New High-Spin Isomer ^{179m_2}Hf and Intraband Branchings in the Ground-State Rotational Sequence of ^{179}Hf

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(Received 11 December 1969)

A new high-spin isomer ^{179m_2}Hf has been produced by irradiation of isotopically enriched ^{176}Yb with α particles. To investigate its decay, Ge(Li) γ-ray spectra, Si(Li) conversion-electron spectra, and NaI(Tl)-Ge(Li) and Ge(Li)-Ge(Li) γ-γ coincidence spectra have been recorded. γ rays with energies 122.7, 146.2, 169.8, 192.8, 217.0, 236.6, 257.5, 268.9, 316.0, 362.6, 409.8, and 453.7 keV have been attributed to the decay of the isomer. These decay with a half-life of (29 ± 1) day. The coincidence measurements establish that the quanta with energies 122.7 through 236.6 keV are in cascade, while the γ rays with energies 268.9 through 453.7 keV represent crossover transitions within a rotational band with levels up to $I=\frac{21}{2}$ built on the ^{179}Hf ground state. The rotational-model quantity $(g_K-g_R)^2/Q_0^2$ has been derived from γ intensity measurements of the cascade and crossover transitions. It is constant within the experimental error for all members of the band. The values for the gyromagnetic ratios $g_K=-0.202\pm0.027$ and $g_R=0.160\pm0.014$ have been deduced.

I. INTRODUCTION

Long-lived isomeric states have been found in a number of isotopes in the Hf region. For the $N=106$ nuclei ^{176}Yb, ^{178}Hf, ^{180}W, ^{182}Os, and ^{184}Pt and the $Z=72$ nuclei ^{176}Hf, ^{178}Hf, and ^{180}Hf, low-energy $K^\pi=8^-$ two-quasiparticle states are known.[1,2] They have been interpreted as two-neutron or two-proton excitations with the Nilsson configurations[3] $\frac{7}{2}^+[514]n$, $\frac{9}{2}^+[624]n$ and $\frac{7}{2}^+[404]p$, $\frac{9}{2}^-[514]p$, respectively. In ^{178}Hf two 8^- states have been found with energies of 1147 and 1480 keV, respectively, It has been pointed out by Helmer and Reich[4] that both these states are mixtures of the cited configurations. In addition, these authors[4] report a long-lived isomer with $K\geq16$ in ^{178}Hf at an energy of about 2.5 MeV. The configuration of this isomeric state can be understood[4] as a coupling of the $K^\pi=8^-$ two-neutron and two-proton states to a four-qasusiparticle state.

K isomers in this mass region are not found only in even nuclei. For example, a three-quasiparticle state with $K^\pi=\frac{23}{2}^+$ at 1315 keV in ^{177}Hf is populated in the decay of the $K^\pi=\frac{23}{2}^-$ 161-day isomer in ^{177}Lu.[1] In this article we report a new isomer in ^{179}Hf, which probably is a three-quasiparticle state with $K^\pi=\frac{25}{2}^-$. This state populates the rotational band built on the $K=\frac{9}{2}^+[624]$ ground state of ^{179}Hf. Members of this band up to $I=\frac{21}{2}$ could be found. Crossover/cascade intensity ratios of transitions within this rotational sequence have been measured. From these ratios the rotational-model quantity $(g_K-g_R)^2/Q_0^2$ was derived and compared with the predictions of the adiabatic limit of the model.[5]

Preliminary reports of this investigation have been given previously.[6]

II. EXPERIMENTAL METHODS AND RESULTS

Two samples of ^{179m_2}Hf have been prepared by irradiation of ^{176}Yb with α particles, making use of the reaction ^{176}Yb$(\alpha,n)^{179}$Hf. The target was isotopically enriched in ^{176}Yb to 96%. In the first irradiation 5 mg of Yb_2O_3 was bombarded with 5000 μAh of 22-MeV α particles in the cyclotron of the Niels Bohr Institute. The second irradiation was done at the Brookhaven National Laboratory. Here, 100 mg of ^{176}Yb was bombarded for 4 h with 5μA of 33-MeV α particles. Both sources showed contaminations of ^{177}Lu and ^{175}Hf activity. In the second source, some of the long-lived ^{178m}Hf, first produced by Helmer and Reich[4] in a (n,γ) reaction, was present.

