Anomalous L-Subshell Conversion Coefficients of the Highly K-Forbidden $E1$ Transition in Hf^{180m} (5.5 h)*

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The extremely K-forbidden $E1$ transition ($8- \rightarrow 8+$) of 57.5 keV in Hf^{180m} was long known to have an anomalously high (L_I+L_{II}) conversion coefficient. In order to resolve these two lines, the electrons emitted from an evaporated Hf_2O_3 source of $\sim$50-μg/cm² thickness were analyzed in a double-focusing spectrometer. The values found for the conversion coefficients in the three different L subshells are $\epsilon_{L_I}=0.308\pm0.025$; $\epsilon_{L_{II}}=0.067\pm0.010$; $\epsilon_{L_{III}}=0.055\pm0.010$, as compared with Rose's theoretical values $\alpha_1(L_I)=0.108$; $\alpha_1(L_{II})=0.047$; $\alpha_1(L_{III})=0.062$. No admixture of $M2$ or $E3$ components fits the experimental results. Of the two explanations for the anomaly considered, namely penetration effects and parity mixing, the second was excluded by the lack of circular polarization of the 57.5-keV γ rays (Bock, Jenschke, and Schopper; and Paul, McKeown, and Scharff-Goldhaber), while the first is compatible with our results. For the $8- \rightarrow 6+$ transition of 501.5 keV, more precise values of the branching ratio, energy, and K-conversion coefficient are obtained. Its L conversion coefficients have been measured. The results are compatible with the mixing ratio reported by Bodenstedt *et al.*: 3.5%$M2$+96.5%$E3$. The $(L_I+L_{II})/L_{III}$ ratio of the 93.3-keV $E2$ transition is found to be somwehat lower than the values reported by other authors, but still anomalously high (1.28±0.03, compared to the theoretical ratio of 1.11). A search for the 834-keV $8- \rightarrow 4+$ transition yielded an upper limit of 2×10^{-5} per decay. The capture cross section of Hf^{179} for thermal neutrons leading to the activation of Hf^{180m} is found to be σ_{act}, $Hf^{179}{}_{th}=0.34\pm0.03b$. The analysis of the resulting isomeric ratio $\sigma(Hf^{180m})/\sigma_{tot}=0.52\%$ leads to the conclusion that the spin of the capturing state for thermal neutrons in Hf^{180} is predominantly 5.

I. INTRODUCTION

THE nucleus Hf^{180} occupies a somewhat unique position in the history of the unified model of the nucleus: An activity with a half-life of $\sim$6 h was first observed by Muehlhause in Hf bombarded with neutrons from a reactor. Burson, Blair, Keller, and Wexler[1] using as targets HfO_2 enriched in various Hf isotopes which had just become available, were able to ascribe this activity to Hf^{180m} (5.5 h). They observed conversion electrons of five transitions with energies of 56.8, 93.2, 214.0, 330.4, and 442.0 keV and found some evidence showing that the two highest energy transitions are in cascade. They further pointed out that the 93.2-keV transition may be identical with a 92-keV transition found in the Ta^{180} decay following K capture and, if so, it probably proceeds to the ground state of Hf^{180}. Der Mateosian and Goldhaber[2] found that probably all four higher energy γ-rays are in cascade and pointed out that, since the 92-keV transition in Ta^{180} is $E2$, the cascade appears to terminate with an $E2$ transition.

Bohr and Mottelson[3] made brilliant use of this information by showing that *if these four transitions take place in the order of decreasing energy*, the Hf^{180} level scheme formed the most striking confirmation of the existence of rotational bands in even-even nuclei. Such a band was expected to have a spin sequence 0, 2, 4, 6, 8, $\cdots$, and level energies $E\propto I(I+1)$. In addition, they suggested that the isomeric transition in Hf^{180m}, because of the long half-life, must be at least octupole and hence the spin of the isomeric state ≥ 11.

Their assumption of four $E2$ transitions in cascade proceeding from spin 8 to 0 was confirmed by γ-intensity, conversion-electron, and angular-correlation measurements.[4,5] Later, lifetime measurements of the two lowest-energy transitions[6] and information showing that the 442.0-keV transition precedes the other three transitions confirmed the sequence postulated by Bohr and Mottelson. Meanwhile Alaga, Alder, Bohr, and Mottelson[7] showed that in an axially symmetric nucleus, the component K of the total angular momentum along the axis of symmetry, is a good quantum number and proposed the "K selection rule," both for electromagnetic and beta transitions: $\Delta K - l \leq 0$, where l is the multipole order of the transition. They pointed out that this selection rule would be strictly obeyed only if the wave functions for each band were quite pure. While the selection rules involving the angular momentum I and the parity π were rigorous, "K-forbidden" transitions could take place but would be retarded. The retardation should increase with the degree of K forbiddenness $\nu=\Delta K - l$.

As an example of an electromagnetic transition with a high degree of K forbiddenness the case of the 57.5-

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[1] S. B. Burson, K. W. Blair, H. B. Keller, and S. Wexler, Phys. Rev. **83**, 62 (1951).

[2] E. der Mateosian and M. Goldhaber (unpublished). See also M. Goldhaber and R. D. Hill, Rev. Mod. Phys. **24**, 179 (1952).

