0–600 kev Gamma-Ray Spectra from Thermal Neutron Capture in the Region $A=104$ to 198*

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The energies and absolute intensities of prominent peaks in the 0–600 kev region of the gamma-ray spectrum following thermal neutron capture have been measured with a single NaI(Tl) scintillation spectrometer. The elements investigated were rhodium, silver, cadmium, indium, antimony, tellurium, iodine, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, hafnium, tantalum, rhenium, iridium, platinum, and gold.

THE absorption of a neutron by a nucleus results promptly in a cascade of ~4 gamma rays. The first members of this cascade are often assumed to be $E1$ transitions since the nucleus is excited by several Mev. This will generally afford appreciable population of most of the low-lying states of both parities and of spins within three or four units each side of the spin of the compound state. Thus the observation of the low-energy part of a capture gamma-ray spectrum will sometimes reveal transitions inaccessible in beta-decay work because of spin considerations. In addition, many of the isotopes which can be excited by neutron capture are not accessible by beta decay—particularly odd-odd nuclei.

I. METHOD

The experimental geometry is shown in Fig. 1. The neutrons were obtained from the 6-Mev electron linear accelerator using a thick gold target for the production of bremsstrahlen and a surrounding mass of Be for neutron production. The beam pulse was 1.2 μsec in duration and was repeated at a rate of 112 cps. The primary neutrons were moderated by paraffin in order to increase the flux of neutrons of thermal energies. The sample was placed next to the paraffin moderator and was viewed by the NaI scintillator through a collimation hole in the lead shielding. The resulting counting rate decreased exponentially with time after the 1.2-μsec accelerator beam burst with a mean life of about 120 μsec. In order to allow ample time for the detector to recover from the effects of the accelerator flash, pulses were analyzed during the interval 120 to 240 μsec after the accelerator pulse.

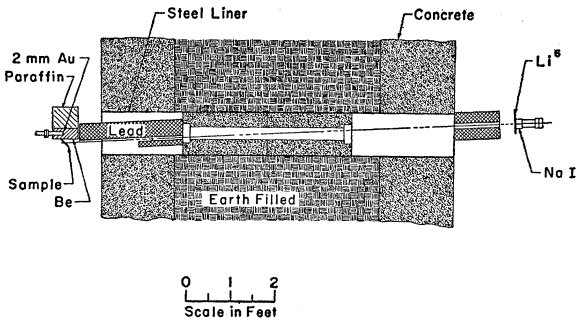

FIG. 1. Experimental geometry.

It should be noted that this use of a pulsed source of neutrons discriminates against the detection of isomeric transitions with half-lives appreciably longer than 100 μsec. Consider that τ is the mean life of the neutron flux (i.e., about 120 μsec), that T is the pulse repetition period of the accelerator, that g_1 and g_2 are the beginning and ending times of the detection gate measured in units of τ and that the mean life of the isomer is $\gg T$. Then the ratio R of the number of prompt disintegrations to the number of isomeric disintegrations, both during the gate g_1-g_2, is

$$R=\frac{T}{\tau}\left(\frac{e^{-g1}-e^{-g2}}{g_2-g_1}\right). \quad (1)$$

For $\tau=120$ μsec, $g_1=1$, $g_2=2$, and $T=10^4$ μsec, then $R=20$.

The scintillator was a 2.5-in. diam by 1.7-in. cylinder of NaI(Tl) which was mounted on a 3-in. diam photomultiplier. The collimated neutron capture gamma-ray beam from the sample was 1 in. by 3 in. in cross section. The Li^6 slab placed in front of the scintillator prevented slow neutrons from reaching the scintillator, without itself producing significant amounts of gamma radiation. There was, however, virtually no difference in trial spectra obtained without the Li^6.

The energy calibration was obtained with points at 70, 192, 279, 511, and 662 kev by using Na^{22}, In^{114}, Cs^{137}, and Hg^{203} sources. These calibrations were made at frequent intervals during the measurements and with the accelerator in operation. This procedure was necessary because of the gain shift (~10%) of the scintillator system caused by the intense accelerator flash. This shift stabilized within about 40 minutes after first operating the accelerator each day, and no data were obtained during this period. After this warmup period the energy calibration was steady, but it was nevertheless carefully monitored. The energy measurement of the center of a peak is considered to be correct within the larger of ±5% or ±6 kev.

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II. ANALYSIS

In order to determine the relative intensities of various gamma rays it is necessary to know the energy dependence of the photopeak efficiency. This was determined by the method described[1] previously. It is further necessary to know what fraction of the gamma rays is absorbed before reaching the scintillator, and this was calculated[1] taking into account the absorption of the intervening air and the Li^6 slab.

In order to obtain information about the absolute intensities of the gamma rays, a comparison was made with the counting rate obtained from the B^{10} sample as shown in Fig. 2. The B^{10} sample was thick enough to capture more than 99% of all slow neutrons entering it. Corrections were made for the counting loss due to the dead time of the analyzer. By using the published values[2] of the thermal capture cross section for the various elements the absolute intensities of the gamma rays could be obtained. In doing this it was assumed that the neutron flux incident on the sample did not depend on the absorptive properties of the sample—i.e., that the flux depression by the sample was small. This was considered a valid assumption since the probability was small that a neutron would return to the paraffin having once left it, and the probability was similarly small that neutrons reach the sample except by proceeding directly from the paraffin. This was tested for two elements by determining the absolute intensity of a peak using a thick sample ($N\sigma \sim 10$) and a thin sample ($N\sigma \sim 0.1$) as well as by adding a paraffin reflector beside the sample. The results were all consistent within $\pm 4\%$.

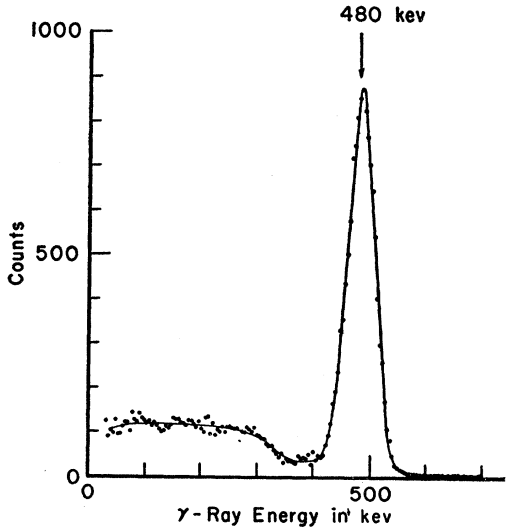

FIG. 2. Gamma-ray spectrum from thermal neutron capture by B^{10} in a thick boron-carbide sample. This is used as a standard of intensity. The figure also demonstrates the absence of extraneous peaks.

