Decay of Ta^{177} and Lu^{177} to Levels in Hf^{177}

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The decays of Ta^{177} and Lu^{177} to levels in Hf^{177} have been investigated with beta-ray spectrometers, NaI(Tl) gamma-ray spectrometers, and fast coincidence and angular correlation techniques. Energy levels in Hf^{177} have been characterized according to their energy (kev), the Nilsson asymptotic quantum numbers ($Nn_z\Lambda$), the total angular momentum and its component along the symmetry axis (I,K), and the parity (π) as follows: 0[514 7/2, 7/2−]; 112.97[514 9/2, 7/2−]; 249.7[514 11/2, 7/2−]; 321.34[624 9/2, 9/2+]; 447.9[624 11/2, 9/2+]; 420.95[642 3/2, 3/2+]; 488.8[642 5/2, 3/2+]; 585.8[642 7/2, 3/2+]; 509.0[512 5/2, 5/2−]; 605.5[512 7/2, 5/2−]; 746.04[633 7/2, 7/2+]; 848.2[633 9/2, 7/2+]; and 1058.38[503 7/2, 7/2−]. The levels at 447.9, 488.8, and 585.8 kev are tentative. The spins and parities have been uniquely determined by angular correlation and internal conversion data for the levels at 746.0 and 848.2 kev, if we assume the spins and parities of the levels at 0, 113.0, 249.7, and 321.3 kev are correct as determined from earlier work. For the level at 1058.4 kev the *ft* value is needed in addition to angular correlation and conversion data in order to determine the spin and parity uniquely. The spins of Lu^{177} and Hf^{177} have previously been measured directly as 7/2, and the Ta^{177} spin is expected to be 7/2 on the basis of other tantalum isotopes. The following half-lives were measured: 56.56 hr for Ta^{177}, 0.32 nsec for the level at 113.0 kev, and 0.52 nsec for the level at 321.3 kev. The K/L electron capture ratio to the 1058.4-kev level and the $\beta+/K$-capture ratio to the ground state determine the total decay energy to be 1166±6 kev.

INTRODUCTION

ENERGY levels in Hf^{177} at 113.0, 249.7, and 321.3 kev have been studied extensively from the decay of Lu^{177}.[1–3] In addition, the first two excited states have been produced by Coulomb excitation.[4] The techniques used in the Lu^{177} work have included angular correlation measurements, energy determinations with beta- and gamma-ray spectrometers to approximately 0.1% accuracy, and conversion coefficient measurements. Recently the ground-state spins of Hf^{177} and Lu^{177} have been found[5] to be 7/2. The parities are predicted with some confidence from theories of the ground state properties of nonspherical nuclei.[6–8] From these investigations the properties of the first three excited states as shown in Fig. 1 seem well established.

In the electron-capture decay of Ta^{177} several more states in Hf^{177} are populated.[2,9,10] The decay properties of these states were studied in the present work by using beta-ray spectrometers, NaI(Tl) gamma-ray spectrometers, and angular correlation and fast coincidence techniques. The results are interpreted in terms of the theories of single-particle energy levels in nonspherical nuclei.[10]

While this work was in progress similar results were obtained by Harmatz *et al.*[11] Their conclusions were based almost entirely on conversion electron data obtained with permanent-magnet beta-ray spectrographs and on previously reported gamma-ray intensities.[10] The present work contains extensive data on transition intensities, gamma-ray multipolarities, and spins and parities. Several additional transitions were observed which indicate the presence of several new levels.

SOURCE PREPARATION

The reactions $Lu(\alpha,2n)Ta^{177}$ and $Hf(p,xn)Ta^{177}$ were used in the Crocker Laboratory 60-in. cyclotron to produce Ta^{177}. In the lutetium bombardments alpha particles of 34 Mev were used. Approximately 10 mC of Ta^{177} were produced after 0.2 ma-hr. Protons of about 11 Mev were used in the hafnium irradiations. With both Lu and Hf targets, four days were allowed for decay of the 8-hr Ta^{176} before experimental work was begun on Ta^{177}. In addition, the hafnium targets produced Ta^{179} which added to the x-ray intensity, and Nb^{92} from zirconium impurity in the hafnium. For these reasons the lutetium targets were preferable.

The separation of tantalum was based on the favorable distribution of certain tantalum-fluoride complexes in a two-phase organic-aqueous system.[12] The tantalum fraction was extracted from an HCl-HF or H_2SO_4-HF solution of the target material into DIPK (di-isopropyl ketone) across the phase boundary. After the DIPK was equilibrated with fresh $12N$ H_2SO_4–$0.4N$ HF solution as a wash, the tantalum was back-extracted from the organic phase with either water or a dilute HCl solution. Repeated cycles of this chemistry were made to give a radiochemically pure tantalum fraction.

For scintillation spectroscopy, sources in small polyethylene tubes were prepared from aliquots of the final aqueous back-extractant. Beta spectrometer sources were prepared by solution evaporation on ¼-mil half-aluminized Mylar film for an axial focusing spectrometer and by electrolytic deposition of tantalum[13] on 10-mil

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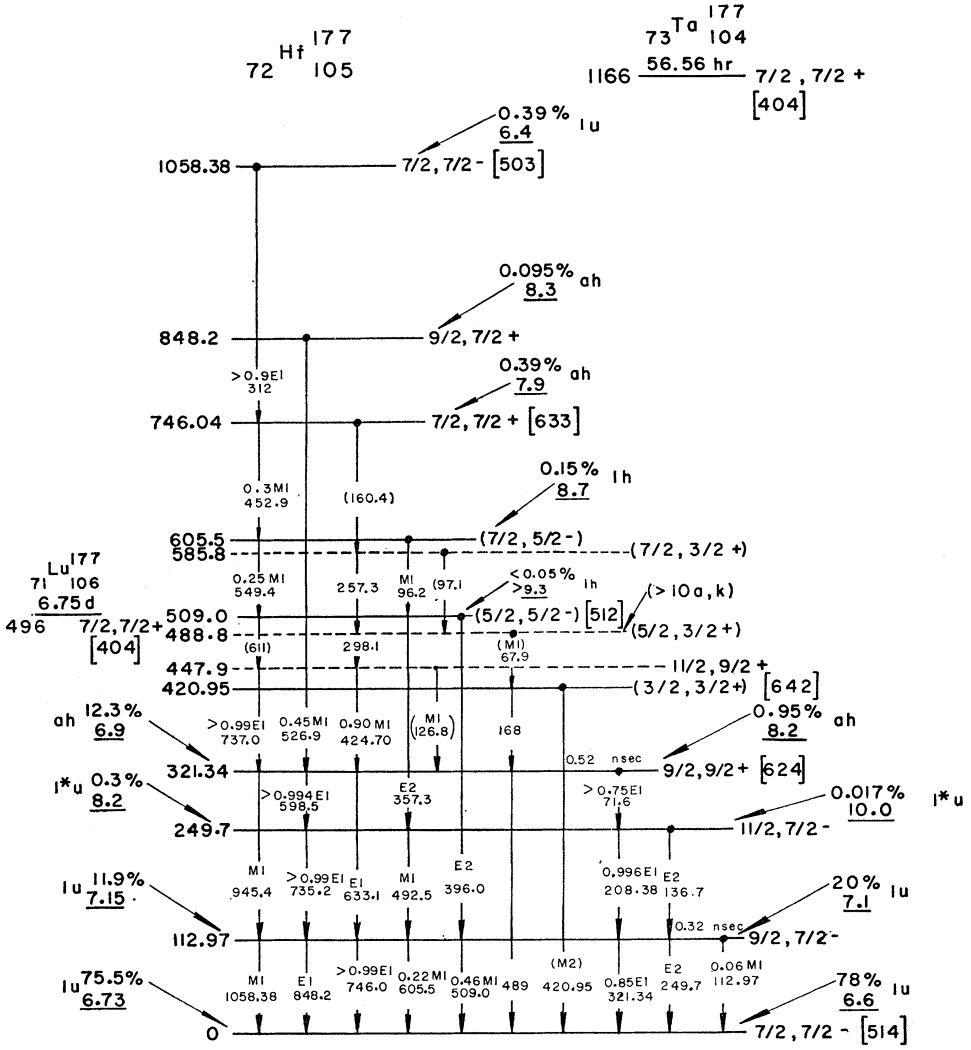

FIG. 1. Energy levels of Hf^{177} populated by decay of Ta^{177} and Lu^{177}. Questionable levels and transitions are shown with dashed lines and parentheses. Spins and parities that are uncertain are enclosed in parentheses. Transitions between two levels are denoted by vertical lines which start (with a dot) at the first level and end with arrow heads at the second level. Energies are given in kev beside each level and for each transition between levels. Multipolarities are indicated in terms of the fractional intensity of the lowest order multipole present (0.4 $M1$ means 40% $M1$+60% $E2$). The proposed Nilsson quantum numbers are given in square brackets for the lowest level in each rotational band. Half-lives are given where measured. Beta decays and electron-capture decays are indicated by slanted arrows with the intensities given in percent and log ft values underlined. Their classifications according to the selection rules of Alaga are given as allowed (a), first forbidden (1), first forbidden unique (1*), hindered (h), and unhindered (u).

platinum wire for a constant-field permanent-magnet spectrometer. Approximately 35% of the Ta^{177} was deposited after running 15 hr at 0.14 amp.

Lu^{177} was produced by neutron capture in Yb^{176} followed by beta decay of Yb^{177}. Natural ytterbium oxide containing less than 20 ppm of lutetium was irradiated in the core of the Livermore Pool Type reactor. Irradiation of 103 mg of the ytterbium oxide for 106 hr over a period of two weeks produced about 10 mC of Lu^{177}. The flux was about 2×10^{13} neutrons/cm^2-sec.

After allowing the sample to decay for three days, carrier-free Lu^{177} was twice separated from the ytterbium by means of a pH 2.75 ammonium lactate elution at 85°C from ion exchange columns loaded with 200–400 mesh Dowex-50×12 cation exchange resin. A Dowex-50×12 column was used to absorb the Lu^{177} activity from the lactate solution after adjusting the pH to 1.2 with HCl. After elution from this column with 9N HCl, the principal residue was found to be iron. This was separated by passing the eluate through a Dowex-1×10 anion exchange column (Lu^{177} not absorbed). The remaining residue was removed by extraction of lutetium from a pH 4.0 solution of 1M NaCOOH and ≈0.4M HCOOH into 0.4M TTA (thenoyl-trifluoroacetone in benzene), followed by back-extraction into 0.5N HCl.

Virtually weightless sources for investigating con-

version electrons of less than 100 kev were made by evaporating lutetium chloride from a tungsten filament onto $\frac{1}{2}$-mil and 1-mil aluminum foils in vacuum. For the beta spectrometer, strong sources were made by evaporating an aqueous solution to dryness on aluminized Mylar film.

APPARATUS

A thin-lens beta-ray spectrometer having 0.8% momentum resolution and about 0.3% transmission was used for measurements of conversion electron energies and intensities up to the maximum decay energy (1166 kev). This spectrometer utilizes a thin anthracene scintillation detector. Data are recorded automatically in momentum increments of $\frac{1}{2}$%. In addition, $\frac{1}{4}$% increments of momentum are available during manual operation. For greater energy resolution the permanent-magnet 180° spectrometers of Hollander[14] and the solenoidal field spectrometers of DuMond[15] and Jungerman[16] were used. These spectrometers gave momentum resolutions of 0.2%, 0.2%, and 0.05%, respectively.

The gamma-ray spectrum was studied with NaI(Tl) crystals 2 in. long$\times 1\frac{3}{4}$ in. in diam, mounted on RCA-6655 photomultipliers for our early experiments and on RCA-6810A photomultipliers during the later experiments. Energy resolution was about 8.5% at 662 kev. The last few dynode voltages of the 6810A tubes were stabilized by means of cathode followers used in a circuit similar to that described by Kane.[17] In addition, the counting-rate-dependent gain drifts associated with Ag-Mg dynodes were eliminated by an electronic stabilizer circuit similar to one described by deWaard.[18] With these control circuits the performance of the 6810A tubes has been excellent.