[3] A. Bohr and B. R. Mottelson, Phys. Rev. **90**, 717 (1953).

[4] J. W. Mihelich, G. Scharff-Goldhaber, and M. McKeown, Phys. Rev. **94**, A794 (1954).

[5] J. W. Mihelich, G. Scharff-Goldhaber, and M. McKeown, Bull. Am. Phys. Soc. **1**, 206 (1956). See also private communications quoted in Ref. 10 and *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Acadamy of Sciences—National Research Council, Washington 25, D. C.,) NRC 6-6-125.

[6] A. W. Sunyar, Phys. Rev. **98**, 653 (1955) (2+ state); A. C. Li and A. Schwarzschild, *ibid.* **129**, 2664 (1963) (4+ state).

[7] G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **29**, No. 9 (1955).

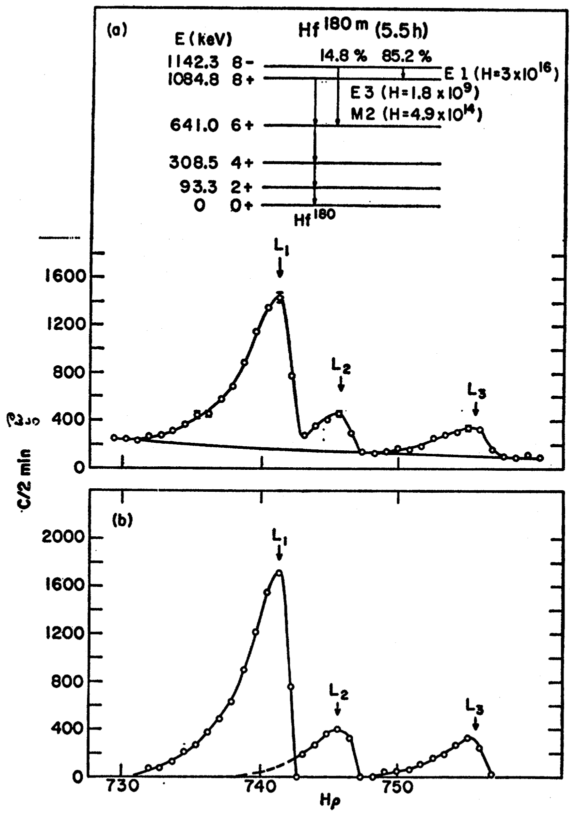

FIG. 1 (a) Spectrum of L-conversion-electron lines of 57.5-keV transition from Hf^{180m} before correction for background and decay. The spectrum was obtained with a double-focusing spectrometer. The insert shows the decay scheme of Hf^{180m}. (b) Average spectrum of 5 runs of the type shown in (a). Each run was individually corrected for background and decay.

keV isomeric transition in Hf^{180m} was discussed: It was suggested that if, e.g., it were $M2$, proceeding from a 10− to the 8+ state of the ($K=0$) rotational band, its retardation of $\sim 10^9$ would not seem excessive. However, a determination[5] of the multipole order of this transition from the intensities of its L-conversion electron lines obtained with a 180° magnetic spectrograph showed that the transition was predominantly $E1$ and hence forbidden by the extraordinarily large factor of $\sim 10^{15}$.[8] The L_I conversion coefficient was found to be anomalously high while the L_{II} and L_{III} conversion coefficients were compatible with the theoretical values within the fairly large limits of error. Two other groups, Gvozdev *et al.*[9] and Edwards and Boehm,[10] measured the subshell ratio $I_{L_I+L_{II}}/I_{L_{III}}$, and found it in agreement with these findings. A possible $M2$ and $E3$ admixture could not explain the anomaly.[10] Since Edwards and Boehm determined very precise γ-ray energies with a curved crystal spectrometer, we shall from here on use their values.

Deutsch and Bauer[11] measured the angular correlation of the 57.5-keV transition with the subsequent $E2$ transitions and concluded that the spin of the isomeric state was 8. This assignment was confirmed by Koički *et al.*,[12] who deduced from their angular-correlation results a 99.84% $E1$+0.16% $M2$ mixture.

A second transition, of $\sim$501 keV, originating from the isomeric state and populating the 6+ state of the rotational band with a branching ratio of $\sim$20%, was also found,[5] determining the location of the 443.8-keV transition in the cascade. A preliminary study of its K and L conversion coefficients by means of an intermediate image spectrometer showed it to be predominantly $E3$, indicating that this transition is retarded by a factor of $\sim 10^9$. Gvozdev *et al.*[9] essentially confirmed these results, assigning an energy of 501.2 keV and a branching ratio of $\sim$15% to this transition. Bodenstedt *et al.*[13] measured the angular correlation of the 501-keV transition with the 332.5 (6+ → 4+) transition, confirming the assignment 8− for the isomeric state. Their results for A_2 and A_4 are compatible only with the mixing ratio: $(3.5\pm0.5)\%$ $M2$ and $(96.5\pm0.5)\%$ $E3$; $\delta<0$. Essentially identical results on spin sequence and multipole mixture were obtained by Koički *et al.*[12]

A search for the 8− → 4+ transition of 834 keV was also carried out by these latter authors and an upper limit of 2×10^{-4} deduced for the branching ratio.