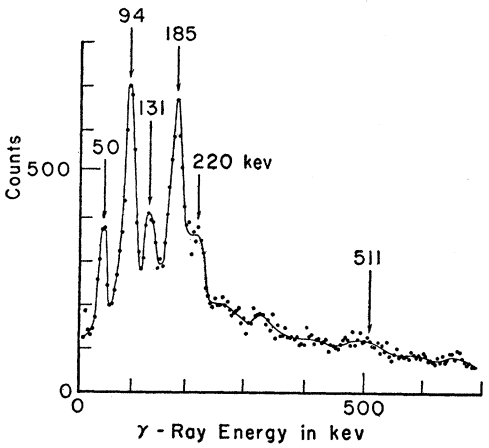

FIG. 3. Rhodium, 0.10 g cm^{-2}.

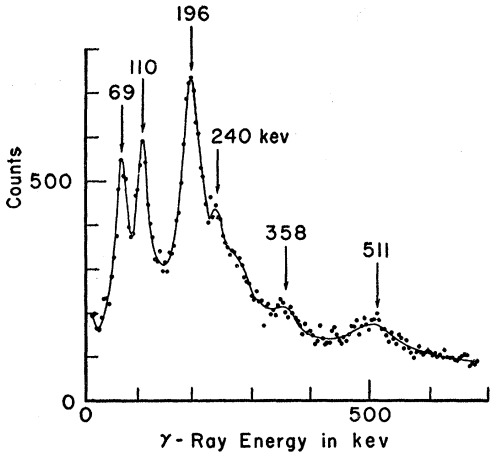

FIG. 4. Silver, 0.12 g cm^{-2}.

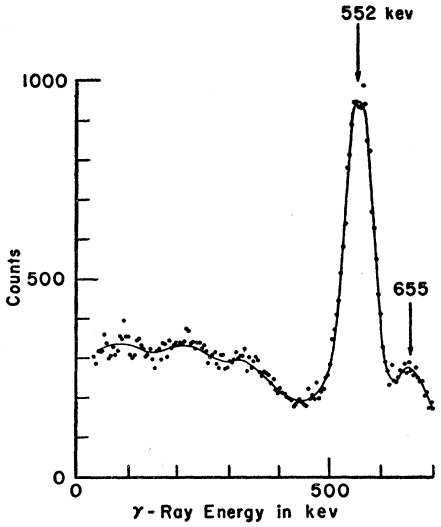

FIG. 5. Cadmium, 0.13 g cm^{-2}.

[1] Draper, Fenstermacher, and Schultz, Phys. Rev. **111**, 906 (1958).

[2] D. J. Hughes and R. B. Schwartz, *Neutron Cross Sections*, Brookhaven National Laboratory Report BNL-325, second edition (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1958).

TABLE I. Summary of results. The intensity I_γ denotes the number of photons per 100 neutrons captured in the natural element.

	$N\sigma_{abs}$	Product A	Percent produced	E_γ (kev)	$I\gamma$ this work	Other $I\gamma$ thermal	Resonance capture[a] $I\gamma$	Resonance energy (ev)
$_{45}$Rh	0.088	104	100	50	17	...		
				94	24	17[b]		
				131	6	$\leqslant$8		
				185	23	19		
				220	10	9		
$_{47}$Ag	0.045	110	73	69	17	...		
		108	27	110	15	...		
				196	34	...		
				240	9	...		
				358	$\leqslant$4	...		
$_{48}$Cd	1.78	114	>99	552	52	42,[c] 85[d]	52[e,f]	0.18
				655	7.2	14, 23	...	
$_{49}$In	0.093	116	~99	67	5	...	3[g]	1.46
				98	16	...	14	1.46
				188	16	...	11	1.46
				280	24	...	12	1.46
$_{51}$Sb	0.017	122	66	75	23	...		
		124	34	115	12	...		
				150	11	...		
				328	23	...		
$_{52}$Te	0.099	124	79	608	90	...	44[e]	2.3
		125	7					
		131	4					
$_{53}$I	0.031	128	100	135	46	32[b]		
$_{62}$Sm	10.9	150	98	330	61	70,[b] 38[c]	60[h]	0.86
		153	2	435	38	34, 33	33	0.86
$_{63}$Eu	2.28	152	94	45	x-ray	...		
		154	6	95	17	20[i]		
				72	<1.5	4.4		
$_{64}$Gd	17.6	158	81	45	x-ray	...		
		156	19	85	5	11[i]		
				190	13	23		
				290	~1	...		
$_{65}$Tb	0.040	160	100	45	x-ray	...		
				76	7	...		
$_{66}$Dy	2.00	165	~99	45	x-ray	...		
				82	2	2.8[j]		
				195	10	16		
				410	9	4[j]		
				(520)	(~5)	...		
$_{67}$Ho	0.12	166	100	46	x-ray	...		
				121	7	20[i]		
				146	34	31		
				245	8	...		
$_{68}$Er	0.06	168	(~100?)	50	x-ray	...		
				80	14	18[i]		
				192	66	64	39[k]	0.5
				285	10	...	5	0.5
$_{69}$Tm	0.051	170	100	50	x-ray	...		
				160	6	7[i]		
				222	3	...		

[a] Since resonance capture is by a particular isotope, the reported isotopic intensity has been multiplied by the appropriate percentage in column 4 of this table for ease of comparison.
[b] See reference 4.
[c] See reference 5.
[d] See reference 6.
[e] See reference 7.
[f] See reference 8.
[g] See reference 1.
[h] See reference 9.
[i] See reference 10.
[j] See reference 11.
[k] See reference 12.

TABLE I.—*Continued.*

	$N\sigma_{abs}$	Product A	Percent produced	$E\gamma$ (kev)	$I\gamma$ this work	Other $I\gamma$ thermal	Resonance capture[a] $I\gamma$	Resonance energy (ev)
$_{72}$Hf	0.058	178	65	55	x-ray	···		
		179	19	90	15	14[i]	4[k]	1.1
							5	2.4
		180	8	220	39	40	18	1.1
							27	2.4
		181	5	330	11	···	2	1.1
							7	2.4
$_{73}$Ta	0.026	182	100	57	x-ray	···		
				107	9	15[i]		
				132		30		
				175	16	22		
				280	39	70		
				405	20	···		
$_{75}$Re	0.051	188	52	60	x-ray	···		
		186	48	143	8	···		
				210	14	···		
$_{77}$Ir	0.148	192	82	65	x-ray	···		
		194	18	140	4	···		
				215	$\leqslant$0.7	···		
				350	$\sim$1.6	···		
$_{78}$Pt	0.013	196	90	65	x-ray	···		
		195	4	330	170	···		
		199	3	358				
$_{79}$Au	0.15	198	100	65	x-ray	···		
				95	3	···		
				165	11	11[b]		
				210	21	19		
				245	22	22		

Thus the absolute gamma ray intensity per captured neutron is obtained by assuming that the flux is the same for all samples, by using the capture cross section[2] to determine what fraction of the incident neutrons is captured, and by using the intensity[3] of 93.5 photons per 100 captured neutrons for the 480-kev gamma ray from neutron capture by B^{10}.