The fast-slow coincidence apparatus is shown in Fig. 2. The linear amplifiers are of the modified Argonne type with delay line clippers at the input. The discriminators are RCL single-channel differential analyzers, and the multichannel analyzer is an RCL 256-channel pulse height analyzer. The coincidence circuit is of the type described by Bell *et al.*[19] When RCA-6655 photomultipliers were used, Hewlett-Packard wide band amplifiers were needed to drive the WE-404A limiter tubes of the coincidence circuit. Later, RCA-6810A photomultipliers were used to drive the coincidence circuit directly. The pulse width at the diode discriminator was usually clipped to about 2×10^{-8} sec. Many diode types were tried for the fast discriminator, the best being the microwave diode IN23D and the Q6-100. The IN23D was used and was an important factor in obtaining good stability. To further improve stability the standing current in the 404A limiters was stabilized.

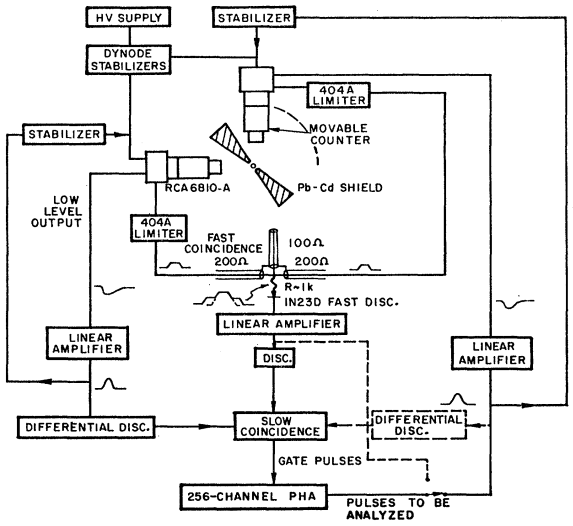

FIG. 2. Block diagram of the fast-slow coincidence system. The resistor R and the circuit arrangement shown with dashed lines are used to convert the circuit to a fast time-to-height converter for short-lifetime measurements.

The coincidence system is easily modified to a time-to-height converter of the type described by Sunyar[20] by inserting the integration resistor R and the circuits shown in dotted lines. The charge left on the integrator capacitor (stray capacity) is proportional to pulse overlap from the limited pulses of the two detectors. The system was calibrated by inserting various lengths of 200-Ω cable between one of the limiters and the shorting stub. Timing resolution obtained with pulses from a pulse generator inserted at the limiter grids was about 3×10^{-11} sec. The best obtained with Co^{60} gamma rays was about 6×10^{-10} sec when RCA-6810A tubes and plastic scintillators were used. With NaI(Tl) scintillators, 4×10^{-9} sec was typical for gamma rays of a few hundred kev. Drift in the position of the centroid of the converter distribution during a run of several hours was not detectable ($\approx 3\times 10^{-11}$ second).

EXPERIMENTS

Electron Spectrum

The spectrum of internal conversion electrons obtained with the thin-lens spectrometer is shown in Fig. 3 and summarized in Table I. The energies measured by Marmier and Boehm[1] for the 113.0-, 208.4-, 249.7-, and 321.3-kev transitions were used for energy calibration. Three sources of about 1 mC each were run and the results were averaged. Energies were determined with accuracies of 0.2–0.5%. Relative intensities were obtained from the areas of the peaks and are summarized

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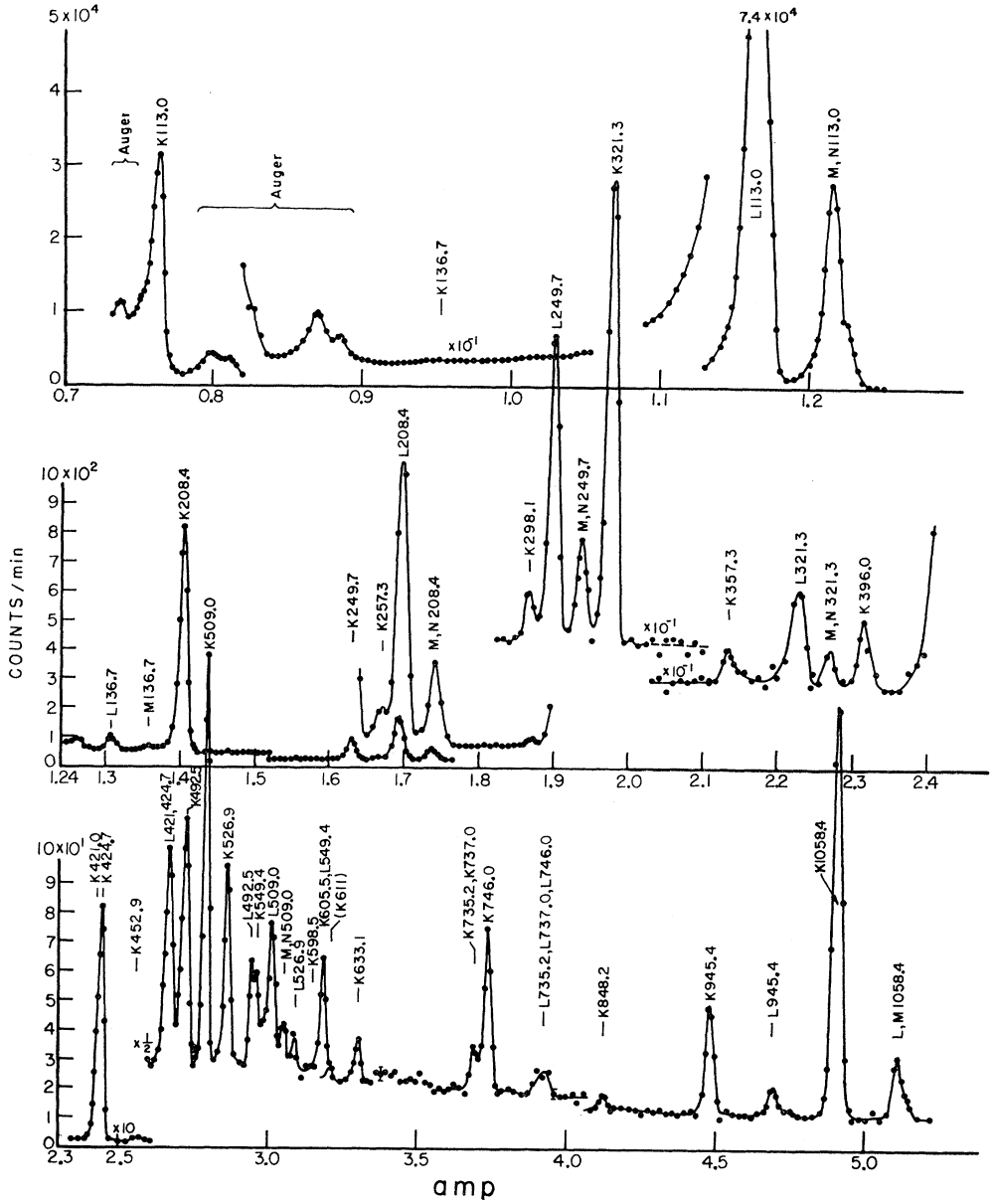

FIG. 3. Spectrum of internal conversion electrons obtained in the thin-lens beta-ray spectrometer. These data have not been corrected for decay or for the spectrometer transmission. The ordinate scale is to be multiplied by the factors affixed to the curves. Data from two different sources are presented in the region of 1.6 to 2.1 amp. Other discontinuities, as at 1.52, 2.60, and 4.06 amp, result either from a change in background due to adjustment of the detector bias or from the decay correction.

in Table I. These sources were the most intense that we were able to produce. Counting times ranged from 1 to 20 minutes per channel, and each run lasted several days. Corrections have been applied for decay up to 4 half-lives.

As indicated in Table I, some of the lines were measured with greater precision in the spectrometers of Hollander and Jungerman. The ThI line was used for energy calibration of Jungerman's spectrometer. These spectrometers resolved the 421.0- and 424.7-kev doublet, which produced only a slightly broader than normal peak in our lens spectrometer. An unsuccessful search for the 421.0-kev line was made with our spectrometer using a Lu^{177} source. This indicates that the logft value to a possible 421.0-kev level is about 8 or larger. The gamma-ray energies in Table I are the best values obtained by averaging all our electron data, and the corresponding best values of the energy levels are given in Fig. 1.

Subshell conversion ratios of $L_{\mathrm{I}}/L_{\mathrm{II}}=0.215\pm0.015$ and $L_{\mathrm{III}}/L_{\mathrm{I}}=4.54\pm0.30$ were measured in Jungerman's spectrometer for the 113.0-kev gamma ray.

TABLE I. Intensities and conversion coefficients of gamma rays in the decay of Ta^{177}. Certain weak transitions observed only in the permanent magnet spectrograph are not included in this table.

γ-ray[a] energy (kev)	Hf^{177} levels (kev)	Intensity per Ta^{177} decay[b] $10^3\times\gamma$	$10^5\times e_K$	$10^5\times e_L$	$10^5\times e_{M+N}$	Conversion coefficient[c] K	L
71.6 ±0.1	321.34–249.7	0.03 ±0.01[d]		<18	<1		<6
96.2 ±0.3	605.5–509.0	0.19 ±0.06[e]		12±3			0.63
112.97±0.02[f,g]	112.97–0	60±3[h]	5070±600	8740±270	2570±90	0.78[i]	1.40[i]
136.7 ±0.1	249.7–112.97	0.05 ±0.02[j]	3.57 ±0.23	3.37 ±0.14		0.71	0.67
168	488.8–321.34	0.030±0.015[k,r]		<0.2			<0.1
187.7	509.0–321.34		<0.3				
208.38±0.02[f,g]	321.34–112.97	10.3 ±0.3[h]	44.5 ±0.8	7.30 ±0.24	2.05 ±0.09	[0.043]	0.0071
210.2	1058.38–848.2	0.05 ±0.03[l]					
249.7 ±0.1[f]	249.7–0	0.21 ±0.03[h,y]	3.11 ±0.18	1.20 ±0.06	0.38 ±0.04	0.148	0.057
257.3 ±0.5	746.04–488.8	0.06[k,m]	0.5 ±0.3				
284.2	605.5–321.34		<0.03				
298.1 ±0.4	746.04–447.9	0.025[m]	0.146±0.018				
308.0	420.95–112.97		<0.2	<0.1			
312.3	1058.38–746.04	0.4 ±0.03[l,n]	<0.2	<0.1		<0.05	<0.025
321.34±0.03	321.34–0	0.236±0.015[h]	1.89 ±0.09	0.416±0.027	0.10 ±0.02	0.080	0.018
339.2	848.2–509.0	<0.013[e]	<0.04				
357.3 ±0.5	605.5–249.7	0.024±0.007[d,o]	0.12 ±0.03	0.07 ±0.04		0.050	
396.0 ±0.4	509.0–112.97	0.12 ±0.03[p]	0.215±0.021			0.018	
400.3	848.2–447.9	<0.015,[m]<0.0053[q]	<0.04				
420.95±0.06[f,g]	420.95–0	0.18 ±0.09[p]	1.8 ±0.3			0.10	
424.70±0.04[f,g]	746.04–321.34	1.27 ±0.09[r]	6.85 ±0.46	1.15 ±0.16[s]		[0.054]	0.0090
452.9 ±0.5	1058.38–605.5	0.04 ±0.02[e,t]	0.12[o] ±0.016			0.03	
488.8[k]	488.8–0						
492.5 ±0.4	605.5–112.97	0.31 ±0.06[u]	1.46 ±0.09	0.224±0.018		0.047	0.0072
509.0 ±0.4	509.0–0	0.95 ±0.09[u]	2.40 ±0.07	0.393±0.027	0.13 ±0.02	0.025	0.0041
526.9 ±0.5	848.2–321.34	0.19 ±0.06[r]	0.51 ±0.02	0.087±0.014	0.029±0.014	0.027	0.0046
549.4 ±0.5	1058.38–509.0	0.12 ±0.02[e,l]	0.20 ±0.02			0.0167	
598.5 ±0.5	848.2–249.7	0.090±0.006[d]	0.05 ±0.03			0.005	
605.5 ±0.4	605.5–0	0.175±0.06[v]	0.223±0.015	<0.05		0.013	<0.003
611	1058.38–447.9		0.02 ±0.02				
633.1 ±0.1	746.04–112.97	0.39 ±0.03[n]	0.105±0.009	<0.03		0.0027	<0.0008
637.4	1058.38–420.95	<0.003[l]	<0.02				
735.2 ±0.5	848.2–112.97	0.44 ±0.04[w]	0.162±0.018			0.0027[x]	
737.0 ±0.1	1058.38–321.34	0.163±0.012[r]					
746.04±0.05	746.04–0	2.16 ±0.09[w]	0.53 ±0.04			0.00246	
809	1058.38–249.7	<0.015[l]	<0.01				
848.2 ±0.5	848.2–0	0.21 ±0.06[h]	0.047±0.006	0.026±0.02		0.0022	0.001
945.4 ±0.1	1058.38–112.97	0.55 ±0.03[h,n]	0.48 ±0.03	0.10 ±0.01		[0.0087]	0.0018
1058.38±0.13[g]	1058.38–0	3.0 ±0.1[h]	1.84 ±0.09	0.31 ±0.03		0.0061	0.0010

