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ATOMIC ENERGY COMMISSION
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THE X-RAY SPECTRA OF THE LAST-ROW ELEMENTS

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Document declassified October 22, 1946

This document consists of 23 pages.

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ABSTRACT

X-ray energy level diagrams as given in the literature are tabulated for radium, thorium and uranium. A level scheme for protoactinium is derived from the published data. After a brief review of the use of X-ray data in studying outer electronic structure, it is pointed out that differences in the X-ray spectra should exist depending on whether the outer electrons are in f or d orbitals. The observed separation of the O_I and O_{II} levels in thorium and uranium indicate that the f levels lie lower than the d. This hypothesis also provides a reasonable explanation for the observed differences between the M_{IV} and M_V absorption edges and M_{IV} and M_V levels calculated from the emission spectra and the L_{III} edge.

THE X-RAY SPECTRA OF THE LAST-ROW ELEMENTSINTRODUCTION

If the X-ray spectra of the last-row elements were completely and accurately known, they would furnish important information as to the electronic structure of these elements. In particular the X-ray spectra might reveal whether the f or d valence levels lie lowest. This summary has been prepared to review the existing data and to see what explanations of these data can be given in the light of present knowledge.

ENERGY LEVEL TABLES

A complete X-ray energy level table is the first goal of an X-ray study. Data have been reported for radium, thorium, protoactinium, and uranium; the resulting energy level schemes are given in Tables I and II. All values given in the tables are based on the L_{III} absorption edge. The values of ν/R for radium, thorium, and uranium should be accurate to ± 0.2 relative to that edge. The probable error in the L_{III} edge itself is about ± 0.3 .

The available data for protoactinium are tabulated in Table III; from the values in that table an energy level scheme has been compiled as shown in Table IV. The data are fairly consistent except for the lines leading to levels N_{II} , O_I and $P_{II,III}$ which may be in error by 1 to 2 units.

INTERPRETATION BY MEANS OF ELECTRONIC STRUCTURE

The present outstanding problem in connection with these metals is the electronic structure. We do not know whether the outer valence electrons are f or d electrons or mixtures of the two. If they

are f electrons we have the beginning of a second rare earth series and our interpretations of chemical and physical properties must be radically altered from the present interpretations which generally assume the outer electrons to be d electrons.

X-ray spectra have not yet been very fruitful in providing information of electronic structure which is directly useful to chemists. However, a number of approaches have yielded information of great importance and promise to yield more as the experimental technique and theoretical understanding improve. We may summarize these approaches as follows:

1. Bohr-Coster Diagrams and Calculation of Screening Constants

This work is discussed by Pauling and Goudsmit, "The Structure of Line Spectra", McGraw-Hill Co., 1930, and Sommerfeld, "Atombau and Spectrallinien" 5 Aufl. Bd. 1. It is found that the X-ray energy levels can be expressed to an excellent approximation by a hydrogen-like energy expression used with suitable screening constants. A Bohr-Coster plot (Moseley diagram) of $\sqrt{\nu/R}$ for the various levels versus the atomic number gives therefore a smooth curve which is almost a straight line for the deep K and L levels. For the higher levels significant changes in slope occur which are related to the outer electronic structure. There is a slight change in slope when a d shell begins, but by far the largest change occurs when the 4f shell begins to fill. Here the slope abruptly decreases because the added electron penetrates deeply and shields the electrons concerned more effectively than a d electron. The change in slope is found to be most pronounced in the N and O levels. The phenomenon may be treated in a semi-quantitative fashion by the use of screening constants. The treatment is given in some detail in Pauling

and Goudsmit (p. 180) where it is shown that the principle term in the energy expression may be considered to involve two screening constants, one for the inner and one for the outer electrons. By making approximate quantum-mechanical calculations of the average radii of the outer orbitals Pauling was able to separate the two effects and evaluate the inner screening constant. It was found that the inner screening constant for a given level was practically a constant for elements of atomic number 44 to 57 but that it rose abruptly for the N_I , N_{II} and N_{III} levels when the $4f$ shells started to fill, increasing by about 0.86 units per atomic number. However the rise for the M levels is very small. This result is significant in that it shows that a $4f$ orbital is penetrating enough to shield both the $4s$ and $4p$ electrons to a high degree but that it does not penetrate much inside the $3s$ or $3p$ levels. Pauling's calculations are less exact for elements of high atomic number and have little significance for the last row elements.