The Hf fractions were chemically separated from these samples in the following manner. The oxide was dissolved in concentrated HNO_3 and diluted to several ml with water. A small amount of a 0.04 M solution of α-thenoyl trifluoroacetone in benzene was used to extract the Hf from the Yb and other side products. The Hf was then back-extracted from the benzene with 2 N HF as the HfF_6^{-2} complex. This solution was evaporated in a platinum dish and the residue heated to burn off a remaining organic portion. The remainder was dissolved in concentrated HF. Sources for the γ-ray and conversion-electron studies were obtained by evaporation of the solution on a Mylar and plati-

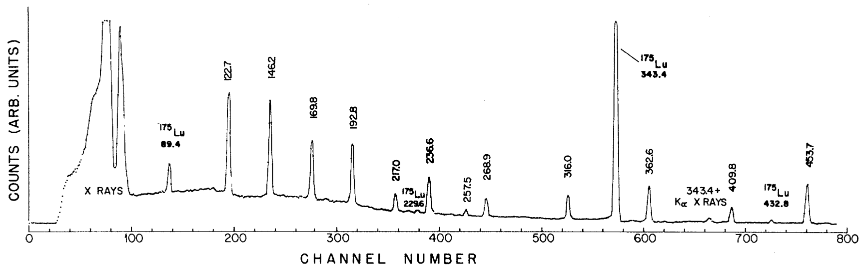

FIG. 1. Linear plot of a γ-ray spectrum of a chemically purified sample of ^{175}Hf and ^{179}Hf measured with a 25-cm^3 Ge(Li) detector. Energies are given in keV.

num backing, respectively.

A 25-cm^3 Ge(Li) detector with a resolution of 2.9 keV at 1.33 MeV was used to measure the γ-ray spectrum shown in Fig. 1. It was obtained from a source prepared by the first irradiation. All γ lines have been assigned to the ^{179m_2}Hf decay except the ^{175}Lu lines labeled in the plot.

The assignments have the following bases: The lowest excited members of the $\frac{9}{2}^+[624]$ ground-state rotational band of ^{179}Hf have been known previously from Coulomb-excitation work.[1,7] We identified the 122.7-, 146.2-, and 268.9-keV γ rays with transitions between these levels. Both by coincidence measurements and by following the decay of the lines, the assignments of the other transitions to the ^{179m_2}Hf decay could be established uniquely.

We have measured Ge(Li)-Ge(Li) and NaJ(Tl)-Ge(Li) γ-γ coincidence spectra with all the γ rays assigned to the decay of the isomer. Figures 2 and 3 show two examples of our Ge(Li)-Ge(Li) coincidence spectra. The coincidence measurements establish that the quanta with energies 122.7, 146.2, 169.8, 192.8, 217.0, and 236.6 keV are in cascade while the γ rays with energies 268.9, 316.0, 362.6, 409.8, and 453.7 keV represent crossover transitions within a rotational sequence with levels up to $I=\frac{21}{2}$ built on the $\frac{9}{2}^+[624]$ ground state of ^{179}Hf. The coincidence spectra shown in Figs. 2 and 3 show that the 257.5-keV γ ray populates the $I=\frac{19}{2}$ rotational state.

In order to determine the half-life of the isomeric state, γ-ray spectra as shown in Fig. 1 have been measured over a period of about two months. Following the decay of several ^{179}Hf lines, we obtain for the half-life $T_{1/2}=(29\pm1)$ day.

The decay scheme of the 29-day isomer ^{179m_2}Hf, which we propose on the basis of these data, is shown in Fig. 4.

The energies and relative intensities for the γ rays assigned to ^{179}Hf are listed in Table I. The energies were obtained either from spectra including a set of standard calibration sources or from spectra from sources of the second irradiation where the accurately measured ^{178}Hf energies[4] served as calibration lines. The peak positions were determined by a computer program and the positions of the calibration lines were fitted to a two-parameter function of the channel number.