[a] The transitions given without errors were not positively identified in the beta spectrometer.
[b] The intensity errors (estimated standard deviations) are based on the internal consistency of the measurements and/or counting statistics. In comparing the electron and gamma-ray intensities to the number of Ta^{177} decays there is an additional normalization error of about 10%.
[c] Conversion coefficients in brackets were used to normalize the electron and gamma-ray intensities.
[d] Coincidence with the 249.7-kev gamma ray.
[e] Coincidence with the 509.0-kev gamma ray.
[f] These lines were measured in the permanent magnet spectrometer of Dr. Hollander.
[g] These lines were measured in the solenoidal field spectrometer of Professor Jungerman.
[h] Single gamma-ray spectrum.
[i] This conversion coefficient is a weighted average of the results obtained from the data presented here and a coincidence experiment described in the text.
[j] Coincidence with the 598.5-kev gamma ray.
[k] The gamma-ray intensities in the (257.3–488.8) and (257.3–168) cascades observed in the 250-kev coincidence experiment were 0.012±0.004 and 0.03±0.01, respectively. The 746.0-kev sum coincidence experiment gave 0.015±0.005 for the (257.3–488.8) cascade. The intensity of the (208.4–168, 160.4) cascade was 0.03±0.015.
[l] 1058-kev sum coincidence experiment.
[m] Derived from the electron intensity by assuming pure $E2$ radiation.
[n] Coincidence with the 113.0-kev transition.
[o] 605.5-kev sum coincidence experiment.
[p] Coincidence with the 113.0-kev gamma ray gives the sum of the 396.0- and 424.7-kev intensities; the singles spectrum gives the sum of the 396.0-, 424.7-, and 421.0-kev intensities.
[q] Derived from the electron intensity by assuming pure $M1$ radiation.
[r] Coincidence with 208.4-kev gamma ray.
[s] An estimated value of 0.37±0.09 for the intensity of L-conversion lectrons of the 421.0-kev transition has been subtracted.
[t] Coincidence with the 605.5-kev gamma ray.
[u] Coincidence with the 113.0-kev gamma ray gives the sum of the 526.9- and 492.5-kev intensities plus a small contribution of 509.0-kev gamma rays from coincidence with the 96.2-kev gamma rays; the singles spectrum gives the sum of the 526.9-, 492.5-, and 509.0-kev intensities.
[v] The singles spectrum gives the sum of the 605.5-, 598.5-, and 633.1-kev intensities. The 598.5- and 633.1-kev intensities must be subtracted.
[w] Coincidence with the 113.0-kev gamma ray gives the sum of the 735.2- and 737.0-kev intensities; the singles spectrum gives the sum of the 735.2-, 737.0-, and 746.0-kev intensities.
[x] Although we have not resolved these two electron lines, this result requires that *both* transitions be >99% $E1$.
[y] An intensity of 0.06 for the 257.3-kev gamma ray has been subtracted.

Some weak low-energy conversion lines that were observed in the permanent magnet spectrometer runs are shown in Table II. The data were obtained from a plate exposed to a Lu(α,xn)Ta source at 8 to 12 days after irradiation.

Gamma-Ray Spectrum

The singles pulse-height spectrum obtained with the NaI(Tl) scintillation spectrometer is shown in Fig. 4(a). Cadmium or copper absorbers up to 2.75 g/cm² in thickness were used to attenuate x rays when investigating the higher energy lines. The effect of the absorbers was obtained experimentally as a function of energy in the same geometry used for the Ta^{177} experiments. Before the spectrum of Fig. 4(a) was analyzed to obtain the gamma-ray spectrum, numerous coincidence experiments were performed which clarified the positions of some of the poorly resolved lines.

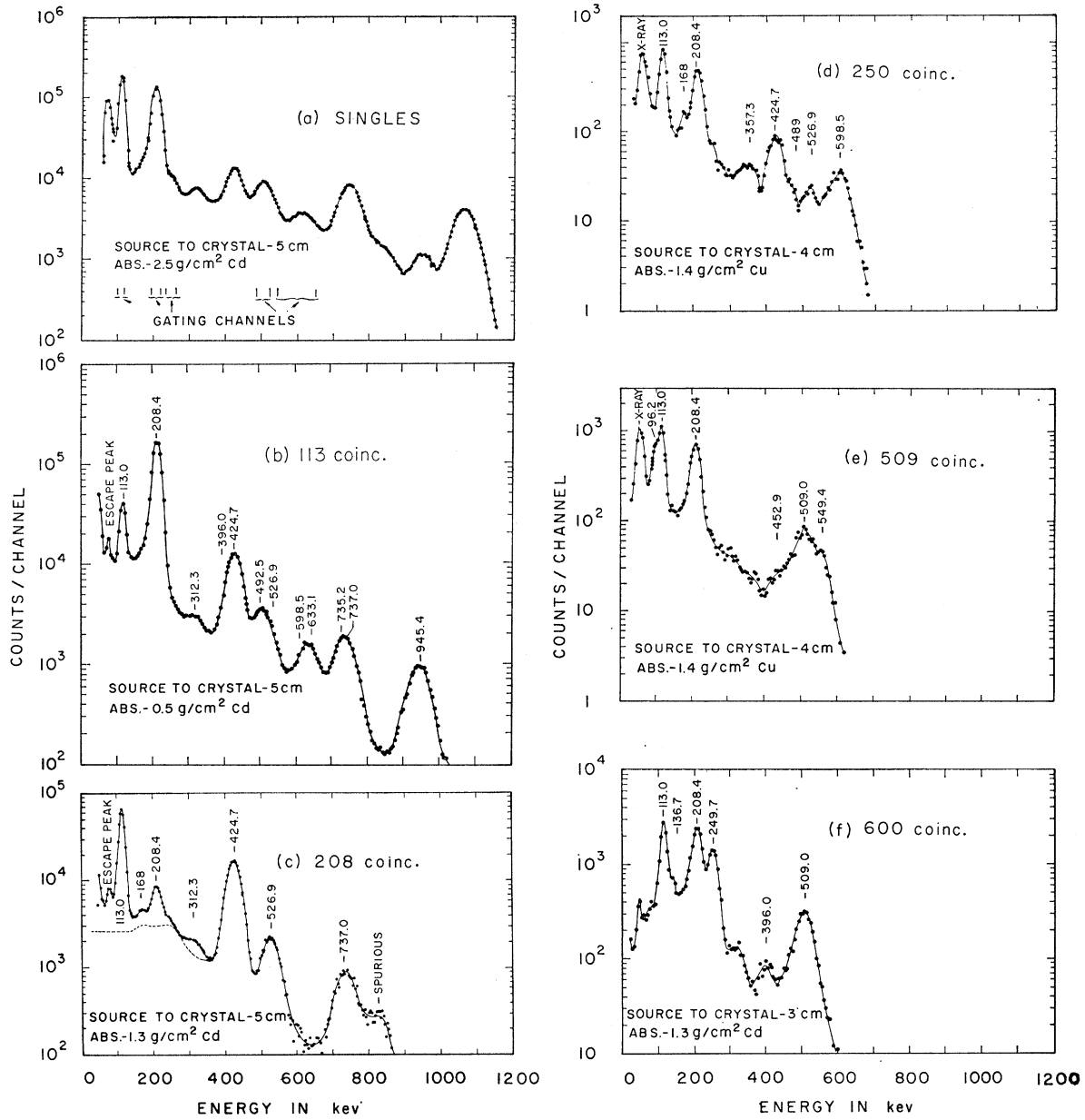

FIG. 4. (a) Scintillation counter spectrum of the gamma rays following decay of Ta^{177}. The data were obtained with the source at 5 cm from a $1\frac{3}{4}$-in. diam×2-in. long NaI(Tl) crystal using 2.5 g/cm² of cadmium absorber. The absorber attenuation was 14.5 for 113 kev, 1.92 for 208 kev, 1.27 for 425 kev, and 1.12 for 1058 kev. (b) Scintillation counter spectrum of the gamma rays in coincidence with approx. 113-kev gamma rays. To improve statistics in this presentation the data from all angles of a 113.0-angular correlation run were summed. (c) Spectrum in coincidence with approx. 208-kev gamma rays. The results of a 208.4-angular correlation run were summed to give the spectrum presented here. The peak at about 825 kev is due to the 1058.4-kev gamma ray being scattered out of the gating crystal and detected in the analyzed crystal. The peak goes away as the angle of counter separation is changed toward 90°. (d) Spectrum in coincidence with gamma rays producing pulses in a gating channel of about 225 to 265 kev. This includes the 249.7- and 257.3-kev gamma rays. (e) Spectrum in coincidence with gamma rays producing pulses in a gating channel of about 485 to 535 kev. These are mainly the 509.0-, 452.9-, 549.4-, 526.9-, and 492.5-kev gamma rays. (f) Spectrum in coincidence with gamma rays producing pulses in a gating channel of about 550 to 650 kev. This includes mainly the 549.4-, 526.9-, and 598.5-kev gamma rays.

The difficult problem of analysis arises because of the continuum of pulse heights in the Compton distribution associated with each full energy peak. If the distributions associated with the most prominent full energy peaks are known precisely, then their subtraction from the spectrum may reveal weaker gamma rays. This procedure was carried out by hand on several runs and was also programmed for an IBM 650 computer.[21]

[21] H. I. West, Jr., and B. Johnston, IRE Trans. on Nuclear Sci. NS-7, No. 2–3, 111 (1960).

In the IBM 650 analysis, the position (energy) of the most energetic photo peak was determined by the operator. A Gaussian curve was fitted to this peak by least-squares analysis; the number of points used in the curve-fitting was determined by the operator. From the area of this Gaussian, the expected Compton distribution (including a backscatter peak at about 200 kev) was computed by the machine and subtracted from the pulse height spectrum. This computation was an interpolation based on the experimental pulse-height distributions obtained from several monoenergetic gamma rays. The entire procedure was repeated automatically for the gamma ray of next highest energy, and so on until all the peaks had been treated. Ideally, the remainder would then be zero except for statistical fluctuations. The effectiveness of this procedure depends largely on the accuracy of the Compton distributions, which must be determined experimentally in the same apparatus as that used for the unknown spectrum. An example of the results obtained from the unfolding procedure is shown in Fig. 5.

After the intensities of the photopeaks were determined the gamma intensities were obtained by dividing by the photopeak detection efficiencies. These efficiencies were measured directly for the crystals, using gamma-ray sources calibrated by 4π beta counting. They are considered to have an absolute accuracy of $\pm 4\%$.

