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Isomeric Transitions in 29-Day ^{179m_2}Hf†

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The 29-day isomer ^{179m_2}Hf has been found to decay via 21.03- and 257.32-keV transitions to the $\frac{21}{2}^+$ and $\frac{19}{2}^+$ members of the ground-state rotational band of ^{179}Hf. From conversion-electron studies, $M2$ and $E3$ multipolarities were deduced, respectively, for the 21.03- and 257.32-keV isomeric transitions. The spin and parity $\frac{25}{2}^-$ is assigned to the isomeric state.

I. INTRODUCTION

In a recent publication,[1] a new isomeric state in ^{179}Hf with a half-life of 29 days has been reported. In its decay, a rotational band built on the $\frac{9}{2}^+[624]$ ground state of ^{179}Hf is populated up to the $I=\frac{21}{2}$ member. The isomeric transitions feeding this band, however, were not identified with certainty. A tentative spin and parity assignment of $I^\pi=\frac{25}{2}^-$ to the isomer was based only on considerations of its half-life and the population of the ground-state rotational band up to high-spin members, but was not substantiated by a direct measurement of the multipole order of the isomeric transitions.

From γ-γ coincidence measurements, it was concluded[1] that the $I=\frac{19}{2}$ state of the rotational band is fed both by a 236.6- and a 257.5-keV transition, the latter transition apparently depopulating the isomeric state. By assuming $E3$ multipolarity for the 257-keV transition, an approximate balance of population and depopulation was achieved for the $I=\frac{19}{2}$ rotational state.[1]

In this article we report measurements of the conversion-electron spectrum accompanying the decay of the 29-day isomer ^{179m_2}Hf. These investigations allow a determination of the isomeric transitions and their multipolarities. The results establish the spin and parity of the isomer.

II. EXPERIMENTAL TECHNIQUES AND RESULTS

A sample of 60-mg Yb_2O_3, enriched to 96% in ^{176}Yb, was irradiated with 30-MeV α particles in the Massachusetts Institute of Technology cyclotron. From the amount of ^{179m_2}Hf activity obtained, we estimate the cross section for the ^{176}Yb(α, n)-^{179m_2}Hf reaction to be approximately 30 μb at this energy.

In addition to the ^{179}Hf activity, the sample showed contaminations of ^{172}Hf, ^{175}Hf, ^{178m_2}Hf, and ^{177}Lu. In order to prepare sources for our conversion-electron studies, the hafnium fractions were

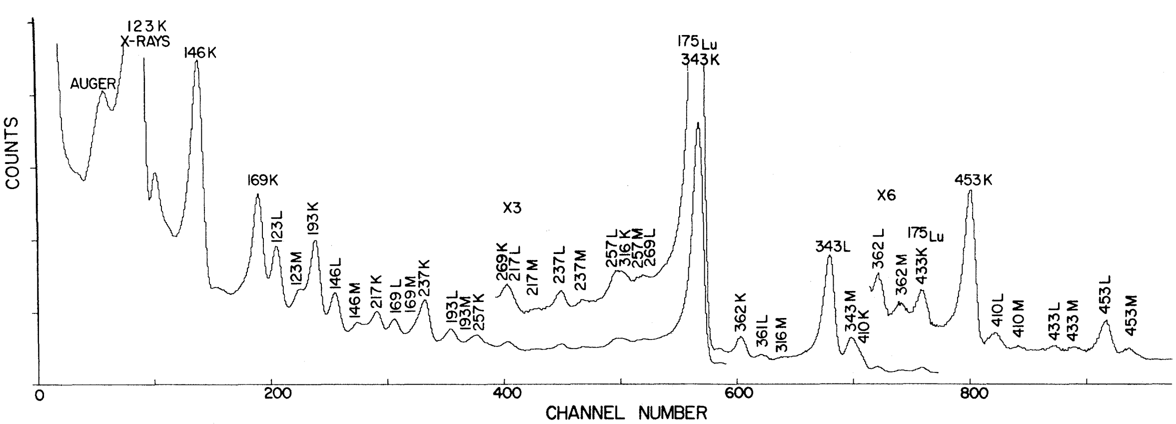

FIG. 1. Conversion-electron energy spectrum of ^{179m_2}Hf measured with a Si(Li) detector. ^{175}Lu lines are labeled in the plot.

