481 (1969).

[16] C. M. Shakin and M. S. Weiss, Phys. Rev. (to be published).

[17] B. Buck and F. G. Perey, Phys. Rev. Lett. 8, 444 (1962).

[18] J. C. Hafele, Phys. Rev. 159, 996 (1967).

[19] H. W. Newson, private communication; J. L. Fowler, Phys. Rev. 147, 870 (1966).

STUDY OF NUCLEAR STATES OF SEVERAL ODD-A NUCLEI $68 \leq Z \leq 79$ THROUGH ELECTROMAGNETIC EXCITATION FROM 2.3 TO 3.6 MeV†

W. T. K. Johnson*‡ and B. T. Chertok*
The American University, Washington, D. C. 20016

and

C. E. Dick
National Bureau of Standards, Washington, D. C. 20234

(Received 23 June 1970)

34 excited states have been studied between 2.3 and 3.5 MeV in ^{167}Er, ^{179}Hf, ^{191}Ir, and ^{197}Au by observing the decay of the isomeric levels in these nuclei following electron and photon activation. 28 of these states are observed for the first time. Of the 34 observed transitions, $M1+E2$ multipolarity assignment is made to 20, two are identified as $E0$ transitions, and one is assigned $E1$ multipolarity. Accurate values for the isomeric half-lives are also presented.

Measurements reported here provide the first systematic investigation of states by inelastic electron scattering and photoexcitation from 2.3 to 3.6 MeV in the region $Z=68$ to 79. Further, the method employing the electromagnetic interaction yields the multipolarity and radiative strength of the transition which will provide important confirmation of quantum numbers, determined by nuclear reactions such as (d,p) and (d,t). Coulomb excitation measurements in this nuclear structure region have only explored states up to ~1.5 MeV. Finally, the use both of electron and of photon excitation allows a search for electric monopole ($E0$) transitions which are, of course, forbidden for photons. $E0$ transitions had not been observed in the region explored prior to the present work.

The sytematic study of radiative-transition probabilities has helped delineate the regions of applicability of various nuclear models. The Nilsson model, with additions such as pair correlation and quasiparticle-phonon interactions, has had some success in describing low-lying states, below 1.5 MeV, in deformed nuclei.[1] Pertinent to this investigation the strength of $M1$ γ rays (4 MeV $< E_\gamma <$ 9 MeV), following neutron capture by deformed nuclei, has been quantitatively explained by a calculation employing pairing and spin-spin effects, together with the standard Nilsson Hamiltonian.[2] In the transition region $76<Z<82$ the model of de-Shalit[3] for odd-A nuclei, where the odd nucleon is weakly coupled to excitations of the even-even core, has met with good success in predicting electromagnetic moments and transition probabilities for low-lying states, <0.8 MeV in several nuclei.[4,5]

The experimental method dictated investigation of only stable nuclei with low-lying isomeric states. Accordingly, the odd-A nuclei $^{167}_{68}\mathrm{Er}_{99}$, $^{179}_{72}\mathrm{Hf}_{107}$, $^{183}_{74}\mathrm{W}_{109}$, $^{191}_{77}\mathrm{Ir}_{114}$, and $^{197}_{79}\mathrm{Au}_{118}$ were investigated with electrons and bremsstrahlung from the National Bureau of Standards' 4-MeV electron Van de Graaff. All but ^{183}W had sufficient cross sections for study. Targets of natural isotopic abundance, in the thickness ranges of ~5g/cm^2 for photoexcitation and ~18 mg/cm^2 for electroexcitation, were placed in a fast shuttle to transport them from the irradiation position to the counting position without a significant decay of the 2- to 20-sec isomeric states. The excitation functions were measured by incrementing the bombarding energy and measuring the subsequent isomeric decays with NaI(Tl) scintillators. A state was identified by comparing the two curves produced where a break corresponded to a new higher-lying state populating the isomer.[6] This method is shown in detail for a 200-keV portion of ^{179}Hf excitation in Fig. 1. The photoexcitation yield curve corresponded to a series of straight lines produced by the intermediate-thickness bremsstrahlung target (0.001 in. platinum, backed by 1 in. water). The elec-