Gamma-gamma coincidence experiments were carried out with each of the lines appearing in Fig. 4(a). The most pertinent of the coincidence experiments are shown in Figs. 4(b)–(f). Triple coincidence experiments were performed on the (113.0–208.4) gamma cascade to show possible weak gamma rays populating the 321.3-kev level. The positron intensity, $(2.9\pm 0.3)\times 10^{-6}$ per Ta^{177} decay, was determined from the (511–511)-kev coincidence rate due to annihilation radiation, using angular correlation to positively identify the radiation. In all coincidence experiments the crystals were unshielded except for $\frac{1}{4}$-in. Pb jacketed with $\frac{1}{16}$-in. Cd which prevented scattering from one crystal to the other. The coincidence experiments were generally carried out at an angle of 54.8° (or the results corrected to this angle), since this eliminates angular correlation effects whenever the correlation contains only the P_0 and P_2 terms. Running times varied from a few minutes to a day. Checks on the position and width of the energy selector channel were made at the beginning and end of each run to guard against drift. For practical purposes the electronic stabilizer completely eliminated all gain drifts whenever it was used (in later experiments).

A gamma-ray summing coincidence experiment as described by Hoogenboom[22] was performed. It was useful in the search for levels populated in the decay to the ground state in a two-step cascade. In this experiment the heights of the coincident pulses are added, and the pulses in the analyzed crystal are accepted only when the sum corresponds to a given initial level. Significant data were obtained for the levels at 1058.4, 746.0, and

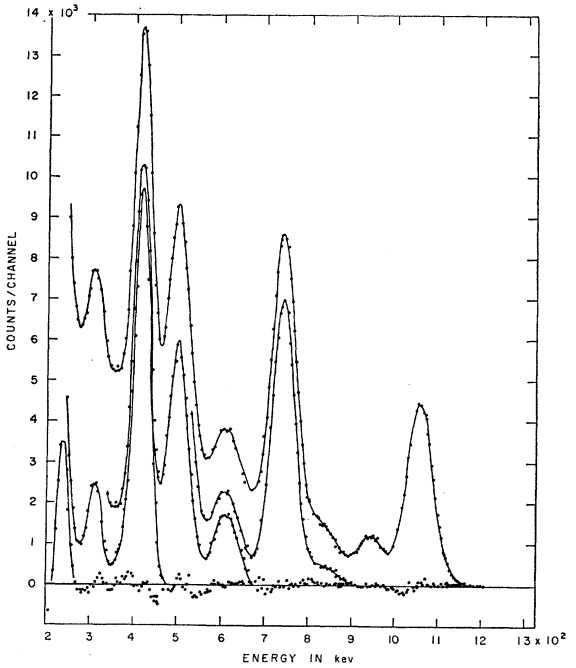

FIG. 5. An example of the IBM 650 computer "peeloff" analysis of scintillation counter data. The spectrum is from a singles run on Ta^{177}. The computer was stopped at various times to show the progress of the analysis. Normally the computer proceeds through the whole analysis giving the area of prominent photo peaks. The residual spectrum is then examined for photo peaks of low intensity.

TABLE II. Weak electron lines observed only in the permanent magnet spectrometer.

Electron energy (kev)	Remarks	Interpretation
30.8	Weak and diffuse	K of 96.2 transition.
31.7	Very weak	K of 97.1 on basis of energy fit in decay scheme.
40.4	Weak	L_{II} of 51.1,[a] not assigned in decay scheme.
41.5	Weak	L_{III} of 51.1, not assigned in decay scheme.
56.6	Weak, but well defined	L_I of 67.9 on basis of energy fit in decay scheme. Would be largely $M1$.
93.5	Very weak	Not assigned in decay scheme.
95.0	Very weak	K of 160.4 on basis of energy fit in decay scheme.
114.5	Very, very weak	May be L_I's of 125.8- and 126.8-kev transitions, in which case they are $M1$ and fit nicely into the 5/2 and 9/2 rotational bands. May be L_{II} and L_{III} of an $E2$ 125.2-kev transition in which case the assignment is questionable.
115.5	Very, very weak	

[a] Observed by Harmatz *et al.* (reference 11). They assigned an energy of 51.3 kev on the basis of only L_I conversion.

[22] A. M. Hoogenboom, Nuclear Instr. 3, 57 (1958).

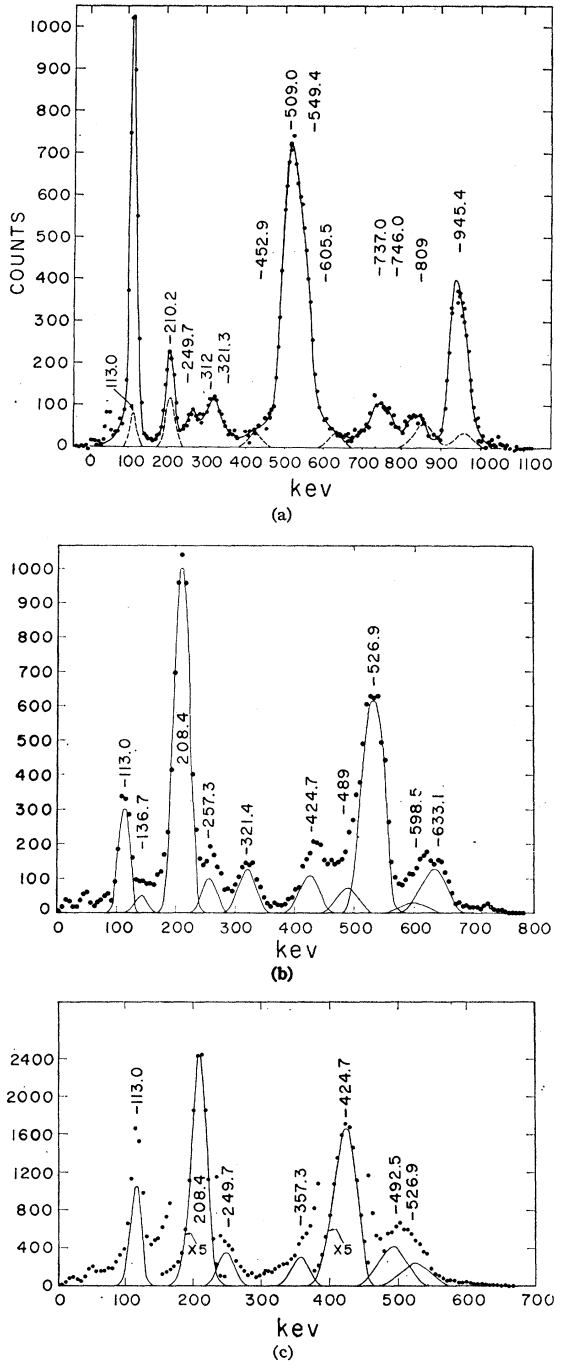

FIG. 6. (a) Gamma-ray pulse-height distribution from the summing (Hoogenboom) coincidence experiment in which the sum of the gamma-ray energies is 1058 kev. Coincidences occur between pairs of gamma rays whose energy sum equals 1058 kev. The areas of pairs of these complementary peaks should be equal. The principal peaks are due to the (945.4–113.0) cascade and the (549.4–509.0) cascade. The major part of the accidental coincidence spectrum has been subtracted experimentally. The dashed peaks are additional background calculated from accidental coincidence effects which were not included in the experimentally determined background. (b) Same as 6(a) but with the sum channel set at 746 kev. The solid peaks are the remainder after subtraction of calculated background (due mainly to the counts in the Compton distribution in coincidence with other photopeaks). (c) Same as 6(b) but with the sum channel set at 606 kev.

605.5 kev. Since the Compton effect is strongly suppressed, weak transitions can sometimes be observed with this method. We were able to put upper limits on several possible transitions as shown in Table I and Figs. 6(a)–(c). As one attempts to use this method on lower-lying levels, spurious effects (such as the photo peak of one gamma ray adding with the Compton distribution of a second) become increasingly important, and hence data obtained on lower levels are not presented. In the above experiments such effects were corrected either by experiment or calculation or a combination of both.

The L/K-capture ratio to the 1058.4-kev level (which yields the total decay energy) was obtained from the gamma-ray spectrum in coincidence with K x rays. A comparison of the gamma intensity ratios with those observed in a singles spectrum gave

$$(K \text{ capture})/(\text{total capture})=0.42\pm0.07,$$

for the 1058.4-kev level. This gives a value of 1168 ± 7 kev for the total decay energy.[23] The value obtained from the positron intensity is 1162_{-3}^{+10}, obtained from equations given by Moszkowski[24] for allowed beta decay.

All the results on gamma-ray energies and intensities are summarized in Table I.

Lifetime Measurements

The lifetimes of the 113.0- and 321.3-kev levels were measured using the fast coincidence apparatus.[20] NaI(Tl) crystals 1 in. long$\times 1\frac{1}{2}$ in. in diam were used to detect the 208.4- and 424.7-kev gamma rays. The 113.0-kev transition was detected by means of its L-conversion electrons in a $\frac{1}{32}$-in.$\times$1-in. diam plastic scintillator. Co^{60} was used to determine the pulse height spectrum for prompt coincidences, with the energy channels set at the appropriate Hf^{177} energies. The lifetimes were determined from the shift in the centroids of the pulse height distributions. Typical data are shown in Fig. 7.

The mean time delays of the 208.4- and 113.0-kev gamma rays relative to the 424.7-kev gamma ray were measured separately, giving $(7.5\pm0.5)\times10^{-10}$ and $(11.8\pm0.5)\times10^{-10}$ sec, respectively. A correction of about 10% was made for coincidences in the (396.0–113.0) cascade. This provided a good check on the mean life of the 113.0-kev level, which was found from the (208.4–113.0) cascade to be $(4.6\pm0.5)\times10^{-10}$ sec. This lifetime has been measured by Berlovich[25] who obtained $(6.1\pm0.9)\times10^{-10}$ sec. Previously Sunyar[26] had listed an upper limit of 7×10^{-10} sec for the 113.0-kev level, and Vartapetian[27] an upper limit of 6×10^{-10} sec for the 321.3-kev level.

[23] H. Brysk and M. E. Rose, Oak Ridge National Laboratory Report ORNL-1830, 1955 (unpublished).
[24] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).
[25] E. E. Berlovich, Bull. Acad. Sci. U.S.S.R., Phys. Ser. (English Translation) **20**, 1315 (1956).
[26] A. W. Sunyar, Phys. Rev. **98**, 653 (1955).
[27] H. Vartapetian, Compt. rend. **244**, 65 (1957).

The Ta^{177} half-life is 56.56±0.06 hours, obtained from a least-squares analysis of the gross gamma-ray decay curve. A previous determination[28] gave 53 hours.

Internal Conversion

Internal conversion coefficients (Table I) were determined from the experimental ratios of electron and gamma-ray intensities. These ratios are proportional to the conversion coefficients. They were normalized by means of certain transitions whose theoretical conversion coefficients were known, as follows. From the previous work on Lu^{177} the multipolarities of the 113.0- and 208.4-kev gamma rays are known, and their theoretical conversion coefficients were taken from tables of Sliv and Band.[29] Neither of these transitions is ideal for normalization, the 208.4-kev because its conversion coefficient is very sensitive to small uncertainties in the $E1/M2$ mixing ratio, and the 113.0-kev because of possible source-thickness effects. However, this normalization gave results which, with our angular correlation data, were sufficient to determine the multipolarities of the 424.7- and 945.4-kev gamma rays. The final normalization constant was a weighted average of the results obtained from the 208.4-, 424.7-, and 945.4-kev transitions. Their conversion coefficients are in brackets in Table I.