Gallagher and Nielsen[14] suggested that the isomeric 8− state is formed by promoting one proton of a proton pair from the $\frac{7}{2}$+ state [404↓] to the $\frac{9}{2}$− state [514↓].

The advent of the current-current theory of weak interactions[15] suggested the possibility that the π selection rule may also be violated to a very small degree in electromagnetic transitions. This made a more precise measurement of the anomalous conversion coefficients of the 57.5-keV 8− → 8+ transition appear worthwhile, since the possibility of an 8+ state ($K=8$) lying close to the 8−($K=8$) state, giving rise to a small amount of $M1$ admixture, cannot *a priori* be excluded (e.g., a two-neutron state $\frac{9}{2}$−[505↓] $\frac{7}{2}$−[514↓]).

TABLE I. Relative L-subshell conversion coefficients for the 57.5-keV isomeric transition in Hf^{180m}.

		Theoretical (El)	
	Experimental	Rose	Sliv
L_I	1	1	1
L_{II}	0.218±0.030	0.435	0.453
L_{III}	0.181±0.028	0.573	0.550

[8] A more accurate computation yields a retardation factor of 3×10^{16} (see Table V).
[9] V. S. Gvozdev. L. I. Rusinov, Yu. I. Filimonov, and Yu. L. Khazov, Nucl. Phys. **6**, 561 (1958).
[10] W. F. Edwards and F. Boehm, Phys. Rev. **121**, 1499 (1961).
[11] M. Deutsch and R. W. Bauer, Nucl. Phys. **21**, 128 (1960).
[12] S. D. Koički, A. H. Kukoč, M. P. Radojević, and J. M. Simić, Bull. Inst. Nucl. Sci. "Boris Kidrich" (Belgrade) **13**, No. 3, 1 (1962).
[13] E. Bodenstedt, H. J. Körner, E. Gerdau, J. Radeloff, C. Günther, and G. Strube, Z. Physik **165**, 57 (1961).
[14] C. J. Gallagher, Jr. and H. L. Nielsen, Phys. Rev. **126**, 1520 (1962).
[15] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).

TABLE II. Comparison of results of present work with previous results on the L-subshell conversion coefficients of the 57.5-keV transition.

	Ref. 9	Ref. 10	Present work	Theor. ($E1$) (Rose)
$L_{III}/(L_I+L_{II})$	$\sim$0.25	0.182±0.036	0.158±0.025	0.390

II. EXPERIMENTAL METHODS AND RESULTS

A. L-Subshell Conversion Coefficients of the 57.5-keV Transition

For this measurement we used Hf_2O_3 evaporated in an electron-beam evaporator. The source thickness was $\sim$50 μg/cm^2 and the backing was a very pure Al foil 1.7-mg/cm^2 thick. The target was bombarded in the Brookhaven graphite reactor for more than one half-life of Hf^{180m} (5.5 h). After a short cooling period it was placed in the source position of the double focusing spectrometer of the BNL Chemistry Department which was operated at a momentum resolution of 0.16%. The 57.5-keV L-conversion electron lines were measured by taking 2-min counts, starting at the lowest momentum setting [Fig. 1(a)]. After three runs the L-conversion lines of the 93.3-keV transition were traversed in the same manner (Fig. 3), then two more runs of the 57.5-keV L lines were taken, and finally the 93.3-keV K line was measured. The background amounted to $\sim$200 counts/min in the beginning and most of it decayed with a 5.5-h half-life. The decaying part may be attributed to scattering of the higher-energy conversion electrons. Each run was corrected for background and the remaining counts were corrected for decay. Figure 1(b) represents the curve obtained from the five runs after corrections. The dashed line was obtained by extrapolating the L_{II} line assuming that its shape is identical with that of the L_I line. In Table I the relative intensities are compared with the theoretical values given by Rose and by Sliv for a pure $E1$ transition, from which they differ considerably. Previous measurements of $L_{III}/(L_I+L_{II})$

TABLE III. Absolute L-subshell conversion coefficients of the 57.5-keV transition in Hf^{180m}.

		Theory				
	experiment[a]	$E1$	$M2$	$E3$	$M1$	(%$E1$,%$M1$) (90.5,9.5) (Rose) (91.9,8.1) (Sliv)
L_I	0.308±0.025	0.108	64	12	2.20	0.308 (Rose)
		0.117	63.0	12.2	2.46	0.308 (Sliv)
L_{II}	0.067±0.010	0.047	5.8	640	0.192	0.061 (Rose)
		0.053	6.15	670	0.230	0.067 (Sliv)
L_{III}	0.055±0.010	0.062	22	640	0.025	0.058 (Rose)
		0.065	21.3	670	0.030	0.062 (Sliv)
M_{tot}	0.088±0.025[b]	0.066			0.55	0.109 (Rose)

[a] The adopted value for the fraction of unconverted γ rays used for the computation of the experimental conversion coefficients is $f_\gamma^{57}=0.54$ (see Sec. II Ab). It should be kept in mind that the errors in the *relative* conversion coefficients are considerably smaller (see Sec. IAb).

[b] This value was computed using the measured M_{tot}/L_{III} ratio (Ref. 10) and the measured L_{III} conversion coefficient given above.