At first sight these methods would appear best adapted for studying the heavy metals; however a number of difficulties became apparent on closer examination. Absolute term values are needed and the recorded values for the outer levels are somewhat uncertain because of the questions as to exactly what transition is involved in the L_{III} absorption edge on which the values are based. The calculations of outer orbital radii are difficult and uncertain especially for heavy elements. Also the number of elements in which a $5f$ electron might appear are so few that a slight break in a function is difficult to determine. For these reasons no detailed application of Pauling's method has been tried.

2. Soft X-ray Spectroscopy of the Solid State.

The application of soft X-ray measurements to the determinations

of electronic energy level density in solids is a relatively new one but offers great promise. A summary of the work to 1938 is given by H. W. B Skinner, "Progress in Physics", Vol. 5, The Physical Society, London, 1939. So far only light elements have been studied and there are no data for the heavy elements.

3. X-ray Satellite Lines.

A number of lines are observed in X-ray spectra which cannot be represented as transitions between known energy levels. These lines are called non-diagram or satellite lines and arise from either double ionization or combination of a non-radiative transition with a regular transition. The satellites are structure sensitive as shown, for example, by measurements of F. R. Hirsh, [Phys. Rev., 38, 914 (1931)] on $M_{\alpha 1}$, $M_{\alpha 2}$ and M_{β} satellites of the heavy metals. He found a break at element 70 in the curve of ΔE between the main line and the satellite line versus the atomic number. Thorium and uranium show a continuum underlying the satellites. However the interpretation of the satellite lines is not yet definite enough to utilize the existing data. A summary of the work on satellite lines is given by F. R. Hirsh [Rev. Mod. Phys., 14, 45 (1942)].

STRUCTURE OF THE LAST ROW ELEMENTS

There are some qualitative arguments based on the X-ray spectra which we may present in regard to the electronic structure of the last row elements. A marked difference between an f and a d orbit is that the f orbit penetrates more deeply into the inner core of electrons. This is shown clearly by the calculations of M. Goeppert Mayer [Phys.

Rev., 60, 184 (1941) and by the observed optical and magnetic properties of the rare earth elements as contrasted to those of the transition elements. From this evidence and from the screening constant curves shown in Pauling and Goudsmit, p.189, it seems likely that an nf orbit penetrates inside both the ns and np orbits a considerable fraction of the time. We would expect a (n+1)d orbit to penetrate the np orbit only slightly and the ns orbit even less. If these expectations are realized it would mean that the ns and np X-ray levels (e.g. M_I and M_{II} or N_I and N_{II}) would have smaller absolute values if an nf rather than an (n+1)d electron were added and would also have a smaller separation. It is difficult to say much about the absolute values, but the separations shown in Table V support the assumptions. Addition of a d electron in either the Y-Pd series or the Hf-Pt series increases the s and p separation in the electron shell below by $\Delta (\nu/R) \approx 0.2$ to 0.4. The addition of an f electron in the rare earths however does not yield as nearly steady an increase in the separation but a fluctuating value with a much smaller average increase in the separation. The separation is less for the rare earth series than for elements adding a d electron. The fluctuations in the rare earth series may be in part attributed to the experimental error in the measurements due to the difficulties of getting pure materials. The fact that the difference in screening constants for s and p levels is less for an added f than for an added d electron is best seen in the values of $\Delta \sqrt{\nu/R}$ which are related to the screening constants by the approximate formula:

$$\Delta \sqrt{\nu/R} = \sigma_1 / R^n$$

where $\Delta \sigma_1$ is the difference between the ns and np screening constants.

When we apply these considerations to the last-row elements we note first that the O_I, O_{II} separation in radius is about equal to N_I, N_{II} separation in barium, (Table V). This shows that the screening perturbations of the s and p levels are very similar in the N and O shells and that we are fairly safe in using the N shell as a criterion for the O shell. If we do this we see (Table V) that the elements thorium and uranium behave like rare earths rather than the elements completing a d shell. The O_I, O_{II} separation in protactinium is not sufficiently well known to use. These considerations therefore indicate that the f shell begins to fill at thorium, although the systems are too complex for this evidence to be conclusive.