The relative γ-ray intensities have been determined using sources from the two separate bombardments. The values agreed within less than 5%. The relative total transition intensities given in the last column of Table I have been calculated from the measured γ-ray intensities using the conversion coefficients tabulated by Hager and Seltzer[8] and the $E2$ admixtures for the $\Delta I=1$ transitions which were determined from the crossover/

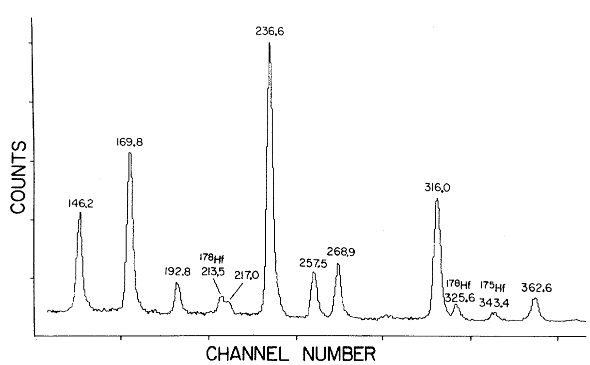

FIG. 2. 140–400-keV region of γ-γ coincidence spectrum employing two Ge(Li) detectors. Gate on 410 keV. Linear plot.

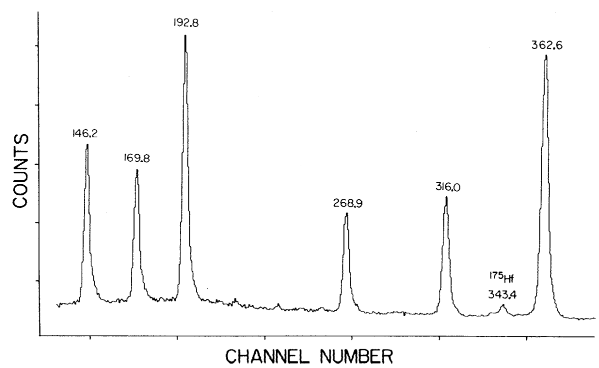

FIG. 3. 140–400-keV region of γ-γ coincidence spectrum employing two Ge(Li) detectors. Gate on 454 keV. Linear plot.

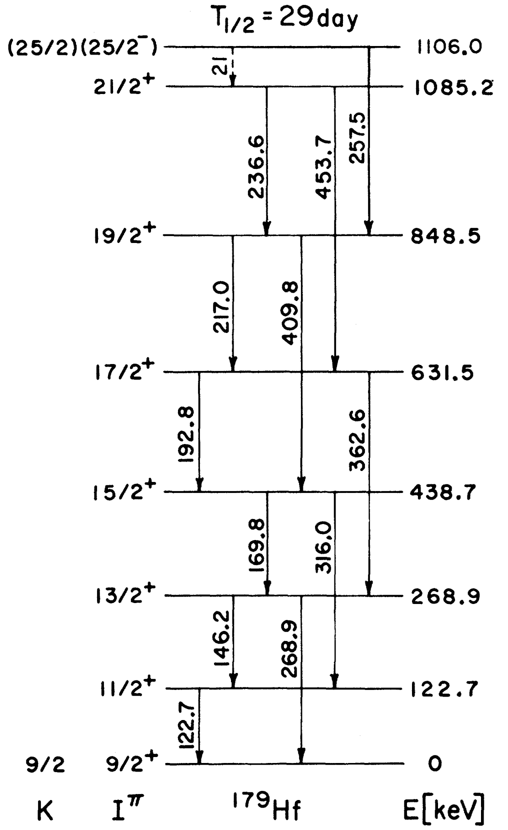

FIG. 4. Decay scheme of the 29-day isomer ^{179m_2}Hf.

cascade intensity ratios (see discussion below).

III. DISCUSSION

In Table II the balance of population and depopulation for the levels of the $\frac{9}{2}^+[624]$ band of ^{179}Hf is given. It can be seen that the isomeric state deexcites primarily to the $I=\frac{19}{2}$ and $I=\frac{21}{2}$ members of

TABLE I. Energies and relative intensities of transitions assigned to the decay of the 29-day isomer in ^{179}Hf.