III. RESULTS

Table I summarizes the intensities of the prominent gamma rays shown in Figs. 3 through 23. The intensities are considered to have an uncertainty of ±10–15% primarily due to the uncertainty in the base line of a peak. All intensities in Table I are listed as gamma rays per 100 neutrons captured in the sample element—they are not isotopic since in some cases the isotope cannot be ascertained. The samples were generally of specified purity 99.9% or better. Intensities found by other investigators are also listed.[1,4–12]

The intensity of a K x-ray peak is not considered significant since K-electron vacancies are created not only by electron conversion, but also by photoelectric absorption of capture gamma rays produced by the

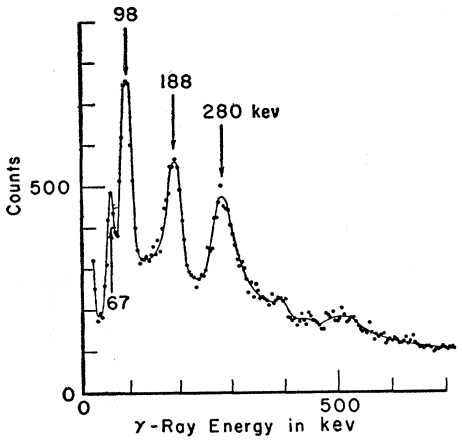

FIG. 6. Indium, 0.10 g cm^{-2}.

[3] J. DeJuren and H. Rosenwasser, Phys. Rev. **93**, 831 (1954).
[4] Estulin, Kalinkin, and Melioransky, Nuclear Phys. **4**, 91 (1957).
[5] Groshev, Adyasevich, and Demidov, *Proceedings of the Conference of the Academy of Sciences of the U.S.S.R. on the Peaceful Uses of Atomic Energy, Moscow, 1955* (Akademiia Nauk, S.S.S.R., Moscow, 1955) [English translation by the Consultants Bureau, New York, Atomic Energy Commission Report TR-2435, 1956], p. 195.
[6] H. T. Motz, Phys. Rev. **104**, 1353 (1956).
[7] Fenstermacher, Bennett, Walters, Bockelman, and Schultz, Phys. Rev. **107**, 1650 (1957).
[8] T. Springer (private communication).
[9] C. A. Fenstermacher, PhD dissertation, Yale University (unpublished).
[10] Skliarevskii, Stepanov, and Obiniakov, Atomnaya Energ. **4**, 22 (1958).
[11] Groshev, Demidov, Lutsenko, and Pelekhov, Atomnaya Energ. **4**, 5 (1958).
[12] Fenstermacher, Draper, and Bockelman, Nuclear Phys. (to be published).

sample and by the paraffin moderator. Similarly the intensity of a peak at 511 kev is not considered significant because of the annihilation radiation following pair production by gamma radiation from the sample and moderator.

It is apparent from the results obtained with high resolution crystal spectrometers (e.g., tantalum and gold) that the heavier odd-odd nuclei produce many transitions in the energy region investigated here. Consequently the peaks shown here are expected to demonstrate the nature of the spectrum and to have the correct intensity when it is taken into account that occasionally even an isolated well-defined peak will contain more than one transition.

$_{45}$Rh: Table I shows that only Rh^{104} is produced. The energies and intensities of 94, 131, 185, 220 kev are in substantial agreement with Estulin *et al.*[4] However, an additional 50-kev gamma ray is shown in Table I. The energy of this peak was determined in a separate run at higher gain with calibrations at 32 kev and 69 kev. This transition may come from the first excited state. There have been recent discrepancies in the literature concerning the question whether the 51-kev level is the 4.3-min isomer,[13] but the results of Jordan *et al.*[14]

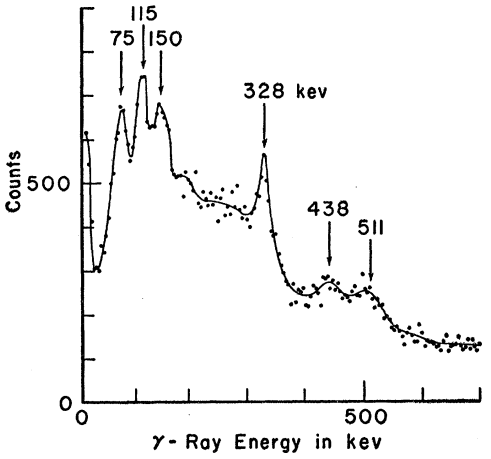

FIG. 7. Antimony, 0.61 g cm^{-2}.

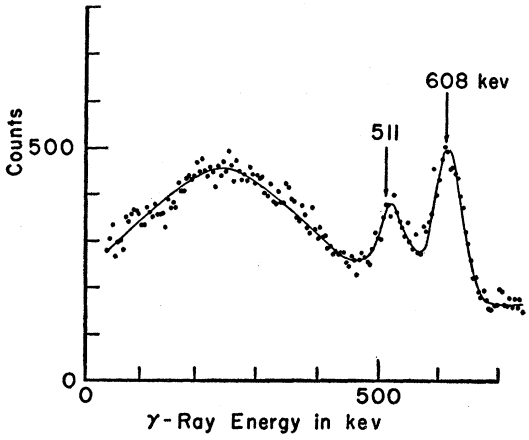

FIG. 8. Tellurium, 4.7 g cm^{-2}.

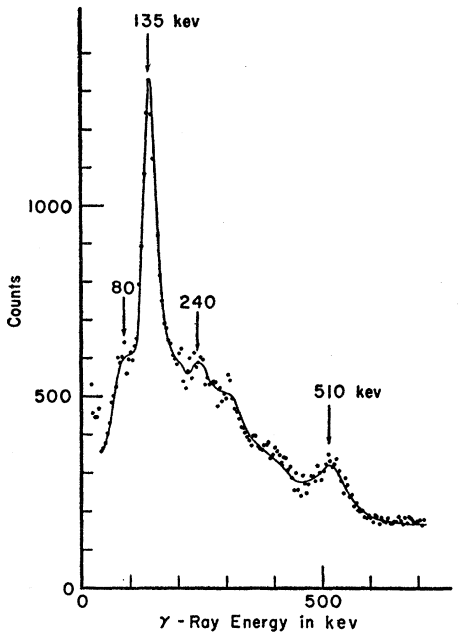

FIG. 9. Iodine, 0.96 g cm^{-2}.