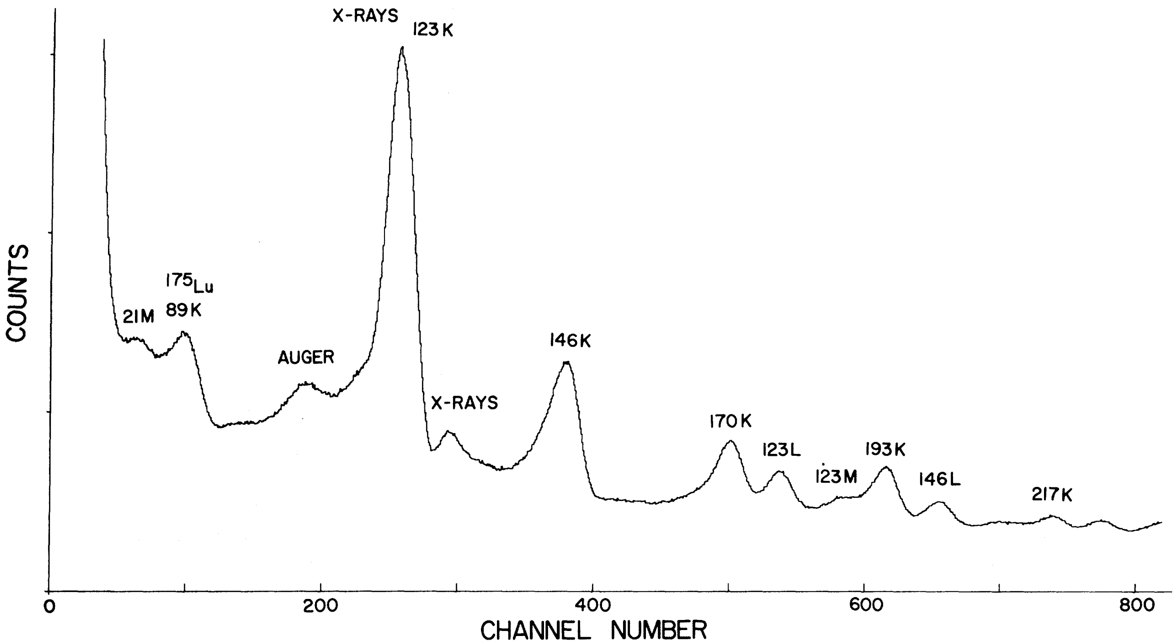

FIG. 2. As Fig. 1, but low-energy part.

TABLE I. Conversion coefficients for transitions in the decay of the 29-day isomer ^{179m}Hf.

Transition energy (keV)	Electron shell	α_{exptl}	$\alpha_{\text{theor}}(E2)^{a}$	$\alpha_{\text{theor}}(M1)^{a}$	$\alpha_{\text{theor}}(E3)^{a}$	Multipolarity
122.7	L	0.27 ± 0.04	0.75	0.30		$M1/E2$
	M	0.06 ± 0.03	0.22	0.07		
146.1	K	1.25 ± 0.13	0.40	1.19		$M1/E2$
	L	0.14 ± 0.02	0.34	0.18		
	M	0.05 ± 0.02	0.09	0.04		
169.8	K	0.56 ± 0.09	0.26	0.78		$M1/E2$
	L	0.10 ± 0.02	0.19	0.12		
192.6	K	0.44 ± 0.08	0.19	0.54		$M1/E2$
	L	0.05 ± 0.02	0.12	0.08		
217.1	K	0.36 ± 0.06	0.136	0.39		$M1/E2$
236.4	K	0.24 ± 0.04	0.109	0.31		$M1/E2$
	L	0.02 ± 0.01	0.047	0.05		
257.3	K	0.35 ± 0.06			0.24	$E3$
	L	0.39 ± 0.05			0.45	
	M	0.15 ± 0.03			0.15	
268.8	K	0.07 ± 0.02	0.078			$E2$
315.9	K	0.05 ± 0.02	0.049			$E2$
	L	0.004 ± 0.003	0.014			
362.5	K	0.023 ± 0.016	0.034			$E2$
409.6	L	0.005 ± 0.002	0.005			$E2$
	M	0.001 ± 0.001	0.002			
453.5	K	0.016[b]	0.016			$E2$[b]
	L	0.004 ± 0.001	0.004			
	M	0.0010 ± 0.0003	0.001			