This normalization depends on the accuracy of the theoretical conversion coefficients for $M1$ radiation, about which there may still be some question.[30] However, we have made a direct measurement of the 113.0-kev L-conversion coefficient which indicates that our normalization is correct to at least ±10% (see Fig. 8). In this measurement a thin anthracene crystal in an aluminum vacuum chamber was used to detect the conversion electrons, and a NaI(Tl) crystal was used to detect gamma rays. A carrier-free Lu^{177} source on 1 mg/cm² Mylar was used. A baffle prevented scattered electrons from reaching the detector. Coincidence experiments on the (208.4_γ–113.0_e) and (208.4_γ–113.0_γ) cascades yielded the intensity ratio

$$\frac{L \text{ electrons}}{113.0\text{-kev gamma rays}}=\alpha_L=1.35\pm0.10.$$

The coincidence experiment was used to suppress the continuum of beta rays; nevertheless there were enough low-energy beta pulses from K-conversion to obscure a small tail associated with the L-electron peak.[31] To correct for this tail the line shape was determined by detecting monoenergetic electrons selected by the thin-lens spectrometer. From this measurement the contribution of the tail was found to be 7%.

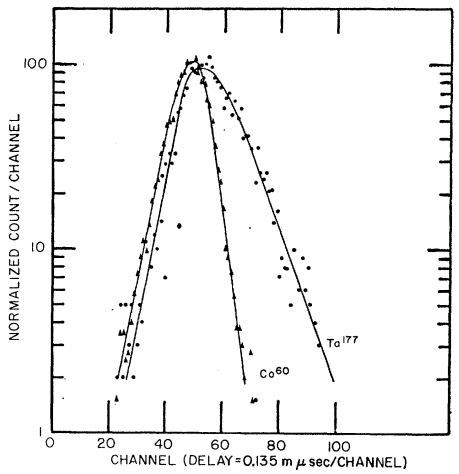

FIG. 7. Pulse-height spectrum obtained with the fast time-to-height converter for coincidences between the 424.7-kev gamma ray and L-conversion electrons of the 113.0-kev gamma ray. The spectrum for prompt coincidences in Co^{60} is also shown. The separation of the centroids of the two curves gives the mean delay of the 113.0-kev transition relative to the 424.7-kev transition. A typical lifetime measurement involves recording of data at various values of fixed delay to ensure that the equipment is being used in its linear region.

The 113.0-kev K/L-conversion ratio was determined from this source in the thin-lens spectrometer (see Table I). Ta^{177} was unsatisfactory because the K electrons are not well resolved from Auger electrons, which are intense because of the large amount of K capture. Our K/L ratio agrees very well with that obtained by other workers.[1,2]

Angular Correlation

Gamma-gamma angular correlations were measured for those cascades listed in Table III. The fast-slow

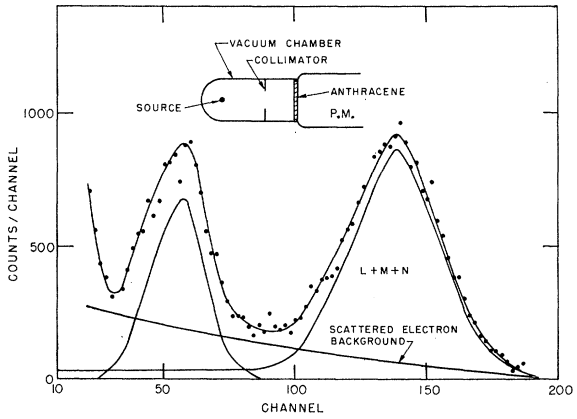

FIG. 8. The spectrum of K- and L-conversion electrons of the 113.0-kev transition obtained from a Lu^{177} source. These data are the difference between two runs. First the spectrum of conversion electrons and beta rays in coincidence with the 208.4-kev gamma ray was obtained and then the beta spectrum in coincidence with the 321.3-kev gamma ray was subtracted.

[28] G. Wilkinson, Phys. Rev. **80**, 495 (1950).
[29] L. S. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57ICCKL, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].
[30] S. G. Nilsson and J. O. Rasmussen, Nuclear Phys. **5**, 617 (1958).
[31] M. S. Freedman, T. B. Novey, F. T. Porter, and F. Wagner, Jr., Rev. Sci. Instr. **27**, 716 (1956).

TABLE III. Angular correlation of gamma rays in the decay of Ta^{177}.

Hf^{177} energy levels (kev)	Coefficients[a] of P_2, P_4 A_2	A_4	Spins of Hf^{177} levels[b]	δ, first γ ray[c]
746.0, 321.3; 113.0, 0	0.31 ±0.04[d]	−0.06 ±0.05	7/2, 9/2; 9/2, 7/2	−0.31 ±0.08
			11/2, 9/2; 9/2, 7/2	0.51 ±0.15
746.0, 321.3, 113.0	−0.32 ±0.01	−0.012±0.012	7/2, 9/2, 9/2	−0.32 ±0.03, −1.9±0.2
			11/2, 9/2, 9/2	0.53 ±0.05, 2.3±0.2
746.0, 113.0, 0	0.10 ±0.02	0.056±0.024	7/2, 9/2, 7/2	0.04 ±0.03
			11/2, 9/2, 7/2	0.035±0.035
848.2, 249.7, 0	−0.097±0.04[e]		9/2, 11/2, 7/2	0.02 ±0.06, <−10
			11/2, 11/2, 7/2	>50, <−1
848.2, 321.3, 113.0	−0.087±0.03	−0.02 ±0.07	7/2, 9/2, 9/2	0.02 ±0.05, −7±2
			9/2, 9/2, 9/2	−1.2 ±0.3, >7, <−20
			11/2, 9/2, 9/2	0.05 ±0.05, >20, <−30
1058.4, 113.0, 0	0.137±0.013	−0.006±0.03	7/2, 9/2, 7/2	0±0.03
			11/2, 9/2, 7/2	0.095±0.025
1058.4, 321.3, 113.0	−0.14 ±0.05	0.06 ±0.10	7/2, 9/2, 9/2	−0.02 ±0.08, −6±2
			9/2, 9/2, 9/2	>10, <−1
			11/2, 9/2, 9/2	0.11 ±0.09, >7, <−30
1058.4, 321.3; 113.0, 0 848.2, 113.0, 0	−0.12 ±0.02[f]			
321.3, 113.0, 0	−0.161±0.009[g]			

[a] The errors listed are the standard deviations, obtained from a least-squares analysis of the data.
[b] The spins of the levels at 0, 113.0, 249.7, and 321.3 kev are assumed to be 7/2, 9/2, 11/2, and 9/2, respectively. All allowable spins of the unknown levels are listed.
[c] The values $\delta_{113.0} = -4.0 \pm 0.2$ and $\delta_{208.4} = -0.07 \pm 0.03$ are used throughout.
[d] A correction of 10% has been made for the (396.0–113.0) coincidences.
[e] This result is based on only two points, at 90° and 180°, assuming a $\cos^2$ correlation.
[f] The interpretation of this result is discussed in the text. A_4 was assumed to be zero.
[g] The best value for this correlation is probably 0.1614 ±0.0015, measured by Klema (reference 40).

coincidence circuit was used with NaI(Tl) detectors and the electronic stabilizer; x rays were attenuated by cadmium absorbers of up to 1.3 g/cm². For some experiments it was necessary to use less absorber to avoid excessive attenuation of the peak in the gating channel relative to the Compton distribution of the higher energy gamma rays. This effect was most serious in the (424.7–113.0) correlation in which only 0.4 g/cm² of cadmium was used. The single-channel analyzer was used to select the 113.0-, 208.4-, 509.0-, or 598.5-kev gamma ray in one crystal, and the coincident pulses from the other crystal were recorded in the 256-channel analyzer. This spectrum was then analyzed by the IBM 650 code described earlier to obtain gamma-ray intensities. Data were taken at 0°, 22½°, 45°, 67½°, and 90° in all cases except the 598.5-kev run. In some runs additional data were taken at 11¼°, 33¾°, 56¼°, and 78¾°. In the (598.5–249.7) cascade only the anisotropy was measured. The stabilizer enabled us to run as long as desired (often several hours) between changes in angle. Angles were selected in a random manner as a further precaution against drift. In each correlation listed in Table II four runs were made at each angle used.

Values of A_2 and A_4 were obtained by a least-squares fit of the gamma-ray intensities to the function

$$W(\theta) = 1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta).$$

An IBM 650 computer was used for the analysis. Corrections of the order of 20% (energy-dependent) were made for the solid angles subtended by the detectors, using curves prepared by West[32] based on the work of Rose.[33] None of the data in Table III are believed to indicate a significant nonzero value for A_4. However, upper limits of A_4 based on the standard error were used in several cases to eliminate mixings which would otherwise satisfy the data.

In addition to the correction for detector solid angles, a correction was necessary in the 208.4-kev correlations for Compton scattering of the high-energy gamma rays from one crystal to the other. This effect produced a peak which entered the 208.4-kev channel. It was controlled as much as possible by lead shielding. The correction, determined experimentally, amounted to 15% in the worst cases. An example of background produced by this effect is shown in Fig. 4(c) at about 825 kev.

The (424.7–113.0) correlation data must be corrected for the (396.0–113.0) cascade, which contributes 10% of the coincidence rate. This correction results in a 10% increase in the (424.7–113.0) correlation if we assume no correlation between the 396.0- and 113.0-kev gamma rays. Possibly a better assumption would be to use 5/2 for the spin of the 509.0-kev state, in which case the (424.7–113.0) correlation (A_2) should be further increased by 6%. An attempt to determine the (396.0–113.0) correlation by assuming the (424.7–113.0) correlation as known from other data was unsuccessful.

The best sources for angular correlation measurements consisted of approx. 10M solutions of an H_2SO_4-HF mixture in a 1-mm-diam polyethylene tube. This is in agreement with the results of McGowan[34] involving an intermediate state of 10^{-8} sec in Ta^{181}. His best

[32] H. I. West, Jr., University of California Lawrence Radiation Laboratory Report UCRL-5451, 1959 (unpublished).

[33] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[34] F. K. McGowan, Phys. Rev. **93**, 471 (1954).

sources were Hf or HfO_2 in $27N$ HF. Several other source forms were tried, including dilute acid solutions. These resulted in attenuation of the correlations involving the 321.3- or 113.0-kev intermediate state. We suspect that with weak solutions the tantalum combined with the polyethylene container. The attenuation was most serious on those cascades involving the 321.3-kev level, for which the theoretical quadrupole moment is three times as large as for the 113.0-kev level.[35] A source giving 78% of the full correlation for the (208.4–113.0) cascade gave approximately 25% of the full correlation for the (424.7–208.4) cascade. This agrees with calculations based on the theoretical treatment of Abragam and Pound.[36] According to their results the attenuation factor G_2, defined by

$$W(\theta)=1+A_2G_2P_2(\cos\theta)$$

in the angular correlation, has the form

$$G_2=1/(1+\lambda_2\tau),$$

if the coincidence resolving time is long compared with the mean life τ of the intermediate state. For the two intermediate states we are considering, λ_2 is proportional to the square of the quadrupole moments, i.e.,

$$\lambda_{321}/\lambda_{113}=9.$$

Using our observed lifetimes in units of 10^{-10} sec,

$$G_{321}=1/(1+63\lambda_{113}),$$

and

$$G_{113}=1/(1+4.6\lambda_{113}).$$

This gives $G_{113}=0.82$ if $G_{321}=0.25$. For *small* attenuations ($G\approx1$), this predicts that correlations involving the 321.3-kev intermediate state will be attenuated 13.7 times as much as those involving the 113.0-kev intermediate state, i.e.,

$$1-G_{321}=13.7(1-G_{113}),\quad G\gg1-G.$$

In Table III we have averaged the data from the two sources that gave the maximum correlation and have assumed there was no attenuation, simply because none was detectable in the (208.4–113.0) cascade. Our results for those cascades involving the 321.3-kev intermediate state could be low by 20% with no detectable effect on the (208.4–113.0) cascade. Such an attenuation seems unlikely, however, in view of McGowan's results on Ta^{181}. This would not affect any of our conclusions except for certain mixings.