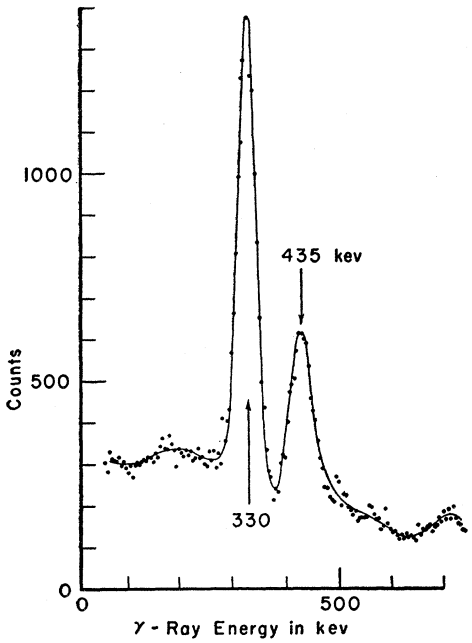

FIG. 10. Samarium, 0.43 g cm^{-2}.

[13] D. E. Alburger, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 42; V. S. Dzelepov and L. K. Peker, Publication of the Academy of Sciences, U.S.S.R., Moscow, 1957, Leningrad [translated and issued at Chalk River, Ontario, July, 1957 as Atomic Energy of Canada Limited Report AECL-457 (unpublished)]; Strominger, Hollander, and Seaborg, Revs. Modern Phys. **30**, 585 (1958). Nuclear data compilation by National Academy of Sciences—National Research Council.

[14] Jordan, Cork, and Burson, Phys. Rev. **90**, 862 (1953).

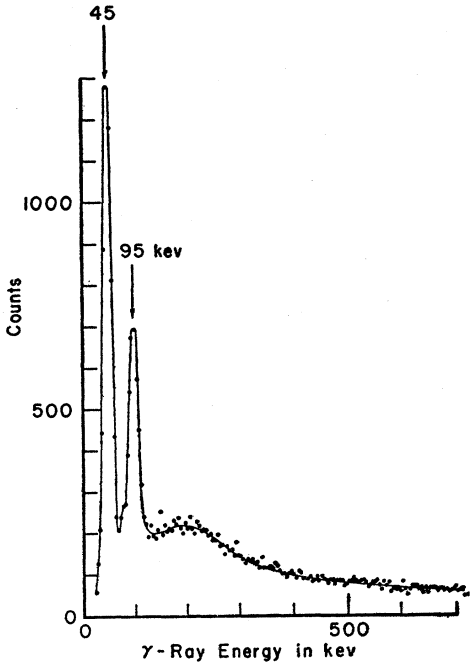

FIG. 11. Europium, 0.12 g cm^{-2}.

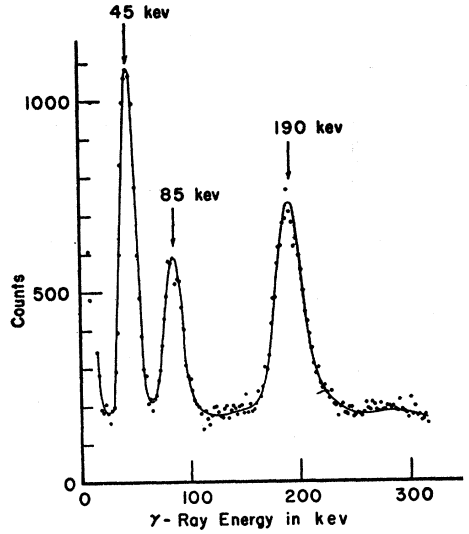

FIG. 12. Gadolinium, 0.10 g cm^{-2}.

indicate levels at 51 and 128 kev with the latter identified as the 4.3-min isomer. The 77-kev transition from the isomeric level was found to be highly converted. The spectrum of Fig. 3 supports this interpretation since the 51-kev level would be populated by the cascade transitions, but the 51-kev gamma ray would not be observed here if it were isomeric. Gamma rays at 80 and 160 kev were reported by Hamermesh and Hummel.[15]

$_{47}$Ag: Thermal neutron capture in silver produces 73% of Ag^{110} and 27% of Ag^{108}. The high-energy gamma rays from neutron capture have been investigated by Bartholomew and Kinsey,[16] who conclude that there are probably levels in Ag^{108} at 210±30 and 320±30 kev. These could account for the 110- and 196-kev transitions in Table I but no unique assignment is possible. Analysis of the capture spectrum from the 5.2-ev resonance producing Ag^{110} and from the 16.6-ev resonance producing Ag^{108} would aid in the isotopic identification of these and high-energy transitions. A gamma ray at 187 kev is reported in reference 15.

$_{48}$Cd: Thermal neutron capture in cadmium produces

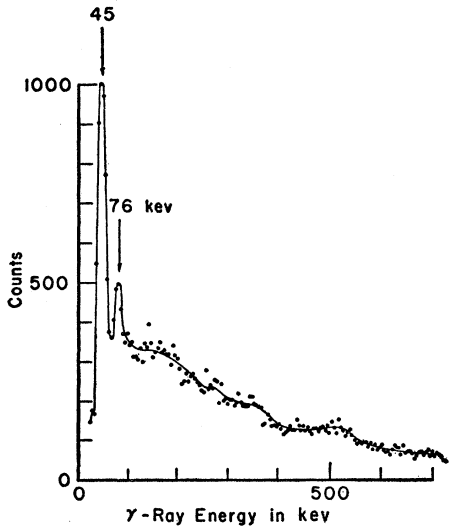

FIG. 13. Terbium, 0.24 g cm^{-2}.

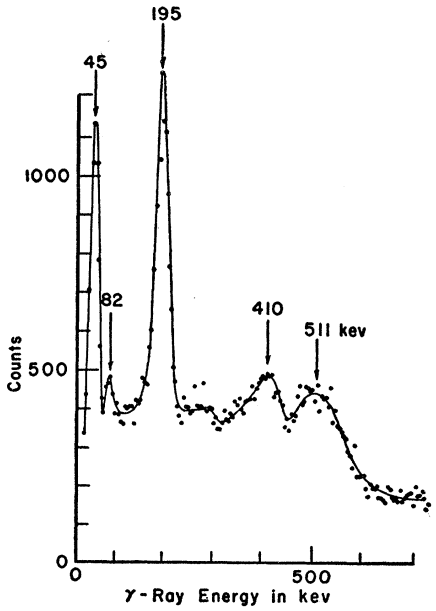

FIG. 14. Dysprosium, 0.49 g cm^{-2}.