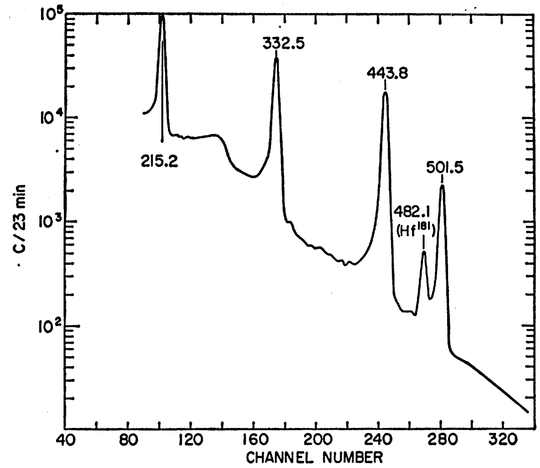

FIG. 2. Spectrum of γ rays from Hf^{180m} obtained with a Ge(Li) spectrometer.

within their larger errors, are in good agreement with these results (Table II).

The absolute L-subshell conversion coefficients were obtained by (a) determining as accurately as possible the branching ratio of the 57.5-keV transition, for which a value of (85.2±0.8)% was obtained, and (b) comparing the L conversion line intensities of the 57.5-keV transition with the intensity of the L_{III} conversion line of the 93-keV ($E2$) (2+ → 0+) transition.[16]

After applying the appropriate corrections for window thickness and using the branching ratio given above, the absolute conversion coefficients given in Table III were obtained.

a. Determination of the Branching Ratio for the 57.5-keV Transition

Since both the 215.2- and the 332.5-keV transitions are 100% branches, their intensities were compared with that of the 501-keV transition. A Ge(Li) diode (6 cm^2×5.5 mm deep), for which an accurate intensity calibration curve was available, served to obtain the γ-ray intensities (Fig. 2), and the total transition intensities I^{215} and I^{332} were obtained by using theoretical (Rose) $E2$ conversion coefficients, while for the computation of I^{501} a 96.5% $E3$ +3.5% $M2$ mixture was assumed.[13]

I^{215} and I^{332} were found to agree within 0.5%. The branching ratio B^{501} obtained by using the average of I^{215} and I^{332} was found to be $B^{501}=(14.8\pm0.8)\%$. Since $B^{57}=1-B^{501}$ may be assumed (see Sec. IIC), one obtains $B^{57}=(85.2\pm0.8)\%$. As $B^{443}=B^{57}$, this result may be checked by directly comparing the photopeak inten-

[16] This line was chosen because it lies close to the lines in question, and its conversion coefficient as determined by Edwards and Boehm (Ref. 10) was found to be in good agreement with the theoretical prediction—the deviation amounted to $(-2.5\pm7)\%$,—whereas the 93-keV (L_I+L_{II}) conversion coefficient was found by these authors to exceed the theoretical one by $(27\pm9)\%$. Our value of the $(L_I+L_{II})/L_{III}$ ratio exceeds the theoretical value (Rose, Sliv) by 15±2% (see Table IV).

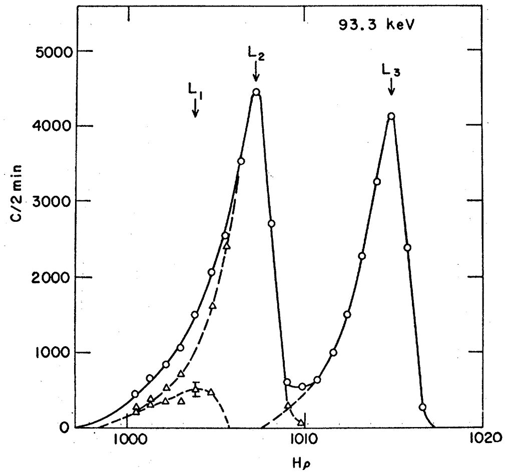

FIG. 3, L-conversion electron spectrum of 93.3-keV transition in Hf^{180m}. The line shapes were determined by linear extrapolation of a log-log plot.

sities of the 215.2-, 332.5-, and 443.8-keV transitions, and using the appropriate $E2$ conversion coefficients. This yields a value $B^{57}=(86.6\pm3.2)\%$, in good agreement with the more accurate value given above.

b. Computation of $L_{I,II,III}$(57.5 keV) Conversion Coefficients

Figure 3 shows the L conversion line spectrum of the 93.3-keV transition, corrected for decay to the time t_0 used for the decay correction of the 57.5-keV L conversion spectrum [Fig. 1(b)]. In Table IV our value for the $L_I/(L_{II}+L_{III})$ ratio is compared with the corresponding values given by other authors.

The counts for each line were integrated and corrected for momentum settings. The relative electron intensities $e(L)$ for the four lines were obtained by multiplying the 57.5-keV L conversion line intensities by a factor 1.05 to correct for absorption[17] in the window of the proportional counter in the double focusing spectrometer (a 0.58-mg/cm² Mylar window covered with ~0.020-mg/cm² gold); no absorption correction was necessary for the 93.3-keV transition.