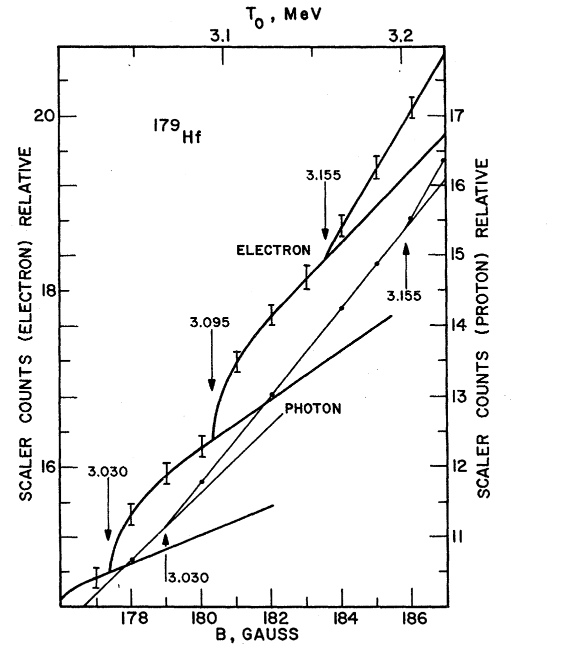

FIG. 1. The electron and photon yield curves correspond to a superposition of isochromat excitation functions and a series of straight lines, respectively. The isomer radioactivity is plotted versus incident electron energy. The corresponding break in the photon curve occurred about 40 keV above the state because of energy losses in the bremsstrahlung target. The absence of a measurable photon cross section for the 3.095-MeV state led to assignment that the multipolarity of the transition to this state from the ground state was $E0$.

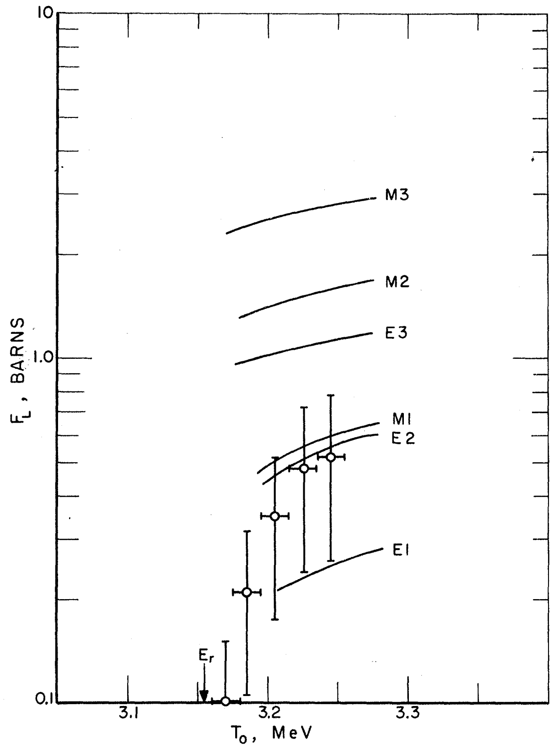

FIG. 2. For the 3.155-MeV state in ^{179}Hf the ratio of electron to photon activation given in Eq. (1) is plotted, where the points are taken from a best-fit line through the data. The large error bars are mainly due to inaccuracies in the stripping method. The lines are theoretical F_L computed from the Duke inelastic electron scattering program. An $M1+E2$ transition is assigned to this state.

troexcitation yield curve is characterized by a superposition of thin-target isochromat excitation functions. The photon flux $N(k)$ for the target geometry has been measured by Booth and Brownson, and Alston, Wilson, and Booth.[7] As discussed earlier,[8] the multipolarity of a transition is determined by the ratio of the electron to photon cross sections,

$$F_L(E_0,k)=\frac{\sigma_{\mathrm{iso},e}}{\int\sigma_{\mathrm{iso},\gamma}dE}\,\frac{\lambda^2m_0c^2}{4}, \qquad (1)$$

where the $F_L(E_0,k)$ are defined by Robl[9] for incident energy E_0 and excitation energy k in a plane-wave calculation of electroexcitation. Specifically for electrons,

$$\sigma_{\mathrm{iso},e}\equiv\sigma_{e,e'}\,\Gamma_{\mathrm{iso}}/\Gamma=F_L(E_0,k)(g\Gamma_0/m_0c^2)\times\Gamma_{\mathrm{iso}}/\Gamma, \qquad (2)$$

where $\Gamma_{\mathrm{iso}}/\Gamma$ is the ratio of de-excitation through the isomer to total de-excitation and Γ_0 is the width of the state. For photons,

$$\int\sigma_{\mathrm{iso},\gamma}dE\equiv(\Gamma_{\mathrm{iso}}/\Gamma)\int\sigma_\gamma dE=(\lambda^2/4)g\Gamma_0\Gamma_{\mathrm{iso}}/\Gamma. \qquad (3)$$

The theoretical F_L is given by a partial-wave-analysis calculation of inelastic electron scattering in the distorted-wave Born approximation developed by the Duke University group.[8,10]

Twenty-eight new excited states are observed in the four nuclei. Typical of the 21 states for which F_L's could be compared is that shown in Fig. 2 for the 3.155-MeV state in ^{179}Hf. Although this method is capable of determining mixing ratios,[8] the errors in F_L do not allow that here.