[15] B. Hamermesh and V. Hummel, Phys. Rev. 88, 916 (1952).

[16] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. 31, 1025 (1953).

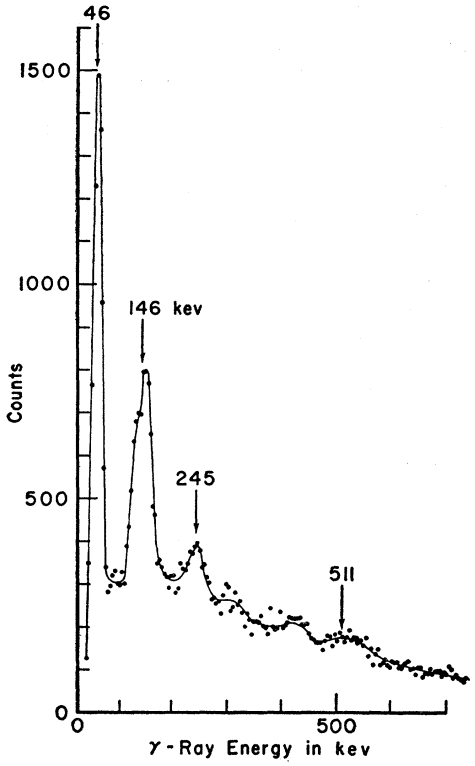

FIG. 15. Holmium, 0.49 g cm^{-2}.

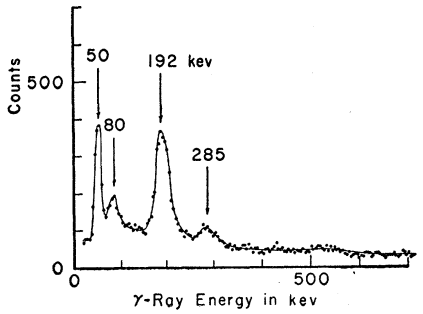

FIG. 16. Erbium, 0.06 g cm^{-2}.

only Cd^{114}. The results in Table I are in substantial agreement with references 5, 7, and 8. The energies of the two transitions are in good agreement with those of Motz,[6] but the absolute intensity measurements differ by more than the expected uncertainty. The weak transition observed by Motz at 576 kev could not be distinguished due to the lack of resolution in this experiment. References to other work can be found in the recent Chalk River review[17] of thermal neutron capture gamma rays.

$_{49}$In: Thermal neutron capture in indium produces only In^{116}. The agreement of energies and intensities with reference 1 is satisfactory. Gamma rays at 160 and 256 kev are reported in reference 15. The high-energy gamma transitions have been measured.[16] Levels at 70 (54 min), 168, 353, and 5915 kev would be compatible with the results of reference 16 and Table I but would not include the 67-kev transition of Table I and would not be compatible with the 6.59±0.2 Mev binding energy measured by Harvey.[18] The latter difficulty arises because of the results of Boley[19] which indicate that the 54-min level is about 70 kev above the ground state. If, instead, this level were at 410±150 kev as found by Slätis *et al.*[20] the binding energy would be 6.26±0.15 Mev. This uncertainty in the energy of the 54-min level makes it difficult to reconcile the energies of the high-energy gamma rays and the binding energy.

$_{51}$Sb: Sb^{122} is produced in 66% of thermal neutron captures and Sb^{124} in 34% of the captures. Little is known about the excited, nonisomeric states of Sb except that 75.3- and 60.7-kev transitions are in cascade[21] from the 3.5-min state of Sb^{122} with the 75-kev transition concluded to be isomeric. The energy of the lowest peak in Fig. 7 was determined with a rerun at higher gain and calibrated with the x-rays from Re and Pb samples. The center of the peak was not well defined but the energy is concluded to be 74±6 kev. This would not be identified, then, with the 75.3-kev

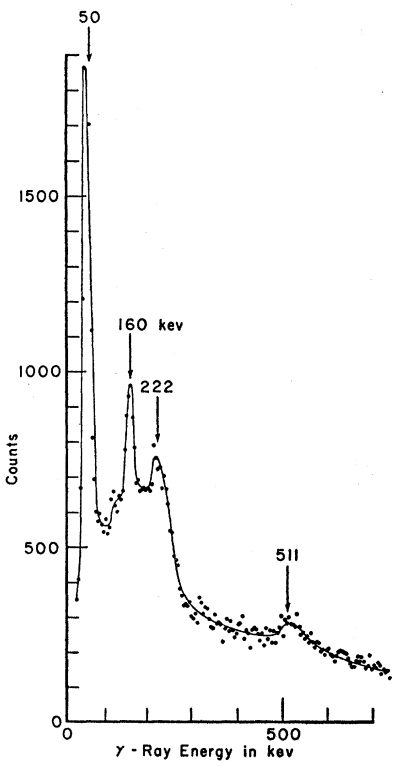

FIG. 17. Thulium, 0.12 g cm^{-2}.

[17] G. A. Bartholomew and L. A. Higgs, Chalk River Report, Atomic Energy of Canada Limited AECL-669 (unpublished).

[18] J. A. Harvey, Phys. Rev. **81**, 353 (1951).
[19] F. I. Boley, Phys. Rev. **94**, 1078 (1954).
[20] Slätis, Du Toit, and Siegbahn, Arkiv Fysik **2**, 321 (1950).
[21] LeBlanc, Cork, and Burson, Phys. Rev. **98**, 39 (1955).

transition of reference 21 if it is a 3.5-min isomer. The spectrum reported in reference 15 was unresolved. The high-energy gamma rays have been measured.[16] It can be noted that the sum of the energies of the first three peaks in Fig. 7 approximates the energy of the fourth peak which in turn approximates the energy difference of the two highest energy lines reported in reference 16. Better resolution in both energy regions would be required to determine the significance of this.

$_{52}$Te: A thick sample was necessitated by the small neutron absorption cross section, and this will obscure any low-energy transitions ($\lesssim$300 kev). The 608-kev gamma ray is from Te^{124} which is produced in 79% of capture events, and it is unusually intense. The reported intensity[7] for the 2.3-ev resonance is appreciably lower as shown in Table I. A line at 608 kev has been observed in the Coulomb excitation[22] of Te^{124} and in reference 15. The 723-kev transition from the second excited state would be outside the energy interval included in this experiment.

$_{53}$I: Only I^{128} is produced for which no level scheme is available. The 135-kev transition appears here substantially as found in reference 4 and unlike the results of Hammermesh and Hummel[15] and Reier and Shamos.[23] These is also evidence of weak transitions at 80 kev and in the 240–300 kev region.