[a]Values taken from Ref. 2.

[b]Normalized to $E2$.

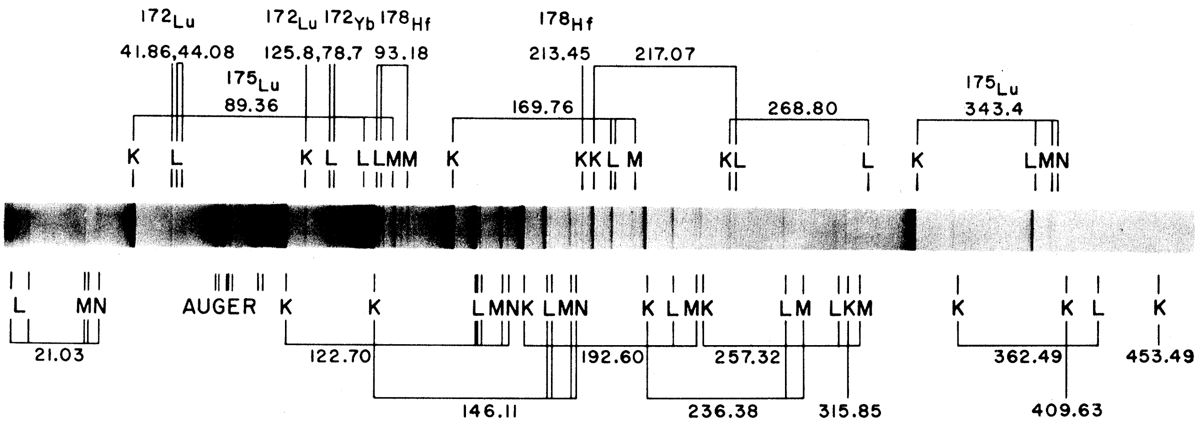

FIG. 3. Photographic plate showing conversion–electron energy spectrum of ^{179m_2}Hf. All lines are assigned to ^{179}Hf except those labeled otherwise.

deposited carrier free on a thin platinum wire of 10-mm length. The procedure for the chemical separation is described in Ref. 1.

Linear plots of the conversion-electron energy spectra measured with a Si(Li) detector are shown in Figs. 1 and 2. All conversion-electron lines are assigned to the decay of the ^{179}Hf isomer except the lines labeled as ^{175}Lu in the plots. In Table I we have listed the experimental and theoretical[2] conversion coefficients. The experimental values were derived by assuming pure $E2$ multipolarity for the 453.5-keV transition, the highest-energy crossover transition within the rotational band, and then comparing the γ ray and conversion-electron intensities with the corresponding intensities of the 453.5-keV transition.

As can be seen from Table I, the $\Delta I = 1$ cascade transitions are of mixed $M1/E2$ multipole order. The crossover $\Delta I = 2$ transitions have pure $E2$ multipolarity. The conversion coefficients for the 257.3-keV transition are compatible only with an $E3$ multipole assignment.

High-resolution conversion-electron spectra were photographically recorded with a 132.4-G permanent-magnet spectrograph. The energy range covered by this instrument is 8 to 440 keV. Figure 3 shows the conversion-electron spectrum recorded during a two-month exposure to our ^{179m_2}Hf source. The assignments of the electron lines are indicated in the figure. All transitions previously found[1] in the γ-ray spectrum of ^{179m_2}Hf are present in the conversion-electron spectrum. Also visible are lines from the other long-lived isotopes ^{172}Hf, ^{175}Hf, and ^{178m_2}Hf.