The absolute cross sections were determined by measuring the NaI(Tl) crystal spectrometer efficiencies with standardized γ-ray sources and computing the number of isomer decays observed per count using decay-scheme data obtained from Lederer, Hollander, and Perlman.[11] The electron beam energy was calibrated to ±3 keV with

Table I. Measured states with photon and electron cross sections and multipolarity assignment of the upward transitions.

	E_r (±.015) (MeV)	$g\Gamma_0\Gamma_{iso}/\Gamma$ (±25%)[a] (eV)	$\sigma_{iso,e}$(at $1.05E_r$) 10^{-32} cm^2 (±40%)[a]	Assignment
^{167}Er	2.320	b	3.9	c
	2.530	0.013	4.3	M1 + E2
	2.725	0.026	5.6	M1 + E2
	2.950	0.040	6.5[d]	M1 + E2
	3.080	0.073	16.	M1 + E2
	3.255	0.054	10.[e]	M1 + E2
	3.355	0.076	19.	M1 + E2
	3.475	b	f	c
^{179}Hf	2.310	f	g	c
	2.390	0.0028	g	c
	2.480	0.0025	0.95[e]	M1 + E2
	2.565	0.0021	1.0[d]	M1 + E2
	2.640	0.0064	f	c
	2.705	0.0046	1.3	M1 + E2
	2.850	h	0.5[i]	E0
	2.930	f	f	c
	3.030	0.0082	h	c
	3.095	h	0.9[i]	E0
	3.155	0.0086	1.0	M1 + E2
	3.240	0.014	1.5[e]	M1 + E2
	3.360	0.019	3.0	M1 + E2
	3.490	0.020	g	c
^{191}Ir	2.500	0.014	2.4	M1 + E2
	2.845	0.016	5.6	M1 + E2
	3.070	0.019	4.2	M1 + E2
	3.250	f	f	c
	3.400	0.027	g	c
^{197}Au	2.405	0.00057	g	c
	2.620	0.0027	0.5	M1 + E2
	2.880	0.0052	0.81	M1 + E2
	3.025	0.012	0.95	M1 + E2
	3.175	0.012	0.72[e]	E1
	3.260	0.020	1.6	M1 + E2
	3.515	0.031	2.2	M1 + E2

[a] Error mainly due to uncertainty in stripping.
[b] Insufficient overlap to observe state with photons.
[c] No assignment made.
[d] At $1.04E_r$.
[e] At $1.03E_r$.
[f] Observed, but too close to next state to measure, or poor data.
[g] Insufficient overlap to observe state with electrons.
[h] Not observed—see text.
[i] At $1.02E_r$.

two photonuclear reactions and reproducible by means of a slit system with magnetic analysis. The excited-state energies were uncertain to ±15 keV, primarily because of the difficulty in stripping the individual contributions, especially near threshold.

Table I summarizes the results for the 34 states observed in the four nuclei. Six of the observed states have been previously identified in ^{167}Er and ^{179}Hf by (d,p) reactions.[12,13] The multipolarity assignments are based on this experiment as can be seen, for example, in Fig. 2; secondary support comes from comparison of the Weisskopf ratios with known electromagnetic strengths. To deduce Γ_0 from Eq. (3) for the latter comparison, a limit of $0.005 < \Gamma_{iso}/\Gamma < 0.05$ was placed, which is plausible but by no means certain.[7] Only one state for which the F_L's could be calculated was thought to be other than $M1+E2$; this was the 3.175-MeV state in ^{197}Au for which an $E1$ assignment is made. Two other states at 2.850 and 3.095 MeV in ^{179}Hf were observed with electrons and not with photons. The possibility of these being either $E1$ or $E3$ transitions was rejected, leaving $E0$ as the tentative assignment. A width of ~10^{-5} eV was calculated for these states from a monopole plane-wave Born-approximation calculation[14] with an assumed factor of 10 distortion and $\Gamma_{\mathrm{iso}}/\Gamma = 0.05$.

For the 20 ($M1+E2$) transitions, even parity can be assigned to the excited states since the ground states are $\frac{7}{2}^+$, $\frac{9}{2}^+$, $\frac{3}{2}^+$, and $\frac{3}{2}^+$ for ^{167}Er, ^{179}Hf, ^{191}Ir, and ^{197}Au, respectively. Since we observe a product of a transition probability up to and cascade probability down to the isomer, the angular momenta can be limited to $|J_f - J_i| \leq L$, i.e., $\frac{3}{2}^+$ to $\frac{11}{2}^+$ in ^{167}Er, for example.