E[keV]	$T\gamma$	T_{tot}
122.7 ±0.1	40.8 ±1.7	128
146.2 ±0.1	39.9 ±1.7	91.7
169.8 ±0.1	28.6 ±1.3	52.7
192.8 ±0.2	31.7 ±2.8	50.4
217.0 ±0.2	13.3 ±1.0	18.8
236.6 ±0.2	27.7 ±0.8	36.5
257.5 ±0.3	4.8 ±0.8	8.5[a]
268.9 ±0.2	16.6 ±1.0	18.4
316.0 ±0.2	29.9 ±0.5	31.8
362.6 ±0.2	58.4 ±1.3	60.2
409.8 ±0.3	31.7 ±0.8	32.0
453.7 ±0.3	100.0 ±3.9[b]	100[b]

[a]Assuming $E3$ multipolarity.
[b]Normalization.

TABLE II. Balance of population and depopulation for levels of the ground-state rotational band of ^{179}Hf derived from total relative transition intensities.

I	Population	Depopulation
$\frac{21}{2}$	?	137(6)
$\frac{19}{2}$	45.0(2.7)	50.8(2.9)
$\frac{17}{2}$	119(6)	111(7)
$\frac{15}{2}$	82.4(6.6)	84.5(3.8)
$\frac{13}{2}$	113(5)	110(5)
$\frac{11}{2}$	124(5)	128(6)

this band. This fact and its long half-life suggest a high K value for this state.

In the neighboring even nucleus ^{178}Hf two $K^{\pi}=8^-$ states with energies 1147 and 1480 keV are known.[1] It has been pointed out by Helmer and Reich,[4] who have studied the decay of the long-lived isomer with $K \geq 16$ in ^{178}Hf, that the absence of appreciable intraband $M1$ transition strength within the rotational band built on the 1147-keV $K^{\pi}=8^-$ state indicates that this state is a mixture of a two-proton state with the Nilsson[3] configuration $\frac{7}{2}^+[404]$, $\frac{9}{2}^-[514]$ and a two-neutron state with the configuration $\frac{9}{2}^+[624]$, $\frac{7}{2}^-[514]$, the former comprising about one-third of the 1147-keV state.[4]

In ^{179}Hf a three-quasiparticle configuration based on the odd neutron in the $\frac{9}{2}^+[624]$ ground state coupled to a $\frac{7}{2}^+[404]$ proton and a $\frac{9}{2}^-[514]$ proton could result in a state with $K^{\pi}=\frac{25}{2}^-$. This state would be analogous to the 1.1-sec isomer in ^{177}Hf at 1315 keV which has been interpreted[9] as a three-quasiparticle excitation arising from a coupling of the $\frac{7}{2}^-[514]$ odd neutron of ^{177}Hf to a proton pair in the $\frac{7}{2}^+[404]$ and $\frac{9}{2}^-[514]$ states forming a state with $K^{\pi}=\frac{23}{2}^+$.

If the spin and parity of the new isomer are $\frac{25}{2}^-$, the population of the ground-state rotational band of ^{179}Hf proceeds via $M2$ and $E3$ transitions to the $I=\frac{21}{2}$ and $I=\frac{19}{2}$ members, respectively. The energy of the $M2$ transition is very probably less than 255 keV, or another rotational level with $I=\frac{23}{2}$ would be populated by an $E1$ transition. This gives an energy range of 236 keV $< E <$ 491 keV for the $E3$ transition leading to the $I=\frac{19}{2}$ state.

From the conversion-electron spectrum, measured with a Si(Li) detector we derive a conversion coefficient for the 257.5-keV transition which is compatible with that of an $E3$ multipole radiation. It therefore very probably is the $E3$ isomeric transition and was placed between the isomer and the $I=\frac{19}{2}$ state in the decay scheme (Fig. 4).

If this interpretation is correct, the isomeric state would have an energy of 1106 keV and the isomeric $M2$ transition would have the energy 20.9 keV. Such a low-energy transition was below the limit of observation of the present experiment.