It may be pointed out also that if the considerations given are true and if the interactions are of the order indicated in Table V, i.e. 1 to 2 units of v/R additional data might be obtained from measurements on the elements containing the f electrons in various chemical states. For example the N_I, N_{II} separation in CoO_2 should be somewhat different from that in the metal or in CoF_2 ; it may also be expected that the absorption edges will vary more than is customary in different compounds. Such differences may tell something of the solid structure. For example, the density of thorium is rather low for a tetravalent metal of its atomic weight. This may be explained qualitatively by assuming that one valence electron is in an atomic f orbital and does not contribute much to the cohesion. The O_2 however probably does not have a Sf electron concentrated about the thorium atom so much of the time and there should be differences between the X-ray spectra of the metal oxide.

Another experimental fact can be presented to support the hypothesis that the 5f shell starts to fill with thorium. It has been known for some time that the values of the M_{IV} and M_V absorption edges differ from the calculated levels, based on the L_{III} edge and the emission spectra by amounts considerably outside the experimental error. Siegbahn [Zeit. f. Physik, 67, 567 (1931)] explained this by assuming that the selection rules hold for absorption as well as emission. For the elements 74 to 77 the L_{III} absorption transition is probably made to the incomplete $O_{IV,V}$ levels but the corresponding M_{IV} or M_V transition would be forbidden and its end level must be a higher one of the correct symmetry. The observed differences for M_{IV} and M_V are shown in Table VI, in which the recent data for thorium, protoactinium and uranium have been included. To note that the differences for the last row elements are not only much less in magnitude but are also of opposite sign! This is readily explained if we assume the edges to correspond to transitions L_{III} to $P_{IV,V}$ and M_{IV} or M_V to $O_{VI,VII}$ and assume that the $O_{VI,VII}$ levels lie lower than the $P_{IV,V}$ levels. For lack of a better measure we may even take about 5 electron volts (0.37 in ν/R) as a rough value for the difference in stability between the f levels and the d levels in solid compounds of elements 90, 91 and 92.

In conclusion we may say that the X-ray spectra offers confirmatory though not decisive evidence for the hypothesis that the 5f electron shell begins to fill as thorium.

TABLE I

X-RAY ENERGY LEVELS OF RADIUM, THORIUM, PROTOACTINIUM AND URANIUM VALUES OF ν/R ARE LISTED

Level	Re 88	Th 90	Pa 91	U 92
K		8075.9		8474
L _I	1416.80	1507.22	1554.6	1602.6
L _{II}	1361.39	1450.31	1496.2	1542.7
L _{III}	1137.54	1200.48	1232.5	1264.2
M _I	355.12	381.63	395.3	403.6
M _{II}	330.62	355.14	368.2	381.7
M _{III}	279.24	297.48	307.6	317.0
M _{IV}	239.24	256.93	266.0	274.5
M _V	218.68	245.32	253.7	261.6
N _I	89.06	97.44	102.3	106.0
N _{II}	77.84	85.43	90.5	93.7
N _{III}	64.73	70.63	74.2	76.7
N _{IV}	46.82	52.40	54.9	57.4
N _V	44.42	40.77	52.2	54.4
N _{VI}	22.02	24.69	27.3	28.3
N _{VII}	} 16.74	} 21.35	26.6	} 23.9
O _I			24.2(?)	
O _{II}	14.76	16.43	18.6	18.9
O _{III}	11.17	12.77		14.8
O _{IV}	} 5.01	} 6.39	} 7.0	} 7.6
O _V				
P _I	3.22	4.4		(5.5)
P _{II} , P _{III}	1.32	3.05	1.1(?)	2.9
P _{IV} , P _V		0.40		

TABLE II
VALUES OF $\sqrt{\nu/R}$ FOR THE
X-RAY ENERGY LEVELS OF RADIUM, THORIUM, PROTOACTINIUM AND URANIUM

Level	Ra 88	Th 90	Pa 91	U 92
K		89.87		92.05
LI	37.64	38.82	39.43	40.03
LII	36.90	38.03	38.68	39.28
LIII	33.73	34.65	35.17	35.56
MI	18.85	19.54	19.89	20.21
MII	18.18	18.85	19.19	19.54
MIII	16.71	17.25	17.54	17.81
MIV	15.47	16.03	16.31	16.57
MV	15.12	15.66	15.93	16.17
NI	9.44	9.87	10.12	10.30
NI	8.82	9.24	9.51	9.68
NII	8.02	8.40	8.61	8.76
NIII	6.84	7.24	7.41	7.53
NIV	6.67	7.05	7.23	7.38
NV	4.69	4.97	5.23	5.32
NVI			5.16	
NVII			4.92(?)	4.88
OI	4.33	4.62	4.31	4.35
OII	3.84	3.96		3.85
OIII	3.34	3.57		2.76
OIV, OV	2.24	2.53	2.65	2.30
PI	1.73	2.10		1.70
PII, PIII	1.15	1.75	1.05(?)	
PIV, PV		.63		

REFERENCES TO TABLES I AND II

Radium:

Horia Hulubei, J. Phys. Radium, 8, 260 (1937)

Thorium:

Y. Cauchois and L. Allais, J. Phys. Radium, I, 44 (1940)

Protoactinium:

Compiled from various data as shown in Tables 3 and 4.

