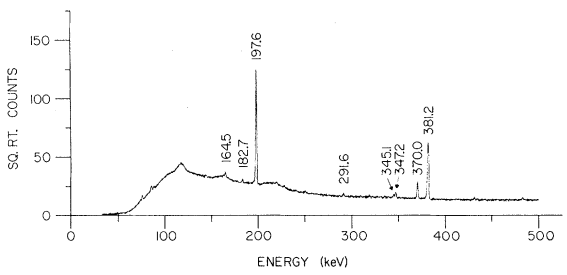

FIG. 8. Energy profile for the decay of ^{136}I.

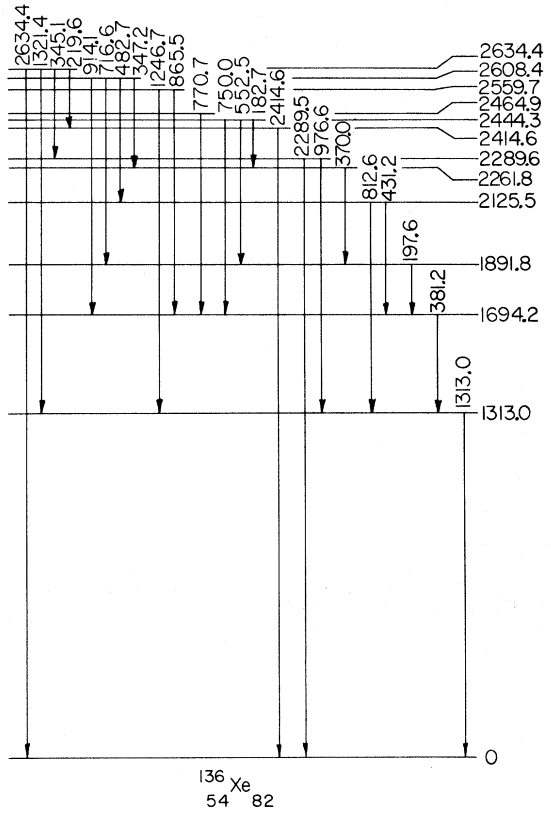

FIG. 9. Low-energy level scheme for ^{136}Xe.

None of the transitions studied had a half-life long enough to be measured. However, upper limits have been set for each of them. The results are shown in Table III. The 197.6-keV transition has been reported by Carraz *et al.*[15] to have a half-life of 2.8± 0.2 μsec. Half-lives in this range are longer than would be detected with the relatively short time scales used in this study.

D. Discussion

The values of the six transition half-lives that were measured, after correction for internal conversion, are given in Table IV in Weisskopf units for multipolarities $M1$ and $E2$. Also shown in the table are the results of a previous study by Clark, Glendenin, and Talbert[16] which will be discussed later.

TABLE III. Half-lives of levels in ^{136}Xe.

Transition energy (keV)	Initial level (keV)	Half-life (nsec)
164.5		<2.1
182.7	2444.3	<2.0
347.2	2608.4	<1.6
370.0	2261.8	<1.4
381.2	1694.2	<1.4

The nucleus ^{141}Cs, because of its odd-A nature, can be discussed easily in terms of the shell model. The ground-state spin and parity are given by the last unpaired proton in the nucleus, which is presumed to be in a $g_{7/2}$ orbital. This assignment is supported by the fact that the odd-A cesium nuclei ^{133}Cs to ^{139}Cs all have $(\frac{7}{2})^+$ ground states.[17]

The first excited state in ^{141}Cs is at 68.99 keV. Comparing the measured half-life to the Weisskopf estimates, and noting that the $E2$ enhancement factor of 44 is higher than would be expected in this nondeformed region, the transition is assigned a multipolarity $M1$. This level can be accounted for by assuming that the odd proton is excited to the next single-particle state available to it, a $d_{5/2}$ orbital, giving the 69-keV level a spin-parity of $(\frac{5}{2})^+$. The transition to the ground state is then an l-forbidden $M1$, with a measured hindrance factor of 1270.

Again, neighboring nuclei give evidence to support this assignment. ^{133}Cs has its first excited state at 81 keV, which is a $(\frac{5}{2})^+$ level.[11] The ground-state transition is an l-forbidden $M1$ with 2.6% $E2$ mixing. The $M1$ hindrance factor calculated from the 6.3-nsec half-life is 389.

The 250-keV transition in ^{135}Cs is from a $(\frac{5}{2})^+$

TABLE IV. Transitions with half-lives as measured in this work, and corresponding values given by Clark *et al.* (Ref. 16). The last two columns represent the half-lives given in column 4 in Weisskopf units (W.u.) for $E2$ and $M1$ transitions.

Transition energy (keV)	Nucleus	Half-life (nsec) Clark *et al.*	Half-life (nsec) This work	$T_{1/2}/T_{1/2}$ (W.u.) ($E2$)	$T_{1/2}/T_{1/2}$ (W.u.) ($M1$)
13.93	^{140}Cs	521 ± 10	471 ± 51	1.67×10^{-1}	2.47×10^{3}
50.82	^{140}Cs	8 ± 1	3.7 ± 0.3	2.18×10^{-3}	1.64×10^{2}
68.99	^{141}Cs	22 ± 6	23.3 ± 0.7	2.24×10^{-2}	1.27×10^{3}
89.17	^{140}Cs	...	7.0 ± 0.4	3.89×10^{-2}	1.74×10^{3}
103.1	^{140}Cs	11 ± 1	7.3 ± 0.3	2.51×10^{-2}	9.60×10^{2}
105.87	^{141}Cs	14 ± 1	8.7 ± 0.2	2.22×10^{-3}	8.29×10^{2}

first excited state to a $(\frac{7}{2})^+$ ground state.[17] This is also an l-forbidden transition, and assuming an $M1$ multipolarity with the half-life of 0.3 nsec, the hindrance factor is 229. The multipolarity has not yet been confirmed.