At the low-energy end of the photographic plate in Fig. 3, a set of lines are observed which must be interpreted as the L_1, L_3, M_1, M_3, and N_1 conversion lines of a 21.03-keV transition converted in Hf. These arise from the isomeric transition

TABLE II. Table of transitions in the decay of ^{179m_2}Hf derived from permanent-magnet spectrographic measurements.

Electron shell	Transition energy (keV)	Average energy (keV)
L_1	21.06	21.03 ± 0.14
L_3	21.01	
M_1	21.03	
M_3	21.00	
N_1	21.06	
K	122.76	122.70 ± 0.10
L_1	122.70	
L_2	122.68	
L_3	122.67	
M_1	122.70	
K	146.22	146.11 ± 0.09
L_1	146.10	
L_2	146.00	
L_3	146.10	
M_1	146.20	
N_1	146.06	
K	169.85	169.76 ± 0.10
L_1	169.80	
L_3	169.77	
M_1	169.66	
K	192.71	192.60 ± 0.13
L_1	192.56	
M_1	192.54	
K	217.11	217.07 ± 0.16
L_1	217.03	
K	236.50	236.38 ± 0.19
L_1	236.25	
K	257.20	257.32 ± 0.20
L_1	257.45	
K	268.80	268.80 ± 0.20
K	315.85	315.85 ± 0.21
K	362.49	362.49 ± 0.24
L_1	362.50	
K	409.63	409.63 ± 0.26
K	453.49	453.49 ± 0.28

feeding the $I=\frac{21}{2}$ rotational state. The energy sum formed with the $\frac{21}{2}\to\frac{19}{2}$ transition of 236.38 keV is 257.41 keV; this agrees within the limits of the experimental error with the energy of the 257.32-keV crossover transition. The intensities of the L subshells (approximately equal intensity of the L_1 and L_3 lines but much weaker L_2 line) is consistent only with $M2$ multipolarity for the 21.03-keV transition.[2]

In Table II we have listed the energies of all transitions assigned to the decay of the 29-day ^{179m2}Hf isomer as derived from the permanent-magnet spectrographic measurements. The agreement with the previous γ-ray work[1] is good.

An intensity ratio of $I(21)/I(257)=14$ for the 21- and 257-keV transitions depopulating the 1106-keV isomeric state can be derived from the γ intensities of the 257-keV and the 236- and 453-keV transitions given in Ref. 1 and the conversion coefficients listed in Table I. Partial mean lifetimes of about 45 and 700 days and retardation factors of 7×10^{11} and 3×10^{10} are obtained for the 21-keV $M2$ and the 257-keV $E3$ transitions, respectively.[1]

III. CONCLUSION

The decay scheme which we propose on the basis of the data presented here and the previously published data[1] is shown in Fig. 4. With the 21- and 257-keV isomeric transitions having $M2$ and $E3$ multipolarity, respectively, no other spin-parity assignment than $\frac{25}{2}^-$ to the isomeric state is possible.

To explain a $\frac{25}{2}^-$ state within the framework of the Nilsson model,[3] we have to assume that it is a three-quasiparticle state, since no single-particle orbitals with spin $\frac{25}{2}$ are available at this excitation energy. The single-particle neutron and proton Nilsson orbitals available in the hafnium region are listed in Table III. The 107th neutron of ^{179}Hf is in the $\frac{9}{2}^+[624]$ state, which explains the ground-state spin. There is no combination of three neutrons available to couple to a state with spin $\frac{25}{2}$. In the neighboring odd-proton lutetium and tantalum nuclei, the ground states are $\frac{7}{2}^+[404]$ states, and the $\frac{9}{2}^-[514]$ states are found at low excitation energies. We, therefore, suggest that the spin-$\frac{25}{2}$ isomer in ^{179}Hf arises from a coupling of the odd neutron of ^{179}Hf in the Nilsson state $\frac{9}{2}^+[624]$ to a broken proton pair promoted to the $\frac{7}{2}^+[404]$ and $\frac{9}{2}^-[514]$ states:

$$\{\tfrac{9}{2}^+[624]n,\ \tfrac{7}{2}^+[404]p,\ \tfrac{9}{2}^-[514]p\}\ \tfrac{25}{2}^- .$$