The $E3$ multipolarity assignment gives a relative intensity of $T_{tot} = 8.5 \pm 1.5$ units for the 257.5-keV transition. Using this value we obtain a population of 45 units for the $I = \frac{19}{2}$ rotational state (see Table II). Thus an approximate balance of population and depopulation is achieved for this state.

The partial lifetime for the assumed 20.9-keV $M2$ transition is about 45 days and for the 257.5-keV $E3$ transitions it is about 700 days. This corresponds to retardation factors of 7×10^{11} and 3×10^{10} for the $M2$ and $E3$ transitions, respectively. The degree of K forbiddenness[5] $\nu = \Delta K - L$ for the $M2$ and $E3$ transitions is $\nu = 6$ and 5, respectively. It has been found empirically that each degree of K forbiddenness for γ transitions in the region of deformed nuclei is associated with a hindrance factor of the order of 10–100. The quoted retardation factors for the isomeric transitions in ^{179}Hf fall into the upper part of this region. Such large retardation factors would be expected for transitions between states with relatively pure K quantum numbers.

We have tried to fit the energies of the rotational band built on the $\frac{9}{2}^+[624]$ ground state of ^{179}Hf to the simple second-order rotational form $E_I = AI(I+1) + BI^2(I+1)^2$. In Fig. 5, $(E_I - E_{I-1})/2I$ is plotted versus I^2. The dashed line indicates a fit to the two lower states which results in $A = 10.9$ keV and $B = 3.8$ eV. The measured points deviate markedly from the predicted straight line. A much better fit is obtained if one includes a term with alternating sign. Just as for the analogous band in ^{177}Hf, this could be attributed to rotation-particle coupling[10] for the $K = \frac{9}{2}$ band in ^{179}Hf. However, in the case of the $\frac{9}{2}^+[624]$ band in ^{177}Hf, the band-mixing calculations which reproduced the experimentally observed energy levels[10] did not give the right results for the $E2/M1$ mixing ratios $\delta^2 = T_\gamma(E2)/T_\gamma(M1)$ for the cascade transitions in this band.[11] Furthermore, it has been pointed out by Mottelson[12] that theoretical estimates of the expected deviations of the mixing ratios of intraband transitions from the adiabatic-rotational-model[5] predictions come out to be at most about 1% in the low-lying states of a rotational band. Therefore it might be interesting to derive the $E2/M1$ mixing ratios for the $\Delta I = 1$ transitions in the $\frac{9}{2}^+[624]$ band in ^{179}Hf from experimental crossover/cascade intensity ratios λ.

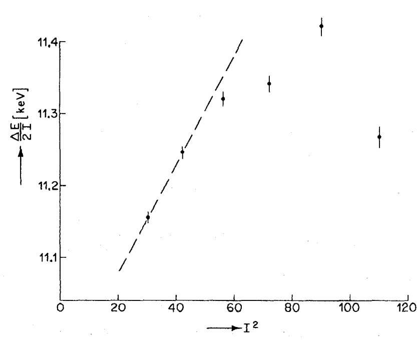

FIG. 5. Fit of rotational energies of the $\frac{9}{2}^+[624]$ band in ^{179}Hf to $E_I = AI(I+1) + BI^2(I+1)^2$.

Provided that the $E2$ transition probabilities $T_\gamma(E2)$ within the band are well described by the rotational model, the $E2/M1$ mixing ratios can be derived from

$$\lambda = \frac{T_\gamma(E2, \Delta I = 2)\,\delta^2}{T_\gamma(E2, \Delta I = 1)\,(1+\delta^2)}\,.$$

For an unperturbed band, δ^2 is related to the I-independent gyromagnetic factors for the independent particle and collective motion, g_K and g_R, respectively, and the intrinsic quadrupole moment Q_0 by (for $K \neq \frac{1}{2}$)

$$\frac{1}{\delta^2} = \frac{2.87 \times 10^5 (2I+2)(2I-2)}{E^2\,(\mathrm{keV}^2)}\,\frac{(g_K - g_R)^2}{{Q_0}^2}\,.$$