The values of δ listed in Table III were obtained by comparing the experimental correlations with theoretical curves. (δ^2 is the intensity ratio of 2^{n+1}- to 2^n-pole radiation.) The theoretical correlations as functions of the multipole orders (δ's) of the gamma rays and of the spins were calculated on an IBM 650 computer, using

[35] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).
[36] A. Abragam and R. V. Pound, Phys. Rev. **92**, 943 (1953).

TABLE IV. Multipolarities of gamma rays in the decay of Ta^{177}.

Gamma ray (kev)	Multipolarity[a] Internal conv.	Other data	Conclusion
71.6	>0.75 *E*1		>0.75 *E*1
96.2	0.95 ±0.2 *M*1	>0.60 *M*1[b]	0.95 ±0.2 *M*1
112.97	<0.10 *M*1[c]	0.054±0.007 *D*[d]	0.060±0.007 *M*1
		0.10 ±0.02 *M*1[e]	
136.7	0.03 ±0.03 *M*1		0.03 ±0.03 *M*1
208.38	0.997±0.003 *E*1	0.994±0.004 *D*[d]	0.996±0.003 *E*1
249.7	0.985±0.01 *E*2		0.985±0.01 *E*2
312.3	>0.9 *E*1		>0.9 *E*1
321.34	0.85 ±0.02 *E*1		0.85 ±0.02 *E*1
357.3	0.2 ±0.3 *M*1		0.2 ±0.3 *M*1
	0.89 ±0.06 *E*1		
396.0	−0.15 ±0.09 *M*1		(100% *E*2)
	0.97 ±0.02 *E*1		
420.95	*M*1, *M*2, *E*3, or *E*4		*M*2[f]
424.70	0.81 ±0.18 *M*1	0.90 ±0.03 *D*[d]	0.90 ±0.03 *M*1
452.9	0.3 ±0.4 *M*1		0.3 ±0.4 *M*1[g]
	0.86 ±0.09 *E*1		
492.5	1.15 ±0.33 *M*1		1.15 ±0.33 *M*1[g]
	0.67 ±0.07 *E*1		
509.0	0.46 ±0.13 *M*1		0.46 ±0.13 *M*1[g]
	0.82 ±0.03 *E*1		
526.9	0.57 ±0.30 *M*1	0.43 ±0.12 *D*[d]	0.45 ±0.12 *M*1
		<0.02 *D*[e]	
549.4	0.25 ±0.18 *M*1		0.25 ±0.18 *M*1[g]
	0.86 ±0.04 *E*1		
598.5	0.98 ±0.05 *E*1	>0.994 *D*[d]	>0.994 *E*1
605.5	0.22 ±0.33 *M*1		0.22 ±0.33 *M*1[g]
	0.86 ±0.08 *E*1		
633.1	1.01 ±0.01 *E*1	>0.998 *D*[d]	>0.998 *E*1
735.2	>0.99 *E*1		>0.99 *E*1
737.0		>0.99 *D*[d]	>0.99 *E*1
746.04	>0.99 *E*1		>0.99 *E*1
848.2	0.988±0.03 *E*1		0.988±0.03 *E*1
945.41	1.14 ±0.21 *M*1	>0.998 *D*[d]	>0.998 *M*1
1058.38	1.00 ±0.20 *M*1		1.00 ±0.20 *M*1

[a] The fractional amount of the lowest order multipole is given, assuming only the two lowest possible orders occur. *D*, *Q*, etc., denote dipole, quadrupole, etc. Two possibilities exist in some cases due to unknown parity change.
[b] This is based on the K/L ratio of >2 reported by Harmatz *et al.* (reference 11).
[c] *K* shell only. The *L*-shell conversion is 32% larger than expected from theory.
[d] Angular correlation. We use Klema's data on the (208–113) cascade.
[e] *L*-subshell ratios. This includes data of Wiedling, Marmier and Boehm, and the present authors.
[f] This is discussed in the Decay Scheme section.
[g] This choice is preferred because it avoids the relatively large *M*2/*E*1 mixing ratios that would otherwise be implied.

data from Ferentz and Rosenzweig[37] and Biedenharn and Rose.[38] The spins of the 0-, 113.0-, 249.7-, and 321.3-kev levels were taken as 7/2, 9/2, 11/2, and 9/2, respectively, from the previous studies of these states.[2,3,39–41] In each experiment the mixing of the second gamma ray (113.0-, 208.4-, or 249.7-kev) was assumed to be known. Unfortunately, the existing data do not determine these mixings as precisely as would be desirable, especially for the 113.0-kev transition. Internal conversion data (see Tables I and IV) give $\delta_{113}=-3.0$ and $\delta_{208}=-0.055$, where only *L*-subshell ratios are used for the 113.0-kev transition. We have used the values $L_I/L_{II}=0.20\pm0.015$ and $L_{III}/L_I=4.6\pm0.3$ for the 113.0-kev gamma ray, and $K/L=6.0\pm0.2$ for the 208.4-kev gamma ray. These are averages of our data and the data of Wiedling[2] and Marmier and Boehm.[1] The theoretical conversion coefficients of Sliv

[37] M. E. Ferentz and N. Rosenzweig, Argonne National Laboratory Report ANL-5324, 1954 (unpublished).
[38] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953). Also private communication with Professor Biedenharn and Dr. Rose.
[39] K. G. Steffen, Z. Physik **147**, 132 (1957).
[40] E. D. Klema, Phys. Rev. **109**, 1652 (1958).
[41] H. J. Behrend, Z. Naturforsch. Pt. a. **13**, 211 (1958).

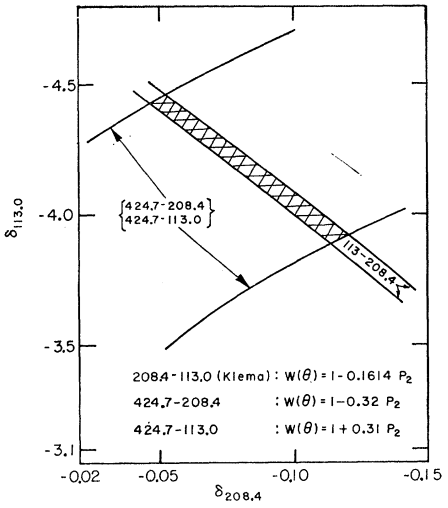

FIG. 9. Values of the mixing parameter δ for the 113.0-kev gamma ray plotted vs the values for the 208.4-kev gamma ray. The values that agree with the angular correlation of Klema for the (208.4–113.0) cascade lie between the two curves slanting downward to the right. The values that agree with the indicated angular correlations measured in Ta^{177} lie between the other two curves. The shaded area represents the possible range of values for $\delta_{113.0}$ and $\delta_{208.4}$.

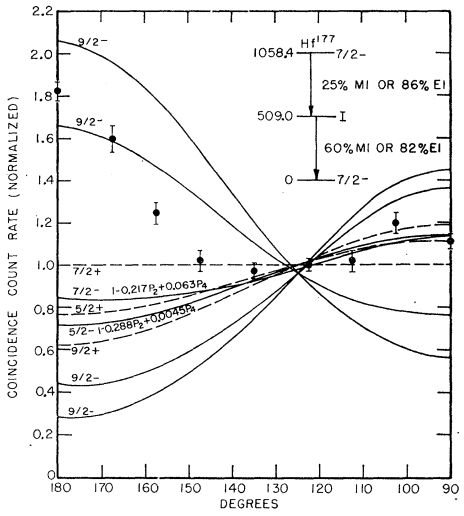

FIG. 10. Angular correlation in the (549.4–509.0) gamma-ray cascade. The curves are theoretical curves for the mixings and spin values indicated. For the 9/2− case all possibilities are shown. For the other spins only the curve giving the best fit is shown. Dashed lines are used for even parity and solid lines for odd parity. The data are distorted at angles >135° due to detection of annihilation radiation.

and Band[29] were used. These mixings have also been determined from the various angular correlations in the (424.7–208.4–113.0) gamma-ray cascade (see Fig. 9). They give $\delta_{113}=-4.20\pm0.25$ and $\delta_{208}=-0.08\pm0.03$. In view of the disagreement between the observed and theoretical L conversion of the 113.0-kev gamma ray, we believe the angular correlation values should carry more weight, and have used

$$\delta_{113}=-4.0\pm0.2,$$
$$\delta_{208}=-0.07\pm0.03.$$

The 249.7-kev transition is assumed to be pure $E2$ (i.e., $\delta_{250}=0$).

Figure 10 shows the (549.4–509.0) angular correlation. The data cannot be used at angles greater than 135° because of coincidences due to annihilation radiation. The counting rates and statistical accuracy were lower than for any of the other angular correlation runs except the (598.5–249.7) cascade. We have used the mixings required by the internal conversion coefficients to calculate the expected correlations for spins 5/2, 7/2, and 9/2 of the 509.0-kev level. Both positive and negative parities were considered. Four different correlations are obtained for each spin and parity, because of the unknown sign of the mixing parameter δ in each radiation. In Fig. 10 the four curves are shown only for the 9/2− case. For the other cases we have shown only those curves which fit the data best. The 7/2−, 5/2±, and possibly 9/2+ give the only reasonable agreement. However, we consider the positive parity unlikely because of the unusually large amounts of $M2$ radiation required in the $E1$-$M2$ mixtures for both the 509.0- and 549.4-kev transitions.

Experiments on Lu^{177} Decay

The beta-decay probabilities to the Hf^{177} levels were determined with better precision than had previously been obtained. A newly acquired 3×3-in. NaI(Tl) crystal giving 7.5% resolution at 662 kev was used to measure intensities of the 113.0-, 249.7-, and 321.3-kev gamma rays relative to the 208.4-kev gamma ray in the Lu^{177} decay. In the measurement of the 249.7- and 321.3-kev intensities, a 1.4-g/cm² Cd absorber was used to attenuate the lower energy peaks and thus reduce coincidence effects. Heath's[42] efficiency curves were used to obtain the relative efficiencies of the 3-in. crystal as a function of energy. In the singles spectrum the gamma-ray intensities obtained relative to the 208.4-kev gamma intensity were

$$I_{113.0}/I_{249.7}/I_{321.3}$$
$$=(0.62\pm0.02)/(0.020\pm0.002)/(0.0228\pm0.001).$$

Corrections were made for coincidence effects due to the (208.4–113.0) cascade.

The 136.7- and 71.6-kev transitions could not be resolved in the singles spectrum. In order to obtain their intensities the (136.7–249.7) branching ratio and the (71.6–249.7) gamma-ray coincidence rate were used. The ratio of the 136.7- and 249.7-kev gamma-ray intensities was determined from their coincidence rates with the 598.5-kev gamma ray in Ta^{177}. The coincidence rate between the 71.6- and 249.7-kev gamma rays was

[42] R. L. Heath, Atomic Energy Commission Report IDO-16408, 1957 (unpublished).

measured in a Lu^{177} source. These results yield gamma-ray intensities relative to the 208.4-kev gamma ray of

$$I_{71.6}/I_{136.7}=(0.003\pm0.001)/(0.0047\pm0.0015)$$

for Lu^{177}.

The total intensity of beta decay of a Lu^{177} source was determined in a 4π-geometry beta proportional counter. This beta-decay intensity was then compared with the 208.4-kev gamma intensity obtained by counting the gamma ray in our accurately calibrated $1\frac{3}{4}\times2$-in. NaI(Tl) crystal, giving 8.77 ± 0.40 beta particles per 208.4-kev gamma ray. These results were used with the total decay energy of 496 kev[1] and the half-life of 6.75 days[43] to calculate the branching ratios and log ft values in Fig. 1.

Ta^{177} Decay Scheme

The energies of the levels in Fig. 1 are based on conversion electron measurements of Marmier and Boehm[1] and those made in the present work. They are in reasonable agreement with those reported by Harmatz *et al.*[11] Single and coincidence gamma-ray measurements were used to help determine the sequence of levels and the modes of decay. Tentative assignments are shown with dashed lines.