The intensities for the four electron lines were:

$$\begin{aligned} 57.5\text{ keV}\quad & e(L_I) && (11.42\pm0.31)\times10^3,\\ & e(L_{II}) && (\ 2.48\pm0.28)\times10^3,\\ & e(L_{III}) && (\ 2.03\pm0.26)\times10^3,\\ 93.3\text{ keV}\quad & e(L_{III}) && (15.87\pm0.19)\times10^3. \end{aligned}$$

The errors given are statistical.

The conversion coefficients for the three subshells are then obtained from the equation

$$\alpha(L_i)^{57}=\frac{e(L_i)^{57}}{I_\gamma^{57}}=\frac{e(L_i)^{57}}{I^{93}f_\gamma^{57}}=\frac{e(L_i)^{57}\alpha(L_{III})^{93}}{e(L_{III})^{93}(1+\alpha_{tot}^{93})f_\gamma^{57}};\quad i=\text{I, II, III}.$$

[17] R. O. Lane and D. T. Zaffarano, Phys. Rev. 94, 960 (1954).

The fraction f_γ^{57} of 57.5-keV γ rays per disintegration is computed from

$$f_\gamma^{57}=\frac{I^{57}-e_{tot}^{57}}{I^{93}}=B^{57}-\frac{e_{tot}^{57}}{I^{93}}.$$

The theoretical conversion coefficients used to compute I^{93} were[18]

$$\alpha(L_{III})^{93}=1.32,\qquad \alpha_{tot}^{93}=4.71.$$

The value for e_{tot}^{57} was obtained by adding e_{M+N+O}[19] to the sum of L-conversion electrons given above.

We thus obtain

$$f_\gamma^{57}=0.56\pm0.03.$$

This value is to be compared with the value $0.48_5\pm0.03$ which we deduce from the relative γ-ray intensities reported by Edwards and Boehm[10] who used a bent crystal spectrometer; because of the difficulties connected with these intensity measurements, we have given our measurement more weight and adopted the value $f_\gamma^{57}=0.54$ for the computation of the measured L conversion coefficients given in Table III, column 2. The theoretical conversion coefficients (Rose and Sliv) for $E1$ (column 3), $M2$ (column 4), and $E3$ (column 5) are given for comparison. It is seen that the measured conversion coefficient for the L_I line far exceeds the $E1$ conversion coefficient, and that no admixture of $M2$ and/or $E3$ can reproduce the measured L subshell conversion coefficients.[20] We therefore computed the $M1$ admixture (column 6) needed to account for the measured L_I conversion coefficient and arrived at 9.5% and 8.1% using Rose's and Sliv's values, respectively. It is seen that for both sets of values good fits are obtained for the L_{II} and L_{III} conversion coefficients (column 6). Also the M_{tot} conversion coefficient is fitted satisfactorily. If this explanation were correct the $M1$ part of the transition would be hindered by a factor of $\sim10^{15}$.

TABLE IV. L conversion coefficient ratio for the 93-keV ($2+\rightarrow0+$) transition.

	Ref. 9	Ref. 10	Present work	Theory ($E2$) Rose, Sliv
$(L_I+L_{II})/L_{III}$	1.4±0.3	1.43±0.15	1.28±0.03	1.11

[18] For $\alpha_{2,\,tot}^{(93\text{ keV})}$ the theoretical conversion coefficients for the K and L shells were used. Sliv's and Rose's values for these are in good agreement ($\alpha_K=1.0$, $\alpha_{L_I}=0.11$, $\alpha_{L_{II}}=1.35$, $\alpha_{L_{III}}=1.32$). The conversion coefficients for the outer shells ($M+N+\cdots$) were taken from the measured intensities of Ref. 10 relative to that of the L_{III} line. One thus obtains $\alpha_{M+N+\cdots}=0.93$.

[19] The ratio $e_{M+N+0}/e_{L_{III}}=1.87$ deduced from values given in Ref. 10 was used to compute e_{M+N+0}.

[20] G. Scharff-Goldhaber and M. McKeown, Proceedings of the Argonne International Conference on Weak Interactions, 1965, Argonne National Laboratory Report No. ANL-7130, (unpublished).

TABLE V. Conversion coefficients of the 501.5-keV $8- \rightarrow 6+$ transition.

		α_K	α_{L_I}	$\alpha_{L_{II}}$	$\alpha_{L_{III}}$	K/L	$L_I:L_{II}:L_{III}$
Theory[a]	(a) 96.5% $E3$+3.5% $M2$	0.041	6.3×10^{-3}	7.7×10^{-3}	2.3×10^{-3}	2.52	1:1.22:0.37
	(b) 96.5% $E3$+3.5% $E2$	0.038	5.6×10^{-3}	7.6×10^{-3}	2.3×10^{-3}	2.44	1:1.35:0.41
Experiment	Present work	0.045±0.004	$(7.0\pm2.7)\times10^{-3}$	$(8.0\pm3.0)\times10^{-3}$	$(3.0\pm1.2)\times10^{-3}$	2.5±0.45	1:1.15:0.43
	Ref. 10	0.037±0.012					
	Ref. 9	0.035±0.014					
	Ref. 12	0.037±0.012					

[a] The values interpolated from Sliv's and Rose's tables are in good agreement.