The makeup of the isomeric state is thus very similar to that of the $K^\pi=\frac{23}{2}^+$ isomer[4] in ^{177}Hf, where the analogous proton pair couples to the $\frac{7}{2}^-[514]$ odd neutron of ^{177}Hf.

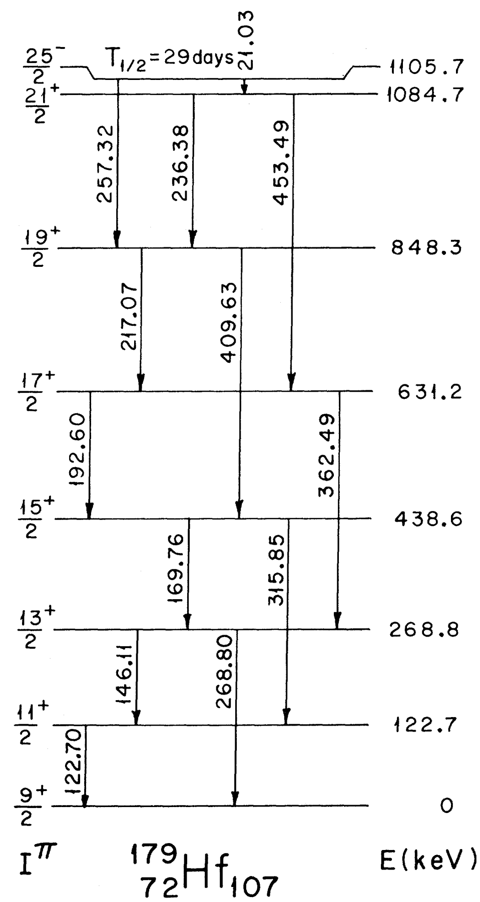

FIG. 4. Decay scheme of 23-day isomer ^{179m}Hf.

ACKNOWLEDGMENT

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TABLE III. Single-particle neutron and proton orbitals available in the Hf region.

Neutron orbitals	Proton orbitals
$\frac{1}{2}^-[521]$	$\frac{7}{2}^-[523]$
$\frac{5}{2}^-[512]$	$\frac{1}{2}^+[411]$
$\frac{7}{2}^-[514]$	$\frac{7}{2}^+[404]$
$\frac{9}{2}^+[624]$	$\frac{9}{2}^-[514]$
$\frac{1}{2}^-[510]$	$\frac{5}{2}^+[402]$
$\frac{3}{2}^-[512]$	$\frac{3}{2}^+[402]$

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Four-Parameter Measurements of Isomeric Transitions in ^{252}Cf Fission Fragments*

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The γ rays emitted from 3 to 2000 nsec after spontaneous fission of ^{252}Cf have been studied in detail. Both fission fragments were stopped on Si detectors; a Ge detector was used to detect γ rays from the fragments on one Si detector. A time-to-amplitude converter was started on the fission-fragment signal and stopped on the γ-ray signal. For each event the two fission-fragment kinetic energies, the γ-ray energy, and the time delay were recorded. The data were then analyzed to obtain the energy, half-life, and intensity of each γ ray as well as the mass of the emitting fission fragment. Some 144 γ rays were so analyzed, corresponding to more than 80 isomeric states.