The spins and parities of the ground state and the 113.0-, 249.7-, and 321.3-kev levels have been regarded as known from the earlier work.[2,3,5,39–41] Also the Ta^{177} ground state has been taken as $7/2+$ to agree with the spins and decay data of the other odd-A tantalum isotopes.[10] With these assumptions the results on internal conversion and angular correlation in Tables I and III determine uniquely the spins of the 746.0- and 848.2-kev levels. The 1058.4-kev level is also determined uniquely if spin 11/2 is considered to be completely rejected by the log ft value of 6.4 ± 0.3 and the apparent $M1$ character of the 1058.4-kev gamma ray. A spin of 5/2 or 7/2 seems preferable for the 509.0-kev level from angular correlation and internal conversion data, but 9/2 is also possible. From our internal conversion data the 605.5-kev level could have any spin from 7/2 to 11/2.

The parities of the 746.0-, 848.2-, and 1058.4-kev levels are determined uniquely by the data in Table I, which indicate a change in parity for the 848.2-, 746.0-, 737.0-, 735.2-, and 633.1-kev transitions ($E1$ radiation). Negative parity seems preferable for the 509.0-kev level; otherwise the 549.4- and 509.0-kev transitions must have an unusually large amount of $M2$ mixed with $E1$ radiation. This is also true for the 605.5-kev level.

The spin and parity assignments receive further confirmation from the angular correlation between the 113.0-kev and the unresolved 737.0- and 735.2-kev gamma rays. The expected correlation in this composite cascade is obtained by adding the intensities of the 737.0- and 735.2-kev gamma rays, using their respective theoretical correlations with the 113.0-kev transition. For example, the expected correlation is $(1-0.106P_2)$ for the decay scheme shown in Fig. 1, to be compared with the experimental value of $[1-(0.12\pm0.02)P_2]$. It turns out that with either spin 7/2 or 11/2 for the 1058.4-kev level and using our observed multipolarities (see Table IV), the spin of the 848.2-kev level must be 9/2 with even parity.

The levels at 421.0, 488.8, and 585.8 kev were determined using less accurate data and hence the coincidence experiments will be discussed. The transitions of 257.3 kev (only K conversion observed), 67.9 kev (only L_I conversion observed), and 421.0 kev fit nicely between the ground state and the 746-kev level on the basis of energy balance. The appearance of a 257-kev peak in the 746-kev sum-coincidence experiment supports the 488.8-kev level. One might pessimistically suggest from the intensity (see reference k in Table I) that this peak results from an $M2$ transition of 496.3 kev to the 249.7-kev level. This seems improbable from any reasonable guess of the transition probabilities (assuming $E1$ radiation is retarded by about 10^5 and $M2$ by about 10^2 over single particle rates[10]). The 250-kev and the 208-kev coincidence experiments add further confirmation to the level at 488.8 kev. The 250-kev coincidence experiment shows the (257.3–168) and (257.3–489) cascades. The 208-kev coincidence shows the 168-kev gamma ray and a possible 160.4-kev gamma ray. The 168/489 branching ratio is consistent with $E2/E1$ radiation when reasonable estimates of the transition probabilities are made. However, the assignment of the 168-kev transition as $E2$ radiation is questionable. The limits on the intensities indicate the conversion coefficient is only half the value expected for $E2$ radiation. We have not been able to explain the gamma-ray intensity by spurious effects such as scattering or simultaneous detection of x rays and 113.0-kev gamma rays. Estimates of the 67.9-kev transition intensity indicate that our intensity of the 168-kev gamma ray may be too large. The results would be more reasonable if this intensity were in line with the upper limits of electron conversion assuming $E2$ radiation. For this reason we leave the 488.8-kev level in the tentative classification. The 585.8-kev level is assigned on the basis of energy fit of the transitions of 97.1 kev (only K conversion observed) and 160.4 kev (only K conversion observed).

The assignment of the transitions into these three levels is consistent with a coincidence experiment between x rays and gamma rays. It was found that the counting rate at about 420 kev was enhanced some 30% over that expected if the 421.0-kev transition has a lifetime greater than 0.1 μsec. This lifetime has a bearing on the multipolarity of the 421.0-kev transition. Our observed value of α_K is 0.1 and the K/L-conversion ratio reported by Harmatz *et al.* is 5.2. The theoretical values for $M2$ radiation are 0.21 and 5.2, respectively. Har-

[43] R. H. Betts, O. F. Dahlinger, and M. Munroe, Can. J. Phys. **36**, 73 (1958).

matz *et al.* were tempted to assign a spin and parity of $\frac{1}{2}-$ to the level (on the basis of less information), which would require $M3$ radiation with $\alpha_K=0.58$ and $K/L=3.9$. A spin and parity of $\frac{1}{2}+$ would require $E3$ radiation with $\alpha_K=0.065$ and $K/L=1.8$. Neither of these assignments is compatible with lifetime or conversion data. $E2$ radiation would require an $\alpha_K=0.023$ and $K/L=3.8$. This value of α_K is outside our expected error. The best agreement with all available data is $M2$ radiation for this transition, requiring that the 421.0-kev level have a spin and parity of $3/2+$. The absence of strong transitions from higher levels into the 421.0-kev level is additional support for a low spin value.

The level at 447.9 kev is placed on the basis of the energy fit of the 298.1-, 611-, and 126.8-kev transitions. The 611- and 126.8-kev transitions are questionable (see Tables I and II). However, the level is expected to occur and the transition from the 746.0-kev level should be observable.

Two transitions are not assigned in the decay scheme. A 51.1-kev transition and a possible 158.9-kev transition (based on K conversion only) were observed (see Table II) which would fit nicely between the 1058.4- and 848.2-kev levels if an additional level is added. However, the possible evidence from coincidence experiments is not very strong and the expected electron conversion lines for transitions to other levels were not observed.

The gamma-ray multipolarities, given in Table IV, are derived from internal conversion and angular correlation data. Where angular correlation data are available they usually give the more precise values for the mixings. The quoted errors allow for a possible 20% attenuation of those angular correlations for which the 321.3-kev level is the intermediate state.

It appears that the 113.0-kev L conversion is about 32% larger than expected from theory. It also appears that the K and L conversion of the 249.7-kev transition is anomalously large by about 65%. As pointed out earlier we do not believe that these anomalies can be due to an incorrect normalization of our gamma-ray and electron intensities, because of the independent measurement of the 113.0-kev conversion coefficient and also because the numerous $E1$ conversion coefficients agree well with theory. Except for these two predominantly $E2$ transitions our conversion coefficients agree with the theoretical values within the accuracy permitted by our knowledge of the mixings. McGowan and Stelson[44] have reported several other cases of conversion coefficients some 20% larger than expected from theory for $E2$ transitions.

Marmier and Boehm have studied the transitions involved in the decay of Lu^{177}. Their original electron intensity ratios[1,45] have been combined with our more accurate gamma-ray data. We have normalized to their 208.4-kev conversion electron intensity as their value of $\alpha_K(208)=0.044$ is close to our value of 0.043. Furthermore the 208.4-kev conversion data are more reliable than those of the 113-kev gamma ray because there is less uncertainty in detector efficiencies at higher energies. This normalization gives $\alpha_K(113)=0.55$, $\alpha_L(113)=1.5$, $\alpha_K(250)=0.16$, $\alpha_L(250)\lesssim 0.05$, $\alpha_K(321)=0.12$, and $\alpha_L(321)\lesssim 0.03$, to be compared with our values from the Ta^{177} decay of 0.78, 1.40, 0.148, 0.057, 0.080, and 0.018, respectively. Their value of $\alpha_K(250)$ includes a 1/3 weight from a later independent measurement of $e_K(208)/e_K(250)=16\pm 7$. Their values of $\alpha_L(113)$ and $\alpha_{K,L}(250)$ appear to be in agreement with our anomalously large values.

The $\log ft$ values were calculated from curves of Moszkowski[24] using the total decay energy obtained from our measured $\beta+/K$-capture and L/K-capture ratios. The relative intensities of capture to the various Hf^{177} levels were deduced from the gamma-ray and x-ray intensities, by equating the rates of decay to and from each level.

DISCUSSION

We have compared the states in Hf^{177} with those predicted for the spheroidally deformed nuclear shapes observed in this region.[35] These nuclei exhibit intrinsic states characteristic of the nuclear structure, and rotational states which correspond to rotation of the nucleus without changing its intrinsic state. Nilsson and others[7,8] have calculated the energies of the intrinsic states of nonspherical odd-A nuclei as a function of the deformation, assuming an independent particle model. These states are characterized by three "asymptotic" quantum numbers shown in square brackets beside the levels in Fig. 1. These quantum numbers (which would accurately characterize the states in the limit of a very anisotropic, axially symmetric, harmonic oscillator potential) are N, the number of modes in the wave function, n_z, the number of nodal planes perpendicular to the symmetry axis, and Λ, the component of the particle's orbital angular momentum along the symmetry axis. In addition, K, the component of the total angular momentum along the symmetry axis, and the parity, which are constant within a rotational band, are used. The energies within a given rotational band are given approximately by

$$E_I=E_0+\frac{\hbar^2}{2\mathcal{I}}[I(I+1)+a(-)^{I+1/2}(I+1/2)\delta_{K,1/2}] +B[I(I+1)+a(-)^{I+1/2}(I+1/2)\delta_{K,1/2}]^2,$$

where E_0 is the energy of the rotational ground state, $\mathcal{I}$ is the effective moment of inertia, and a is a constant that occurs only for $K=1/2$. The last term, with the constant B, is small and may be due to rotation-vibration interactions,[35,46] in which case the sign is negative;

[44] F. K. McGowan and P. H. Stelson, Phys. Rev. **107**, 1674 (1957).
[45] F. Boehm (private communication).
[46] A. K. Kerman, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **30**, No. 15 (1956).

or it may be due to particle-rotation interactions, in which case the sign can be either positive or negative. In addition to the energy predictions, which are often of enough precision to identify the bands, the gamma-ray and beta-ray reduced transition probabilities of order L from a given level to the members of a rotational band are predicted[47] to be proportional to the squares of the Clebsch-Gordan coefficients

$$\langle I_i L K_i K_f - K_i | I_i L I_f K_f \rangle.$$

The nuclear deformation δ may be obtained from the reduced $E2$ transition probabilities $B(E2)$, in the ground-state rotational band.[10] The values of $B(E2)_{up}$ obtained from lifetime measurements of the 113.0-kev level are 3.14 ± 0.34 (in units of $e^2 10^{-48}$ cm^4) for the present work and 2.39 ± 0.34 for the work of Berlovich.[25] Reported Coulomb excitation values are 3.34 and 3.95 from gamma-ray detection and 1.0 from L-conversion electron detection. For all the above values of $B(E2)_{up}$ we have used our measurements of 2.59 ± 0.15 for the total internal conversion and 16 ± 2 for the $E2/M1$ gamma-ray mixing ratio. The value of δ is 0.27 from the lifetime measurements and 0.31 from the first two Coulomb excitation measurements mentioned above.

As expected, the $E2$ part of the 113.0-kev transition is especially fast. The transition probability is enhanced over the single-particle estimate[4] (Eq. II, A.58) used by Alder *et al.* by a factor of 107, based on an average of the $B(E2)_{up}$ values.

A first attempt at correlating the Hf^{177} levels with the Nilsson model has been made by Mottelson and Nilsson[10] incorporating our earlier incomplete experimental data. They assigned the levels at 0, 113.0, 249.7, and 321.3 kev, previously studied from Lu^{177} decay, as indicated in Fig. 1. They also made tentative orbital assignments for the levels at 746.0, 848.2, and 1058.4 kev, in agreement with the assignments in Fig. 1. From our observed properties of these levels the assignments now appear quite certain.

The interpretations of the other levels are more speculative because their spins and parities are not definitely known. The intrinsic levels which could occur in this region are the [512 5/2−], [505 11/2−], [512 3/2−], [521 1/2−], and [510 1/2−]. Also at this distortion several of the orbitals normally associated with neutron numbers >126 could occur, including the [651 1/2+], [640 1/2+], and [642 3/2+].