Uranium:

The levels to L_{III} are taken from Siegbahn, "Spectroskopie der Röntgenstrahlen", Springer, 1931. The rest are from H. Claesson, Zeit. f. Physik, 101, 499 (1936) except P_I which is quoted by Cauchois and Allais.

TABLE III

X-RAY DATA FOR PROTOACTINIUM

Absorption Edges

Edge	λ in X.U.	ν/R
L _{III}	739.4 ± 0.1	1232.5
L _{II}	608.9 ± 0.1	1496.7
L _I	585.6 ± 0.2	1566.2
M _V	3601	253.1
M _{IV}	3429	265.8

Emission Spectra

L Series

(Most lines ± 0.1 X. U. The starred lines are less accurate)

Transition	λ in X.U.	ν/R	Transition	λ in X.U.	ν/R
M _I L _{III}	1088.5	937.20	M _{III} L _I	730.75	1247.0
M _{IV} L _{III}	942.75	966.60	M _{IV} L _I	707.3 *	1288.4
M _V L _{III}	930.91	978.90	M _V L _I	700.3 *	1301.3
M _I L _{II}	827.8	1100.8	N _I L _{II}	653.6	1394.3
M _I L _{III}	806.2	1130.4	N _{IV} L _{II}	632.5	1440.8
N _V L _{III}	772.1	1180.3	N _{II} L _I	622.6	1453.7
M _{II} L _I	768.3	1186.1	N _{III} L _I	615.6	1480.3
N _{VII} L _{III}	755.3 *	1206.5	O _{IV} L _{II}	612.0	1489.0
O _I L _{III}	753.0	1210.2	O _{II, III} L _I	592.5	1538.0
O _{IV, V} L _{III}	743.7	1225.3	P _{II, III} L _I	586.6 *	1553.5
M _{IV} L _{II}	740.75	1230.2			

TABLE III (continued)

M Series

Transition	λ in X. U.	ν/R	Transition	λ in X.U.	ν/R
O_{IV}^{MII}	2522	361.3	N_{VI}^{MIV}	3819	2386.
N_{IV}^{MII}	2904	313.8	N_{VII}^{MV}	4014	227.0
O_{V}^{MIII}	3032	300.6	N_{VI}^{MV}	4027	226.3
O_{I}^{MIII}	3238	281.4	N_{I}^{MIII}	4441	205.2
$N_{I}^{MII} (?)$	3434	265.4	N_{III}^{MV}	{5081	179.4
N_{V}^{MIII}	3570	255.3		{5066	179.9
N_{IV}^{MIII}	3607	252.6	N_{II}^{MIV}	5182	175.9
O_{II}^{MIV}	3683	257.4			

TABLE IV.

X-RAY TERM VALUES FOR PROTOACTINIUM

Values of ν/R are listed.

$L_{III} =$	<u>1232.5</u>	Experimentally determined absorption edge.
$L_I - L_{III}$	$M_V L_I^* - M_V L_{III} =$	322.40
	$M_{IV} L_I^* - M_{IV} L_{III} =$	<u>321.8</u>
	Average	322.1
$L_I =$	1554.6	Absorption edge = 1556.2
$L_{II} - L_{III}$	$M_I L_{II} - M_I L_{III} =$	263.6
	$M_{IV} L_{II} - M_{IV} L_{III} =$	263.6
	$N_I L_{II} - N_I L_{III} =$	<u>263.9</u>
	Average	263.7
$L_{II} =$	<u>1496.2</u>	Absorption edge = 1496.7
$L_{III} - M_I$	$M_I L_{III} =$	837.2
	$M_I L_{II} - (L_{II} - L_{III}) =$	<u>837.1</u>
	Average	837.2
$M_I =$	<u>395.3</u>	
$L_{III} - M_{II}$	$M_{II} L_I - (L_I - L_{III}) =$	864.1
	$N_I L_{II} - N_I M_{II} - (L_{II} - L_{III}) =$	865.2
	$N_{IV} L_{II} - N_{IV} M_{II} - (L_{II} - L_{III}) =$	<u>863.3</u>
	$O_{IV} L_{II} - O_{IV} M_{II} - (L_{II} - L_{III}) =$	<u>864.4</u>
	Average	864.3
$M_{II} =$	<u>368.2</u>	