Another possible explanation of the anomaly are $E1$ penetration effects. It can be shown[21] that the anomalous L_I and L_{II} conversion coefficients can be obtained, within limits of error, by choosing a suitable dynamic penetration term $\mathbf{j}\cdot\mathbf{r}$. If one writes

$$\alpha_1(L_I)=0.0886+|-0.170+18.18Y|^2,$$
$$\alpha_1(L_{II})=0.0491+|-0.0479-13.00Y|^2,$$

where the values $\alpha_1(L_{I,II})_{Y=0}$ agree with the theoretical values listed by Sliv, one finds that with $Y=-0.0158$ we obtain $L_I=0.308$ and $L_{II}=0.074$, in satisfactory agreement with the measured values.

Here the following relation holds:

$$\frac{\int \mathbf{j}\cdot(\hat{r}/R)(r/R)^2Y_{1M}d\tau}{\int \mathbf{j}\cdot\nabla(r/R)Y_{1M}d\tau}=\frac{2}{(3\pi\alpha)^{1/2}}\frac{1}{kR^2}Y=2.20\times10^5Y,$$

where the numerator represents the penetration matrix element and the denominator the γ-ray matrix element. It was assumed that the other penetration matrix element ratio

$$\frac{\int \mathbf{j}\cdot\nabla(r/R)^3Y_{1M}d\tau}{\int \mathbf{j}\cdot\nabla(r/R)Y_{1M}d\tau}\sim0.$$

A similar analysis based on our internal conversion coefficient values[20] has been given by Hager and Seltzer.[22]

Lawson and Segel[23] have recently discussed the possibility of parity mixing in the 57.5-keV transition and have come to the conclusion that this would imply that also the $8- \rightarrow 6+$ 501-keV transition should have an appreciable parity admixture, namely an $E2$ component admixed to the $E3$ and $M2$ components. This seemed to be disproved by angular-correlation results[13] (for further developments concerning this possibility, see Sec. IIB). We note, however, that if the 8+ component admixed into the 8− were such as to favor $M1$, their argument would lose its strength. In view of the importance of experimental tests of parity mixing and of the contradictory results of such tests for other transitions, attempts to detect the circular polarization of the 57.5-keV transition were made.[24,25]

B. Conversion-Coefficient Measurements of the 501.5-keV Transition

In order to search for possible anomalies due to parity mixing in the 501-keV transition for which only the K-conversion coefficient had been measured previously,[9,10,12] we carried out a measurement of the K and L conversion coefficients with the double focusing spectrometer and, incidentally, were able to obtain the somewhat more accurate value of 501.5±0.7 keV for the energy of this transition.

Figure 4(a) and (b) show the 501.5-keV K and L conversion lines, respectively, and, for comparison, the K conversion line of the 443.8-keV transition [Fig. 4(c)]. It is seen that the conversion lines of the L subshells are not resolved, but since the positions of the three peaks can be fairly accurately determined, using the position of the 501.5-keV K conversion line for calibration, the conversion coefficients for the three lines can be estimated. In Table V(a) the measured values are compared with the theoretical values for the $M2-E3$ mixture determined by angular correlation in line (a).[13] In order to take the possibility of parity mixing into account, the values for the "maximum violation" mixture 3.5% $E2$+96.5% $E3$ were also computed [Table V, line (b)].

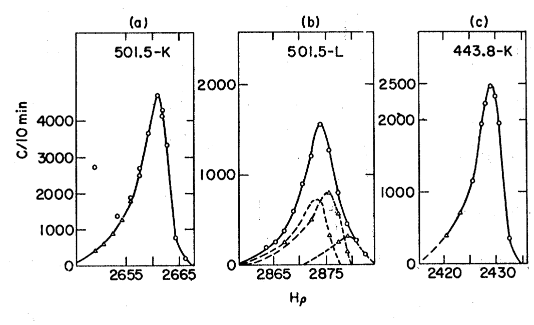

FIG. 4. K- and L-conversion electron lines of 501.5-keV transition in Hf^{180m} [(a) and (b)]. The two high points at the low-energy side of the 501.5-keV K line arise from the adjacent 443.8-keV L_{III} line. The K conversion line of the 443.8 transition (c) was used for intensity and energy calibration.

[21] G. T. Emery (private communication). The notation (Y) was introduced in an article by G. T. Emery and M. L. Perlman, Phys. Rev. **151**, 984 (1966). Dr. Emery's analysis served as basis for the statement that penetration effects are a possible explanation of the anomaly in the $E1$ conversion coefficients (Ref. 20).

[22] R. Hager and E. Seltzer, Phys. Letters **20**, 180 (1966).

[23] R. D. Lawson and R. E. Segel, Phys. Rev. Letters **16**, 1006 (1966).

[24] P. Bock, B. Jenschke, and H. Schopper, Phys. Letters **22**, 316 (1966).

[25] See H. Paul, M. McKeown, and G. Scharff-Goldhaber, following paper, Phys. Rev. **158**, 1112 (1967).

TABLE VI. Gamma-ray mean lives and hindrance factors for isomeric transitions in Hf^{180m}.