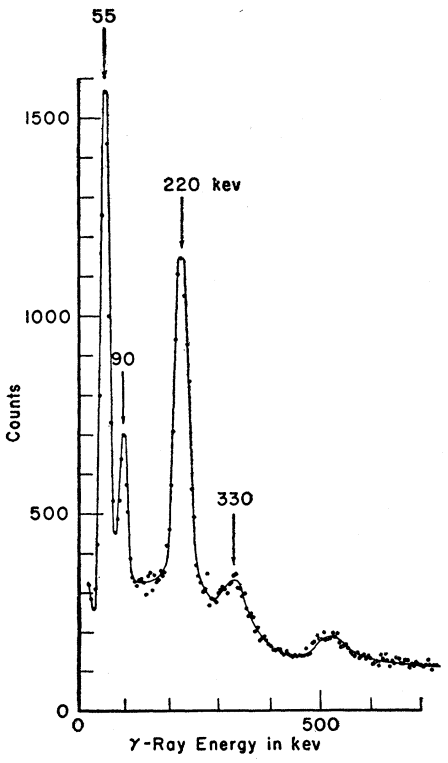

FIG. 18. Hafnium, 0.16 g cm^{-2}.

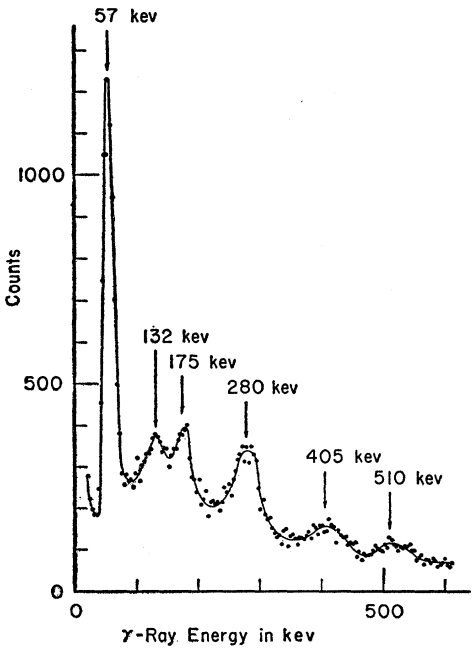

FIG. 19. Tantalum, 0.37 g cm^{-2}.

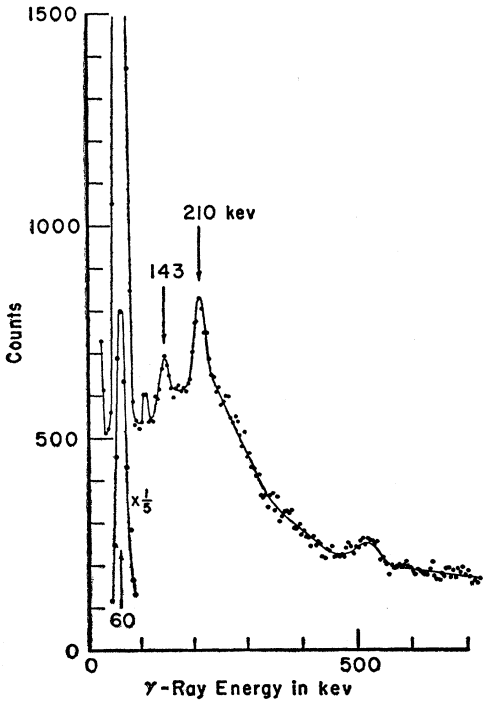

FIG. 20. Rhenium, 0.40 g cm^{-2}.

$_{62}$Sm: The prominent gamma rays at 330 and 445 kev are attributed to Sm^{150} which is produced in 98% of capture events. The measured intensities in Table I are in reasonable agreement with references 4 and 7, but these are not in as good agreement with reference 5. These two gamma rays were also reported by Hibdon

[22] N. P. Heydenburg and G. M. Temmer, Bull. Am. Phys. Soc. Ser. II, 1, 164 (1956).
[23] M. Reier and M. H. Shamos, Phys. Rev. **100**, 1302 (1955).

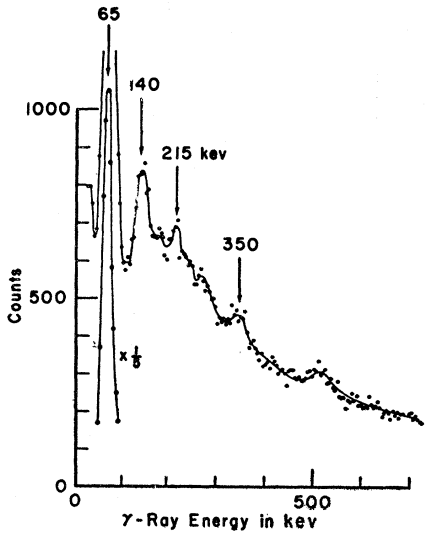

FIG. 21. Iridium, 0.11 g cm^{-2}.

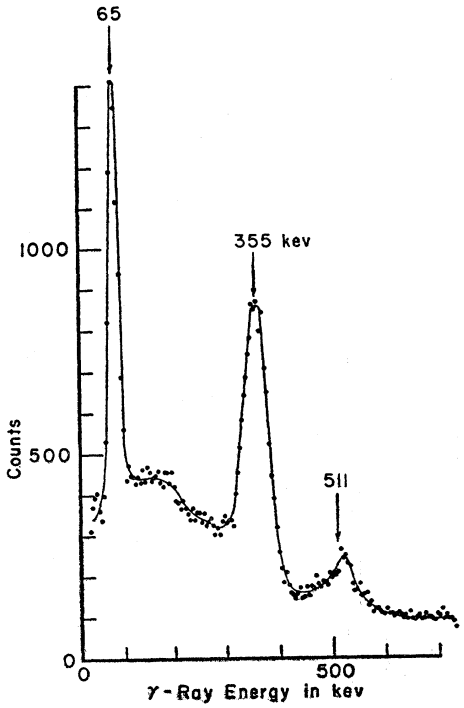

FIG. 22. Platinum, 0.54 g cm^{-2}.

and Muehlhause.[24] They have recently been shown[25] to be in coincidence following neutron capture. Both the 330- and 445-kev gammas were observed in coincidence in earlier work[26] with Pm^{150}, and levels in Sm^{150} were proposed at 337 and 777 kev. More recent work[27] prescribed the 337-kev level but no 777-kev level. A level at 777 kev has been suggested[5] from the spectra of high-energy gamma rays[5,28] following neutron capture. Angular correlation experiments[25] of limited accuracy with the 330- and 445-kev gamma rays following neutron capture indicate that the 775-kev level would have spin 2, 3, or 4.