Other nearby nuclei which have an unpaired proton in a $g_{7/2}$ orbital also exhibit l-forbidden $M1$ transitions. The 166-keV transition in ^{139}La is $M1$ with less than 0.4% $E2$ mixing.[17] The half-life is 1.7 nsec, for a hindrance factor of 427. The 114-keV transition in ^{139}Pr is $M1$, with a half-life of 2.5 nsec[17] and a hindrance factor of 281.

Based on a comparison with these transitions in nuclei having similar proton configurations, it is very probable that the 69-keV transition in ^{141}Cs is mostly $M1$.

The second excited state of ^{141}Cs is at 105.87 keV. The $E2$ enhancement factor for the ground-state transition is 455, which is very high for a nondeformed nucleus such as ^{141}Cs. Since the $M1$ hindrance factor of 829 is more reasonable, the transition can be classified as $M1$, possibly with a very small admixture of $E2$. Among the possible spin-parity assignments for this level are $(\frac{3}{2})^+$, $(\frac{5}{2})^+$, and $(\frac{7}{2})^+$. Systematics for nearby nuclei are little help in this case, and it is not possible to say which spin-parity is correct.

The nucleus ^{140}Cs has 85 neutrons and 55 protons. A recent study by Adams *et al.*[2] suggests spin-parities and multipolarities based on internal conversion coefficient measurements. The 13.9-keV level has been assigned a spin-parity of 2^- and the transition to the ground state, which is either 1^- or 2^-, is designated $M1$. According to their work, the 64.75-keV level has a spin-parity of 3^-, and the transition to the 13.9-keV level is $M1$. The 103.1-keV, 104.5-keV doublet could not be resolved for conversion coefficient measurements in the study, and the combined transition is assigned a mixed multipolarity of $M1$ and $E2$.

Comparing results, the measured half-life of 471 nsec for the 13.9-keV transition, with an $M1$ hindrance factor of 2470, agrees with the multipolarity assignment of Adams *et al.*

The 50.8-keV transition from the 64.7-keV level has a very high $E2$ enhancement factor of 459, which is higher than the values normally found outside deformed regions. The $M1$ hindrance factor of 164 compares favorably with other $M1$ transitions, and the 50.8-keV transition is assigned a multipolarity $M1$. This agrees with the internal-conversion measurement prediction.

In the case of the 103.1-keV level, there are two γ rays depopulating the level, and partial half-lives for each transition must be calculated. Using the intensities given by Adams *et al.*[2] the partial half-life of the 89.2-keV transition is 23.9 nsec and that of the 103.1-keV transition is 10.6 nsec. These values were used to calculate the half-lives in Weisskopf units listed in Table IV for these two transitions. With $M1$ hindrance factors of 1740 and 960 for the 89.2- and 103.1-keV transitions, respectively, both transitions are classified as $M1$. The $E2$ enhencement factors of 26 and 40 are higher than would be expected, but do not rule out the possibility of some $E2$ mixing. The two assignments agree with the measurements of Adams *et al.*

E. Comparison to previous work

A recent study by Clark *et al.*[16] gives the values of the half-lives of isomeric transitions in many nuclei observed following the spontaneous fission of ^{252}Cf. Their results for the transitions under consideration in the present study have been listed in Table IV.

For timing purposes, the fission-γ coincidences were sorted into successive time bins, the upper limits of the first few bins being 5, 9, 15, 29, ... nsec. For half-lives under 9 nsec, this time-sorting technique gives at most four data points to use in calculating the half-life.

The values reported by Clark *et al.* for the half-lives of the 13.9- and 68.99-keV transitions agree reasonably well with the values reported here. Clark *et al.* also report an 89.9-keV transition in ^{141}Cs with a half-life of 12 nsec. This transition has probably been assigned to the wrong nucleus, and is possibly the same transition reported in this work as the 89.1-keV transition in ^{140}Cs with a half-life of 7.0 nsec.

For the 50.8-, 103.1-, and 105.87-keV transitions, the half-lives given by Clark *et al.* are all longer than those measured in this work. Their values for these short half-lives are probably overestimated because of the method used in the study of ^{252}Cf to determine the half-lives.

In the present work, the time interval between successive data points was less than 1 nsec. Thus, even for short half-lives many more data points were used to find the half-life, and the reliability of the fitted results should be much greater. The possibility cannot be excluded, however, that the fission-product half-lives reported by Clark *et al.* arise from a directly populated state not fed in β decay which deexcites through the levels measured in this work, but with a longer lifetime.

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[17]*Nuclear Level Schemes A=45 through A=257 from Nuclear Data Sheets*, edited by Nuclear Data Group, Oak Ridge National Laboratory (Academic, New York, 1973).