In Table III we give the mixing ratios δ^2 and the quantity $(g_K - g_R)^2/{Q_0}^2$ for five transitions, $I \to I-1$, within the $\frac{9}{2}^+[624]$ band of ^{179}Hf. It can be seen from Fig. 6, where we have plotted $(g_K - g_R)^2/{Q_0}^2$ versus the spin I, that this quantity is constant within the limits of error for the investigated transitions in the band, as predicted by the simple rotational model. The situation is essentially the same as for the $K = \frac{9}{2}$ band in ^{177}Hf where also the energies vary from the model predictions, whereas for the $E2/M1$ mixing ratios no deviations can be found.[10, 11]

From[7] Coulomb-excitation measurements, $Q_0 = (6.85 \pm 0.18) \times 10^{-24}$ cm^2 has been found for the ground-state band in ^{179}Hf. Combining this result

TABLE III. Experimental ratios λ between crossover $I \to I-2$ and cascade $I \to I-1$ transitions, $E2/M1$ mixing ratios δ^2 of transitions $I \to I-1$, and rotational-model parameters $(g_K - g_R)^2/Q_0^2$ for the $\frac{9}{2}^+[624]$ band in ^{179}Hf.

I	λ	δ^2	$(g_K-g_R)^2/Q_0^2$
$\frac{13}{2}$	0.416(35)	0.146(12)	$3.08(27) \times 10^{-3}$
$\frac{15}{2}$	1.045(45)	0.166(7)	$2.75(13) \times 10^{-3}$
$\frac{17}{2}$	1.84(18)	0.173(17)	$2.62(26) \times 10^{-3}$
$\frac{19}{2}$	2.37(18)	0.153(15)	$3.01(31) \times 10^{-3}$
$\frac{21}{2}$	3.61(20)	0.163(9)	$2.75(16) \times 10^{-3}$

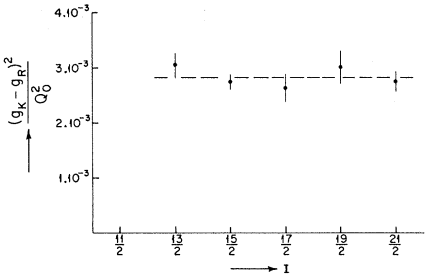

FIG. 6. Rotational-model parameter $(g_K-g_R)^2/Q_0^2$ determined from crossover/cascade intensity ratios of γ transitions within the $\frac{9}{2}^+[624]$ band of ^{179}Hf.

with the average value for $(g_K-g_R)^2/Q_0^2$ from our measurements we obtain $|g_K-g_R| = 0.363 \pm 0.011$. This value is in agreement with the value $g_K-g_R = -0.385 \pm 0.012$ derived from angular-correlation and conversion-electron studies[11] of the $\frac{9}{2}^+[624]$ band in ^{177}Hf.

We apply the procedure described in Ref. 11 to obtain the magnetic moment of the ground state of ^{179}Hf, $\mu = -(0.611 \pm 0.017)\mu_N$, and can now calculate g_K and g_R separately:

$$g_K = -0.202 \pm 0.027,$$

$$g_R = 0.160 \pm 0.014\,.$$

These values are in agreement with those[11] for the $\frac{9}{2}^+[624]$ band of ^{177}Hf. They can be compared with theoretical predictions. g_K can be calculated within the framework of the Nilsson model[3,13] using an effective spin g factor of $g_s^{\rm eff} = (0.57 \pm 0.09)g_s^{\rm free}$. This value is in agreement with the general trend of effective spin g factors in the region of deformed nuclei.[14]

Values of $g_R = 0.12$ and 0.14 have been predicted by Prior, Boehm, and Nilsson[15] for the $\frac{9}{2}^+[624]$ state in ^{179}Hf, which is in good agreement with our experimental value.

ACKNOWLEDGMENTS

One of us (R.A.N.) would like to express his appreciation to Professor Aage Bohr and the other members of the Niels Bohr Institute for the many kindnesses and warm hospitality received during a one-year stay in Copenhagen, where he first participated in this investigation.

We wish to thank Dr. P. K. Hopke and R. Johnson who have assisted us with these experiments.

†Work supported partially by the U.S. Atomic Energy Commission.

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