$_{63}$Eu: Since 94% of captured neutrons produce Eu^{152} the 95-kev transition of Fig. 11 is assigned to that isotope. Its energy and intensity are in satisfactory agreement with reference 10 which also reports a 72-kev transition with an intensity 22% as large as that of the 95-kev transition. To investigate this, a rerun was made with the amplifier gain 4 times as large as that for Fig. 11. The results indicated that if a 72-kev gamma ray were present it would have an intensity significantly less than that of reference 10. This might be indicative of an isomeric 72-kev transition. There is no information[13] available on the nonisomeric levels of Eu^{152}.

$_{64}$Gd: Thermal neutron capture produces 81% of Gd^{158} and 19% of Gd^{156}. The capture gamma rays from these have been individually investigated[10] using separated isotopes. Gamma rays of 79 and 183 kev were observed from Gd^{158} with an isotopic I_γ of 10.4 and 22, respectively, while 87- and 196-kev gamma rays were observed from Gd^{156} with an isotopic I_γ of 13.7 and 27.7. The energies of the gamma rays in Table I for elemental Gd are in satisfactory agreement with reference 10. However, the values of I_γ for the element as shown in Table I are in less satisfactory agreement. The energies of these transitions and their prominence in the spectrum (after correction for internal conversion) suggest that these are collective transitions involving the 0+, 2+, and 4+ ground-state rotational band. Measurements[24,29] of internal conversion coeffi-

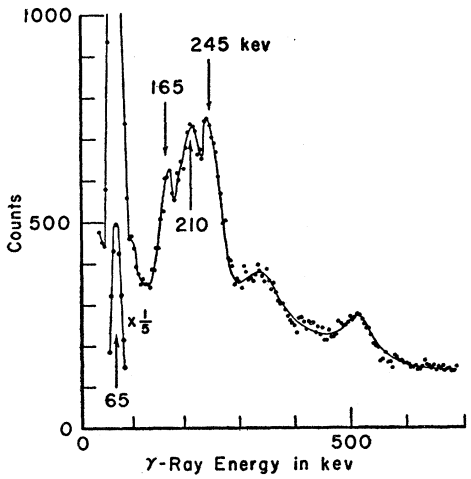

FIG. 23. Gold, 0.50 g cm^{-2}.

[24] C. T. Hibdon and C. O. Muehlhause, Phys. Rev. 88, 943 (1952).
[25] L. Rosler, Ph.D. dissertation, Yale University (unpublished).
[26] V. K. Fischer, Phys. Rev. 96, 1549 (1954).
[27] V. K. Fischer and E. A. Remler, Bull. Am. Phys. Soc. Ser. II, 3, 63 (1958).
[28] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. 31, 1051 (1953).
[29] E. L. Church and M. Goldhaber, Phys. Rev. 95, 626(A) (1954).

cients following thermal neutron capture in Gd have shown that these transitions are $E2$. A separate run was made with lower amplifier gain in order to investigate the expected 290-kev, $6+ \rightarrow 4+$ transition, of which there is some indication in Fig. 12. It was detected but is weak.

$_{65}$Tb: The compound nucleus is Tb^{160} since the target nucleus is mono-isotopic. No information is available[13] about the excited states of Tb^{160}.

$_{66}$Dy: The thermal capture gamma-ray spectrum has been reported in reference 11 for high-energy transitions and in reference 10 for transitions below 200 kev. The conversion electron spectrum is reported in reference 24, in which a level is suggested to be at 188 kev in addition to the 1.2-min isomer at 108 kev. These levels could account for the peaks in Fig. 14 at 82 kev and 195 kev and the absence of a peak at 108 kev. The intensities listed in Table I of these gamma rays are in fair agreement with reference 10, and the intensity of the peak at 410 kev is in less satisfactory agreement with reference 11. There is some evidence of a peak near 520 kev (in addition to the usual annihilation peak at 511 kev) when the spectra are compared for Dy and Ho of Figs. 14 and 15 and for Gd obtained with a lower amplifier gain than that of Fig. 12. That is, the Ho and Dy samples were of the same thickness in g/cm^2 while the Gd and Dy samples absorbed about the same number of neutrons. The peak near 511 kev in Dy is much larger than for Gd or Ho.

$_{67}$Ho: The peaks in Fig. 15 are from transitions in Ho^{166} since Ho is mono-isotopic. In reference 10, peaks are reported at 121 and 142 kev. The energy and intensity of the latter are in good agreement with the results in Table I. In order to investigate the former, a rerun was made with higher gain which verified the kink on the low-energy side of the 146-kev peak of Fig. 15 and showed its energy to be 125 kev. However, its intensity was 0.20 times that of the 146-kev peak rather than 0.65 as obtained in reference 10. If this difference is a real one, it implies the existence of an isomer in Ho with a mean life of the order of milliseconds. No information is available[13] concerning the levels of Ho^{166} except that there is an isomeric level (>30 years) above the 27-hr ground level.

$_{68}$Er: The peaks in Fig. 16 are probably from transitions in Er^{168} since the spectrum is quite similar to that of the even-even nuclei $_{64}Gd^{156}$, $_{64}Gd^{158}$, and $_{72}Hf^{178}$ which are also highly deformed nuclei. There are no isotopic thermal neutron cross sections available, however. Furthermore, the energies of these peaks correspond to those seen by Mihelich and Harmatz[30] following the beta decay of Tm^{168}. The gamma-ray intensities following resonance neutron capture have been reported, as well as the relative intensities following thermal neutron capture.[12] However, for completeness it is repeated here that the 80- and 285-kev peaks are consistent in energy and intensity with the rotational transitions $2+ \rightarrow 0+$ and $6+ \rightarrow 4+$. The width and energy of the 192-kev peak indicate that it may be composed of the 185-kev second rotational transition[30] ($4+ \rightarrow 2+$) and the 199-kev delayed (0.12-μsec) transition[30] with about equal intensities of each.

$_{69}$Tm: The peaks in Fig. 17 are from transitions in Tm^{170}. The energy and intensity of the peak at 160 kev are in agreement with those of reference 10, but the peak at 222 kev was not reported there. No information is available[13] on the level scheme.

$_{72}$Hf: These transitions are mostly in Hf^{178} as shown in reference 12 although the level scheme[13] for Hf^{180} is very similar and there may be $\sim 10\%$ contributions to the peaks by Hf^{180}. Reference 12 contains absolute intensities from resonance capture, relative intensities from thermal capture and references to other work. The energies and intensities of the peaks in Fig. 18 are consistent with their being in the rotational cascade $6+ \rightarrow 4+ \rightarrow 2+ \rightarrow 0+$.