	Initial state $I\,K\,\pi$	Final state $I\,K\,\pi$	Multipole order	τ_γ (sec)	ν	H[f]
57.5 keV	8 8 −, $p[514\uparrow]+p[404\downarrow]$[a]	8 0 +	$E1$	5.3×10^4	7	3.6×10^{16}
			$M1$	$\geq5\ \times10^7$[b]	7	$\geq3.1\times10^{17}$
			$M2$	$\geq1\ \times10^8$[c]	6	$\geq2.1\times10^{11}$
501.5 keV	8 8 −, $p[514\uparrow]+p[404\downarrow]$[a]	6 0 +	$M2$	5.8×10^6	6	4.9×10^{14}
			$E2$	$\geq1\ \times10^8$[d]	6	$\geq2.4\times10^{17}$
			$E3$	2.1×10^5	5	1.8×10^9
834 keV	8 8 −, $p[514\uparrow]+p[404\downarrow]$[a]	4 0 +	$M4$	$\geq1.4\times10^9$[e]	4	$\geq4.2\times10^8$
			$E5$	$\geq1.4\times10^9$[e]	3	$\geq1.6\times10^4$

[a] See Sec. I and Ref. 14.
[b] Deduced from upper limit for the polarization of γ rays (Ref. 24).
[c] Deduced from experimental L_{III} conversion coefficient (see Table III).
[d] Deduced from upper limit given in Ref. 26.
[e] Present results (see Sec. IIC).
[f] The hindrance factors (H) are computed using Moszkowski's formulas for γ ray transition probabilities for a single proton, assuming $S=1$ [K. Siegbahn, *Alpha-, Beta-, and Gamma-Ray Spectroscopy* (North Holland Publishing Company, Amsterdam, 1965), 2nd ed.

The agreement with both (a) and (b) is satisfactory; thus from these measurements, parity violation cannot be excluded.

However, Blumberg *et al.*[26] recently measured the circular polarization of the 501.5-keV γ transition and obtained $P_c(501\text{ keV})\leq2\%$. Combining this result with the 501.5 keV ($8-\rightarrow6+$)−332 keV ($6+\rightarrow4+$) angular-correlation results,[12] the parity-forbidden $E2$ component of the 501.5-keV transition is found to be less than 0.2%, thus excluding solution (b).

C. Search for the $8-\rightarrow4+$ Crossover Transition of 834 keV

In view of the large fluctuations of hindrance factors of K-forbidden transitions it seems of great interest to establish the existence of a transition from the isomeric $8-$ state to the $4+$ state of the ground-state band, which would be $M4(\nu=4)$ and/or $E5$ ($\nu=3$). Koički *et al.*[12] have found an upper limit of $\leq2\times10^{-4}$ for the $I_{834\text{ keV}}/I_{443\text{ keV}}$ intensity ratio. The advent of Ge(Li) detectors made a more efficient search possible. Figure 5 shows parts of the photon spectrum measured with the Ge(Li) spectrometer described in Sec. IIAa showing the photopeak of the 443.8-keV transition and the 834-keV region. As a calibration line we used the 834.96±0.2 keV line of Mn^{54}. In order to suppress an addition peak of the 332.5+501.5 keV transitions, a Pb absorber of 19.2 g/cm² was interposed. This absorber reduced the areas of the 443.8- and 835-keV photopeaks by factors of 26.1 and 5.12, respectively. No 834-keV peak was observed. The symbol ● indicates a peak with a total area of 100 counts above the background. From the statistical error we compute an upper limit for $I_{834}/I_{443}\leq2.3\times10^{-5}$. This corresponds to a half-life $\tau_{1/2}$(834 keV)$\geq1.0\times10^9$ sec and to a hindrance factor $H\geq4.2\times10^8$ for the $M4$ component ($\nu=4$), and $H\geq1.6\times10^4$ for the $E5$ component ($\nu=3$) of this transition. Since the average K-forbiddenness factor per unit of ν is generally assumed to be 10 to 100, and in view of the fact that the 501.5-keV $E3$ transition is relatively "fast" (see Table VI), it appears that a further increase of a factor of 10 in "signal-to-noise ratio" might possibly reveal the 834-keV line.

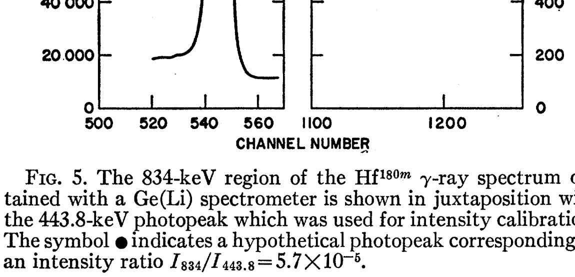

FIG. 5. The 834-keV region of the Hf^{180m} γ-ray spectrum obtained with a Ge(Li) spectrometer is shown in juxtaposition with the 443.8-keV photopeak which was used for intensity calibration. The symbol ● indicates a hypothetical photopeak corresponding to an intensity ratio $I_{834}/I_{443.8}=5.7\times10^{-6}$.