The spacing of the levels at 509.0 and 605.5 kev is compatible with a $K=5/2$ rotational band assignment using the [512 5/2−] orbital. The intensity of the 96.2-kev $M1$ transition between the levels supports this assignment. Also, the questionable transition of 125.8-kev (Table II) could be the transition between the 9/2 and 7/2 members of this band. This would require an additional level at 731.3 kev.

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

TABLE V. Empirical constants for the rotational bands in Hf^{177}.

$[Nn_z\Lambda K\pi]$	E_0 (kev)	$3\hbar^2/\mathcal{I}$ (kev)	B (kev)
[514 7/2−]	0	76.9	−0.0064
[624 9/2+]	321.3	69.0	
[642 3/2+]	421.0	80.8	0.012
[512 5/2−]	509.0	80.9	0.0074[a]
[633 7/2+]	746.0	67.7	

[a] This assumes that the questionable 125.8-kev transition (see Table II) is the transition between the 9/2 and 7/2 members of this band.

We can assign the levels at 421.0, 488.8, and 585.8 kev to a $K=3/2$ rotational band using the orbital [642 3/2+]. The 67.9-kev $M1$ transition between the 488.8- and 421.0-kev levels supports the assignment as a rotational band.

The questionable level at 447.9 kev is assigned as the 11/2 member of the [624 9/2+] rotational band. The intensity of the 298.1-kev transition is in satisfactory agreement with this interpretation if we assume $E2$ radiation. However, the questionable 611-kev transition would have to be $M2$. Its observed intensity is several orders of magnitude larger than that expected for $M2$ transitions.

The inertial parameter $3\hbar^2/\mathcal{I}$ and the correction term B can be calculated from the level spacings. The values are given in Table V. The value of B is usually negative.[11]

Gamma-ray branching ratios from an initial level to the various levels in a rotational band are predicted with enough accuracy to be of considerable help in classifying levels. Table VI gives the comparison between the observed and calculated branching ratios to the levels in each rotational band. For transitions to the ground-state band we have considered in addition to the spins adopted in Fig. 1 other spins which are not completely rejected by our other data. We have not done this for transitions to the bands starting at 321.3 and 509.0 kev because there are not enough experimental data.

We see that the values I, $K=7/2$, 7/2 are strongly preferred for the 1058.4-kev level. The rotational band assignment with $K=7/2$ for the 746.0- and 848.2-kev levels is clearly favored over any other possible assignment. For the 605.5-kev level the probable errors in the experimental ratios are greater, but the values I, $K=7/2$, 5/2 are clearly preferred. There is also a definite preference for negative parity. The ratios for transitions from the 509.0-kev state are in satisfactory agreement with either I, $K=5/2$, 5/2 or 7/2, 7/2, but not 7/2, 5/2. For all these levels, and also for the 249.7-kev level, the theoretical branching ratios to members of the ground-state band agree with those observed within a factor of 2. In fact, the 598.5-kev transition from the 848.2-kev level is the only one whose intensity disagrees by more than the experimental error.

For the transitions from the 321.3-kev level to the ground-state band there is a strong disagreement be-

TABLE VI. Gamma-ray branching ratios to members of the rotational bands in Hf^{177}.

Rotational band: $[Nn_z\Lambda K\pi]$, (kev)	Initial level: kev (I,K)	Relative γ-ray intensities (K denotes K forbidden) Theoretical[a] $L=1$	Theoretical[a] $L=2$	Observed[b] $L=1$	Observed[b] $L=2$
[514 7/2−], (0, 113.0, 249.7)	1058.4 (7/2, 7/2)	100/20/0	100/52/6	100/18/<0.002 ($M1$)	
	(7/2, 5/2)	100/250/0	100/13/33		
	(11/2, 11/2)	0/K/K	100/22/2.6		
	(11/2, 9/2)	0/18/4.6	100/3.4/4.1		
	(11/2, 7/2)	0/18/14	100/270/0.07		
[514 7/2−], (0, 113.0, 249.7)	848.2 (9/2, 7/2)	55/100/36	1150/100/240	48/100/21 ($E1$)	
	(9/2, 9/2)	680/100/5.4	280/100/5.9		
	(9/2, 5/2)	11/100/110	72/100/0.6		
[514 7/2−], (0, 113.0, 249.7)	746.0 (7/2, 7/2)	100/17/0	100/40/3	100/18/(<0.01) ($E1$)	
	(7/2, 5/2)	100/210/0	100/10/17		
[514 7/2−], (0, 113.0, 249.7)	605.5 (7/2, 5/2)	53/100/0	44/3.5/4.0	12/100/1.5 ($M1$)	44/0/6 ($E2$)
	(9/2, 5/2)	13/100/78	44/44/0.1		
	(7/2, 7/2)	690/100/0	44/9/0.8		
[514 7/2−], (0, 113.0, 249.7)	509.0 (5/2, 5/2)	85/0/0	100/22/0	85/0/<5 ($M1$)	100/23/<15 ($E2$)
	(7/2, 5/2)	85/144/0	100/9/6		
	(7/2, 7/2)	85/11/0	100/25/0.9		
[514 7/2−], (0, 113.0, 249.7)	447.9 (11/2, 9/2)	0/100/9	100/14/3		
[514 7/2−], (0, 113.0, 249.7)	421.0 (3/2, 3/2)		100/0/0		100/(<2)/(<2) $M2$
	(5/2, 5/2)	100/0/0	100/16/0	100/(<7)/(<5) ($M1$ or $E3$)	
	(7/2, 7/2)	100/10/0	100/19/0.3		
	(1/2, 1/2)		100/0/0 ($L=3$)		
[514 7/2−], (0, 113.0, 249.7)	321.3 (9/2, 9/2)	1630/100/0.4	5/0.4/0.003	2.0/100/0.3 ($E1$)	0.3/0.4/(<0.07) ($M2$)
[514 7/2−], (0, 113.0, 249.7)	249.7 (11/2, 7/2)	0/100	100/23		100/24 ($E2$)
[624 9/2+], (321.3, 447.9)	1058.4 (7/2, 7/2)	100/0	100/22	100/(<50) ($E1$)	
	(11/2, 11/2)	100/10	100/71		
[624 9/2+], (321.3, 447.9)	848.2 (9/2, 7/2)	82/161	100/12	82/(<5) ($M1$)	100/(<14) ($E2$)
[624 9/2+], (321.3, 447.9)	746.0 (7/2, 7/2)	100/0	11/1.1	100/(<1) ($M1$)	11/(<2.2) ($E2$)
[512 5/2−], (509.0, 605.5)	1058.4 (7/2, 7/2)	33/6	100/43	33/13 ($M1$)	100/31 ($E2$)

[a] These are the ratios of the squares of the Clebsch-Gordon coefficients multiplied by the third power of the gamma-ray energy for $L=1$ and the fifth power of the gamma-ray energy for $L=2$. The relation between the ratios for $L=1$ and $L=2$ is arbitrary, and has been adjusted for best agreement with the observed mixing in those cases where the gamma rays are mixed.

[b] Values in parentheses were obtained from the conversion electron data by using the theoretical conversion coefficient for pure multipoles. Errors may be deduced from Tables I and IV.

tween theoretical and observed intensity ratios. The $E1$ component in the 321.3-kev transition is too weak relative to that in the 208.4-kev transition by a factor of about 800, and there is some indication that the $M2$ component is also weak by a factor of about 10. However, this discrepancy in $M2$ ratios could be due to the uncertainty in the mixing of the 208.4-kev transition. We have calculated the reduced $E1$ transition probability for the 208.4-kev gamma ray, using Nilsson wave functions.[6] We find $B(E1)=0.90\times10^{-30}e^2$ cm^2 for $\delta=0.095$, and $2.9\times10^{-30}e^2$ cm^2 for $\delta=0.29$. This agrees well with the observed value of $0.90\times10^{-30}e^2$ cm^2. This is a retardation of 7×10^4 over the single particle estimate[4] and is considered a normal retardation.[30] It is concluded that the disagreement between observed and theoretical intensity ratios for the 208.4- and 321.3-kev $E1$ transitions is due to excessive retardation in the 321.3-kev transition. Nilsson[48] has indicated that in view of this extreme retardation it is not surprising that the theoretical branching ratio does not hold. In such a case, modes of decay other than normal may be involved.

For transitions to the [624 9/2+] band there is one apparent disagreement, for the transitions from the 848.2-kev level. This discrepancy would largely be removed if the 526.9-kev radiation is nearly 100% $E2$. This is compatible with the angular correlation, but would disagree with the internal conversion by a factor of about 2. The expected error for the internal conversion coefficient is $\pm40\%$.

Table VII shows the comparison between observed ratios of the electron-capture ft values and the theoretical ratios for each rotational band. The agreement is good for the bands starting at 0 and 746.0 kev. For the band starting at 321.3 kev the decay to the higher members would be second forbidden and is not expected to occur. The absence of electron capture to the 509.0-kev level is in strong disagreement with the theoretical predictions for a $K=5/2$ band. There appears to be little or no electron capture to the levels of the $K=3/2$ band. Such a retardation might be expected in view of the K forbiddenness of the transitions.

[48] S. G. Nilsson (private communication).

The classification of the beta decay branches according to the asymptotic quantum number selection rules[47] is given in Fig. 1 for the indicated level assignments. The log ft values are in satisfactory agreement with these classifications only for the ground state band and the 1058.4-kev level, and possibly the 605.5-kev level. The levels at 321.3, 746.0, and 848.2 kev have ft values approximately 10 times larger than usually observed. However, there seems to be very little chance that the spin and parity assignments of these levels are in error.

The gamma-ray transitions may also be classified as hindered or unhindered according to the asymptotic quantum numbers. We find two cases where the mixing might be affected because of a hindrance of one component relative to the other. For the transitions from the 321.3-kev level to the ground state band the $E1$ components are hindered while the $M2$ components are allowed. This helps explain the small amount of $M2$ mixing in the 208.4-kev transition, but does not explain the extra hindrance of the $E1$ component in the 321.3-kev transition. The only other similar situation in this decay scheme is the 737.0-kev transition to the 321.3-kev level. Here, in spite of the fact that $M2$ is unhindered and $E1$ is hindered, we have not detected an $M2$ component.

A comparison of ft values shows that Lu^{177} and Ta^{177} have very nearly equal values for decay to the 0- and 113.0-kev levels. This would seem to be a significant success for the nuclear model as the ground states of both parents have been assigned [404 7/2+]. The decay to the 321.3-kev state is quite different, the ft value of the decay from Ta^{177} being about 20 times larger than that from Lu^{177}. Also, the ft values of the decay of Ta^{177} to the 746.0- and 848.2-kev levels are about 10 times larger than those usually observed for allowed hindered transitions. We have tried to explain the results by invoking the idea of pairing energy in which the order of pairwise filling of the Nilsson orbitals may be different from the single particle order. Our attempts at a detailed explanation using these ideas have not been completely successful. However, there seems to be strong evidence of pairing effects in the ground state of Ta^{177}, since the model would prefer [514 9/2−] or [402 5/2−], whereas we find [404 7/2+]. Part of the explanation of the large ft values probably centers around the particle rearrangement required in the Ta^{177} decay as a result of the [404 7/2+] ground state. The decay from Lu^{177} involves only single-particle transitions.

TABLE VII. Intensity ratios of beta decay from the Ta^{177} and Lu^{177} ground states to rotational bands in Hf^{177}. The Ta^{177} and Lu^{177} states are assumed to have I, $K=7/2$, 7/2.

Rotational band in Hf^{177} $[Nn_z\Lambda K\pi]$, (kev)	Ratio of ft values: Theoretical ($L=1$)	Observed	
[514 7/2−], (0, 113.0, 249.7)	1/3.5/∞	1/3.0/1600 1/2.7/30	(Ta^{177}) (Lu^{177})
[512 5/2−], (509.0, 605.5)	1/3.5	1/0.25	(Ta^{177})
[633 7/2+], (746.0, 848.2)	1/3.5	1/2.5	(Ta^{177})

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