$_{73}$Ta: The transitions are in Ta^{182}. The energies of the peaks are in agreement with those of reference 10 and Bartholomew *et al.*,[31] except that the 405-kev transition was not reported in reference 10. The intensities in Table I are not in good agreement with those in reference 10, and no intensities are reported in reference 31. It was presumed that in the geometry of Fig. 1, little of the 18-μsec isomer of Ta^{181} would be excited by the gamma rays from the accelerator target,[32] and this was confirmed by spectra taken at various times after the beam burst and taken with and without the Be in front of the accelerator target. The more detailed (n,γ) studies with crystal spectrometers have led to a proposed level scheme[31] for Ta^{182}. While those detailed results show more than 20 transitions in the range below 509 kev, nevertheless there appears to be satisfactory agreement with Fig. 19 and Table I when the resolution and efficiency are taken into account.

$_{75}$Re: Little information is available[13] on the levels of Re^{186} or Re^{188} except that from Re^{188m} there are 105- and 63.5-kev gamma rays, both of which decay with a 22-min half-life.[33]

$_{77}$Ir: No pertinent information is available[13] on the levels of Ir^{192} or Ir^{194}.

$_{78}$Pt: In 90% of capture events Pt^{196} is produced. Although the peak in Fig. 22 at first appears to be single, Table I shows that its intensity would require the presence of more than one transition in the peak. Consequently, it must contain two cascade transitions (perhaps with others in parallel), with negligible crossover and with negligible production of one transition

[30] J. W. Mihelich and B. Harmatz, Phys. Rev. **106**, 1232 (1957) and private communication.

[31] Bartholomew, Campion, Knowles, and Manning, Proceedings of the International Conference, on Neutron Interactions with Nuclei, Columbia University, September, 1957 [U. S. Atomic Energy Commission Report TID-7547 (unpublished)].

[32] J. E. Draper and R. L. Hickok, Phys. Rev. **108**, 1280 (1957).

[33] J. W. Mihelich, Phys. Rev. **89**, 907(A) (1953).

without the other. The spectrum near 700 kev shows that the maximum possible intensity of a cross-over transition is less than 15% of the intensity of either of the cascade transitions. Pt^{196} has been shown[34,35] to have a level sequence of 0(0+), 354(2+), and 685(2+) kev, and the ratio of the intensity of the cross-over from the 685-kev level to the intensity of the 331-kev transition[36] is $<4\times10^{-4}$. The evidences for the collective vibrational character of the levels have been discussed by Scharff-Goldhaber.[37] If the peak in Fig. 22 is attributed entirely to Pt^{196} and if it were composed only of 331- and 354-kev transitions, then after taking into account the measured[35] conversion coefficients the transition intensities for each of these two would be 100 ± 15 gamma rays per 100 neutrons captured. On the other hand, there might be a closely spaced triplet of levels near 685 kev which produce more than two transitions unresolved in Fig. 22. In either case it is noteworthy that virtually all cascades would appear to proceed through the level (or levels) near 685 kev, a situation unlike that for the rotational transitions of Gd, Er, and Hf. Of course, there is also the possibility that a transition contributes appreciably to the peak of Fig. 22 which is unrelated to the levels just discussed. The high-energy spectrum[28] is interesting in appearing to favor transitions to the second 2+ level rather than to the first 2+ level. However, the estimated ratio of these intensities is quite dependent on a detailed knowledge of the background in the presence of the sample.

$_{79}$Au: The transitions are in Au^{198}. The positions and intensities of the peaks in Fig. 23 are in reasonable agreement with those of reference 4. In addition there is evidence for transitions near 350 kev. A sample of 0.054 g/cm^2 also revealed a peak at 95 kev which is less clearly revealed in Fig. 23. The detailed results from a crystal spectrometer[38] show more than 30 transitions below 450 kev. However, when those results are folded with the resolution function for NaI(Tl), the agreement of shape and intensity with those in Fig. 23 and Table I is quite satisfactory.

SUMMARY AND CONCLUSIONS

Of the radiating nuclei represented in Table I and Figs. 3 through 23, there are 13 odd-odd, 7 even-even, and 1 even Z-odd N nuclei. Little is known about the levels of these odd-odd nuclei since they are not easily excited in radioactivity studies. Nine of them are known to have isomeric levels and for three of them a level below the isomer has been observed. The neutron capture gamma-ray spectra of Rh, Ag, In, and Sb can roughly be characterized as having an isolated cluster of partially resolved low-energy peaks. The same description can be approximately applied to the heavier Tm, Re, Ir, and Au. However, the intervening I, Eu, Tb, and Ho have a single low-energy peak.

All of the prominent features of the spectra of the present even-even nuclei are apparently due to collective motions. There are three nuclei with transitions which are probably vibrational (Cd, Te, and Pt), when one takes into consideration the energies, spins, and parities of the first two levels. The nuclei Gd, Er, and Hf apparently have well-developed rotational spectra with the $6+\rightarrow4+\rightarrow2+\rightarrow0+$ triple cascade presumably observed for Er and Hf. For Gd the presumed $4+\rightarrow2+\rightarrow0+$ cascade is strong, but the 290-kev transition expected for $6+\rightarrow4+$ is only just visible. The nucleus Sm^{150} is at the border between the highly deformed nuclei with ground-state rotational bands and the more nearly spherical nuclei where vibrational motion characterizes the lowest levels. Nevertheless, the most prominent features of this spectrum apparently involve the first two excited levels.†

ACKNOWLEDGMENTS

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[34] Steffen, Huber, and Hummel, Helv. Phys. Acta **22**, 167 (1949); R. M. Steffen and D. M. Roberts, Phys. Rev. **83**, 222(A) (1951); R. M. Steffen, Phys. Rev. **89**, 665 (1953).

[35] M. T. Thieme and E. Bleuler, Phys. Rev. **101**, 1031 (1956).

[36] D. E. Alburger, in *Proceedings of the Rehovoth Conference on Nuclear Structure* (Interscience Publishers, Inc., New York, 1958), p. 107.

[37] G. Scharff-Goldhaber, in Proceedings of the University of Pittsburgh Conference, June, 1957 (unpublished report).

[38] Hamermesh, Rose, and Smither, Bull. Am. Phys. Soc. Ser. II, **1**, 346 (1956).

† *Note added in proof.*—Recently available data of Groshev, Demidov, Lutsenko and Pelekhov ("Atlas of spectra of gamma rays from radiative capture of thermal neutrons," Publication of the Main Office for the Use of Atomic Energy under Ministry of the U.S.S.R., Moscow, 1958) corroborate the Pt data of reference 28 by indicating primary high-energy transitions which go preferentially (intensity ratio 7:2) to the vicinity of the second 2+ state as compared with transitions to the vicinity of the first 2+ state of Pt^{196}.