Because of the singular decay mode and low background, the half-lives of the isomers could be measured to one standard deviation, ≈1%. The results for the half-lives are ^{167m}Er, 2.28 ± 0.03 sec; ^{179m}Hf, 18.77 ± 0.08 sec; ^{191m}Ir, 4.88 ± 0.04 sec; and ^{197m}Au, 7.85 ± 0.04 sec.

These results of Table I show that this method of electron and photon excitation provides a means of determining electromagnetic multipolarities in a heretofore unexplored region. When nuclear-reaction studies are performed in this region, our results will help in the eventual assignment of J^π and K quantum numbers to the individual states. However, the method is restricted to nuclei with isomers, but can be extended to lower energies[15] and, with improved techniques, up to about 5 MeV.

It is not possible to make detailed comparisons of our results with the extended Nilsson model because the isomer-activation method selects only states with finite $B(\uparrow)\Gamma_{\mathrm{iso}}/\Gamma$. Instead, we have taken the extrema for the 20 ($M1+E2$) transitions to compare with theory. If it is assumed that these states are pure $M1$, the enhancement of the radiative widths over the Weisskopf limit ranges from 1 to 10. Shapiro and Emery have calculated the $M1$ transition probabilities in deformed nuclei using an intrinsic Hamiltonian consisting of the Nilsson terms plus pairing and spi spin-spin interactions.[2] They compute radiative strengths 10 to 20 times the single-particle estimates using renormalized values of the g factor. For the other limit we compute $B(E2)$, assuming the observed transitions are pure $E2$, by summing up all the strengths for each nucleus. The results are: $B(E2)_{\mathrm{core}} = 15\times10^4$ for ^{167}Er, 4.7×10^4 for ^{179}Hf, 4.1×10^4 for ^{191}Ir, and 4.4×10^4 for ^{197}A ^{197}Au, where the units are fm^4. The weak-coupling core-excitation model appears to be valid in ^{191}Ir and ^{197}Au, where it was tested up to 0.8 MeV excitation. For these nuclei the $d_{3/2}$ odd proton can be coupled to 2^+ excitations of the even-even cores, $^{190}_{76}$Os and $^{196}_{78}$Pt, respectively. Accordingly, measurements of the $B(E2)$ strengths between 2.9 and 3.5 MeV in ^{190}Os and ^{196}Pt could decide whether or not the weak-coupling model is valid for $E > 2$ MeV in the transition region.

Since the method is very selective in the states observed, the states will probably be in two or three rotational bands in the deformed nuclei ^{167}Er and ^{179}Hf. The appearance of two closely spaced $E0$ transitions in ^{179}Hf at 2.850 and 3.095 MeV is an intriguing problem for theorists. Related to this point, in a fuller version of this work to be published, experimental evidence for an abrupt change in the mode of excitation at 2.85 MeV in ^{179}Hf will be presented.

We are grateful to Dr. Carl Hammer of the Univac Corporation, Washington, D. C., for making computer time available on the Univac 1108 Computer.

---

†Research supported in part by the National Science Foundation.

*Guest workers, National Bureau of Standards.

‡U. S. Atomic Energy Commission Laboratory Graduate Fellow. This work forms a part of the Ph.D. dissertation submitted by W. T. K. Johnson to the College of Arts and Sciences of The American University. Present address: The Rand Corporation, Santa Monica, Calif. 90406.

[1] W. Michaelis *et al.*, to be published.

[2] C. S. Shapiro and G. T. Emery, Phys. Rev. Lett. 23, 244 (1969).

[3] A. de-Shalit, Phys. Rev. 122, 1530 (1961).

[4] A. Braunstein and A. de-Shalit, Phys. Rev. Lett. 1, 264 (1962).

[5] R. Avida, J. Burde, and A. Molchadski, Phys. Rev. Lett. 21, 441 (1968).

[6] G. B. Collins, E. M. Stubblefield, and M. Goldhaber, Phys. Rev. A 55, 1129 (1939).

[7] E. C. Booth and J. Brownson, Nucl. Phys. A 98, 529 (1967); W. J. Alston, H. H. Wilson, and E. C. Booth, Nucl. Phys. A 116, 281 (1968).

[8] B. T. Chertok and W. T. K. Johnson, Phys. Rev. 174, 1524 (1968).

[9] H. Robl, Nucl. Phys. 2, 641 (1956).

[10] S. Tuan, L. Wright, and D. Onley, Nucl. Instrum. Methods 60, 70 (1968).

[11] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1967), 6th ed.

[12] R. A. Harlan and R. K. Sheline, Phys. Rev. 168, 1373 (1968).

[13] M. N. Vergnes and R. K. Sheline, Phys. Rev. 132, 1736 (1963).

[14] See Appendix of Ref. 8 for a treatment of the $E0$ electron cross section.

[15] Y. Cauchois, private communication.