D. Hindrance Factors of the Isomeric Transitions in Hf^{180m}

In Table VI we have summarized the gamma-ray mean lives and hindrance factors for the electric and magnetic multipole components of the 57.5- and 501.5-keV isomeric transitions in Hf^{180m} (Secs. IIA and IIB), and limits for these quantities for the 834-keV transition (Sec. IIC). The limit of ~0.1% for the parity-violating $M1$ component of the 57.5-keV transition is deduced from the results of circular-polarization measurements[24,25] and the relation between circular polarization and $E1-M1$ mixing ratio.[27] The limit for the $M2$ com-

[26] H. Blumberg, K.-H. Speidel, H. Schleus, R. L. Rasera, and E. Bodenstedt, Phys. Letters **22**, 328 (1966).

[27] R. A. Carhart, Bull. Am. Phys. Soc. **11**, 353 (1966); Phys. Rev. **153**, 1077 (1967).

TABLE VII. Activation cross sections of Hf^{179} and Hf^{180} for thermal neutrons.[a]

Target nucleus	Spin of target nucleus	Spin of final state	E_γ (keV)	Transitions per 100 decays	α_{tot}	$\sigma_{act}/\sigma_{act,\,th}$	$\sigma_{act,\,th}$ (barn) Present work	Ref. 9
Au^{197}	$\frac{3}{2}+$	$2-$	411.8	100	0.045	1.18 ± 0.03	(98.6 ± 0.2)[b]	
Hf^{179}	$\frac{9}{2}+$	$8-$	443.8	85.2	0.025	1.29 ± 0.08	0.34 ± 0.03	0.18 ± 0.07
Hf^{179}	$\frac{9}{2}+$	$0+$					(65 ± 15)[c]	
Hf^{180}	$0+$	$\frac{1}{2}-$	482.1	83	0.030	$1.04_5\pm0.03$	12.6 ± 0.7	(10 ± 3)

[a] The values in parentheses are adopted from the literature. [b] Reference 29. [c] Reference 30.

ponent of this transition is deduced from the work of Koički *et al.*[12]

The hindrance factor for the $E1$ part of the 57.5-keV transition, while it is higher than any other known hindrance factor for an electromagnetic transition, does not seem excessively high for an $E1$ transition with $\nu=7$.[28]

E. Determination of the Activation Cross Section of $Hf^{179}+n\rightarrow Hf^{180m}$ for Thermal Neutrons

The activation cross section of Hf^{179}, using an unspecified neutron spectrum, was measured by Gvozdev *et al.*[9] by comparing conversion electron lines of Hf^{180m} with those of Hf^{181} from a target with known isotopic composition in a reactor. The cross section assumed for the production of Hf^{181} was 10 ± 3 b. The reported cross section value was $\sigma_{act,\,Hf^{179}}=0.18\pm0.07$ b.

We have measured the activation cross section of Hf^{179} for thermal neutrons by calibrating our neutron flux with a Au^{197} sample which was bombarded together with the HfO_2 sample. The latter contained 47.55% Hf^{179} and 46.27% Hf^{180}. The weights of both samples were carefully determined. Au and Hf oxide samples were also bombarded wrapped in Cd in order to correct for resonance neutron effects. All samples were bombarded for one-minute periods. To determine the activation cross section we used the equation

$$\sigma_{act,\,Hf{th}^{179}}=\frac{A_{Hf^{179}}-A_{Hf^{179}}(Cd)}{A_{Au^{197}}-A_{Au^{197}}(Cd)}\sigma_{act,\,Au{th}}.$$

Here $A=\sigma_{act}\phi$, where ϕ denotes the neutron flux. We thus obtained $\sigma_{act,\,Hf_{th}^{179}}=0.34\pm0.03$ b.

Similarly, the activation cross section for $Hf^{180}+n\rightarrow Hf^{181}$ was determined by measuring the γ-ray spectrum of the irradiated Hf samples after the Hf^{180m} activity had decayed. The result was $\sigma_{act,\,Hf^{180}}=12.6\pm0.7$ b.

[28] K. E. G. Löbner, Proceedings of the Physikertagung, Munich, 1966 (to be published); G. T. Emery and G. Scharff-Goldhaber (to be published).

The activation cross sections were based on the intensities of suitable γ rays which were measured by means of a NaI(Tl) spectrometer whose γ-ray efficiency had been carefully calibrated. The well-known energies, branching ratios, and total conversion coefficients of these γ rays are listed in Table VII, columns 4–6. In column 7 the ratio $\sigma_{act}/\sigma_{act,\,th}=A_{act}/(A_{act}-A_{act\,(Cd)})$ is given. In column 8 the thermal activation cross sections are listed. The activation cross section of Au^{197} for thermal neutrons was assumed to be 98.6 ± 0.2 b.[29] For comparison, the total absorption cross section which mainly leads to the ground state of Hf^{180} is also listed.[30] The resulting isomeric ratio $\sigma(Hf^{180m})/\sigma_{tot}=0.52\%$. Using the theoretical analysis developed by Huizenga and Vandenbosch[31] one arrives at the conclusion that of the two possible spins for the capturing state in Hf^{180}, $I_c=4$ or 5, $I_c=5$ is preferred.[32] This conclusion is further strengthened by the result that the γ rays following neutron capture in Hf^{179} populate both the 6+ and the 4+ level of the ground-state band in Hf^{180}.[33]

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[30] D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report No. BNL 325 (U. S. Government Printing Office, Washington, D. C., 1958).
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