γ rays were observed from practically all masses. However, the intensity was concentrated in the mass regions near 96, 108, 134, and 146. The energy spectrum consisted of a group of γ rays below 500 keV and a group near 1300 keV. The high-energy group associated with masses 134 and 136 dominates the energy intensity after 50 nsec. A strong cascade from a 162-nsec isomeric state is assigned to $^{134}_{52}Te_{82}$, and a 3000-nsec isomeric state to $^{136}_{54}Xe_{82}$. Rotational cascades were not observed, in contradiction with earlier low-resolution work. The observed energies and half-lives can be accounted for by $E1$, $M1$, or $E2$ transitions, either allowed or K forbidden by a few units. The interpretation of these results is that the initially high spins of the fragments have less effect on the delayed γ rays than was previously thought.

Fragment kinetic energy distributions were obtained for fissions leading to the emission of a particular γ ray. The γ ray serves to restrict the events to those having a definite final isotope for one fragment. The average kinetic energy of such events is found to be slightly greater than the average for all fissions yielding the same mass.

I. INTRODUCTION

Fission fragments deexcite by first emitting neutrons and then γ rays. The bulk of the γ radiation has a half-life of the order of 10^{-11} sec.[1,2] A delayed[3] component in the time region of 50 nsec to 10 μsec after thermal-neutron-induced fission of ^{235}U was first observed by Maienschein *et al.*[4] Further measurements were made by Johansson[5] on γ rays from spontaneous fission of ^{252}Cf in the time range 10–300 nsec and by Popeko *et al.*[6] on ^{235}U fission from 10–70 nsec. Walton, Sund, and their collaborators[7-9] observed isomeric[10] γ rays with half-lives from 2 to 600 μsec following fission.

Johansson[5] measured the mass distribution of the γ rays for the time interval 30 to 70 nsec after fission and found it to be strongly peaked at certain masses. In these mass regions the fraction of the γ rays which were delayed was found to be surprisingly high. This high probability of populating isomeric states was attributed to the comparatively high initial spins of the fission fragments. These are neutron-rich nuclei which are normally inaccessible for study. The peaking of the intensity of delayed γ rays at certain masses is dependent on the nuclear structure of the fragments. Thus there are interesting features of the delayed γ rays deserving of further investigation.

In the present work the use of semiconductor detectors made it possible to measure the energies, intensities, and half-lives of individual γ rays and to determine the masses of the emitting fission fragments. The experiment covered the time range from 3 to 2000 nsec after fission.

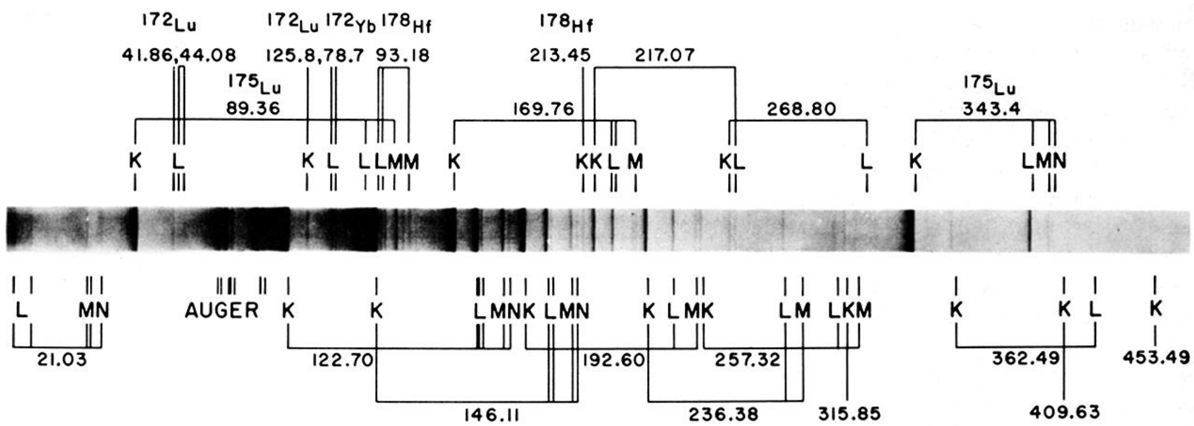

FIG. 3. Photographic plate showing conversion-electron energy spectrum of ^{179m_2}Hf. All lines are assigned to ^{179}Hf except those labeled otherwise.