TABLE IV (CONTINUED)

L _{III} -M _{III}	M _{III} L _I -(L _I -L _{III})	= 924.9
	O _V L _{III} -O _V M _{III}	= 924.7
	O _I L _{III} * - O _I M _{III}	= (928.8)
	N _V L _{III} - N _V M _{III}	= 925.0
	N _{IV} L _{II} -N _{IV} M _{III} -(L _{II} -L _{III})	= 924.5
	N _I L _{II} -N _I M _{III} -(L _{II} -L _{III})	= <u>925.4</u>
	Average	924.9

$$M_{III} = \underline{307.6}$$

L _{III} - M _{IV}	M _{IV} L _{III}	= 966.6
	M _{IV} L _{II} - (L _{II} -L _{III})	= 966.5
	M _{IV} L _I * - (L _I -L _{III})	= 966.3
	O _{II, III} L _I -O _{II, III} M _{IV} -(L _I -L _{III})	= (968.5)
	N _{II} L _I -N _{II} M _{IV} -(L _I -L _{III})	= <u>(965.7)</u>
	Average	966.5

$$M_{IV} = \underline{266.0}$$

L _{III} -M _V	M _V L _{III}	= 978.90
	M _V L _I * - (L _I - L _{III})	= 979.2
	N _{III} L _I -N _{III} M _V -(L _I -L _{III})	= <u>978.8, (978.3)</u>
	Average	978.9

$$M_{V} = \underline{253.7}$$

TABLE IV (CONTINUED)

$L_{III} - N_I$	$N_I L_{III}$	= 1130.4
	$N_I L_{II} - (L_{II} - L_{III})$	= 1130.6
	$N_I M_{II} + (L_{III} - M_{II})$	= 1129.7
	$N_I M_{III} + (L_{III} - M_{III})$	= <u>1129.9</u>
	Average	1130.2

$N_I = \underline{102.3}$

$L_{III} - N_{II}$	$N_{II} L_I - (L_I - L_{III})$	= 1141.6
	$N_{II} M_{IV} + (L_{III} - M_{IV})$	= <u>1142.4</u>
	Average	1142.0

$N_{II} = \underline{90.5}$

$L_{III} - N_{III}$	$N_{III} L_I - (L_I - L_{III})$	= 1158.2
	$N_{III} M_V + L_{III} - M_V$	= <u>1158.3</u>
	Average	1158.3

$N_{III} = \underline{74.2}$

$L_{III} - N_{IV}$	$N_{IV} L_{II} - (L_{II} - L_{III})$	= 1177.1
	$N_{IV} M_{II} + L_{III} - M_{II}$	= 1178.1
	$N_{IV} M_{III} + L_{III} - M_{III}$	= <u>1177.5</u>
	Average	1177.6

$N_{IV} = \underline{54.9}$

TABLE IV (CONTINUED)

$L_{III} - N_V$	$N_V L_{III}$	= 1180.3
	$N_V M_{III} L_{III} - M_{III}$	= <u>1180.2</u>
	Average	1180.3
$N_V = \underline{52.2}$		
$L_{III} - N_{VI}$	$N_{VI} M_V + L_{III} - M_V$	= 1205.2
	$N_{VI} M_{IV} + L_{III} - M_{IV}$	= <u>1205.1</u>
	Average	1205.1
$N_{VI} = \underline{27.3}$		
$L_{III} - N_{VII}$	$N_{VII} M_V + L_{III} - M_V$	= 1205.9
$L_{VII} = \underline{26.6}$		
$L_{III} - O_I$	$O_I L_{III}^*$	= 1210.2
	$O_I M_{III} + L_{III} - M_{III}$	= <u>1206.3</u>
$O_I = \underline{24.2}$		1208.3
$L_{III} - O_{II}$	$O_{II} M_{IV} + L_{III} - M_{IV}$	1213.9
	$O_{II, III} L_I - (L_I - L_{III})$	= (1215.9)
$O_{II} = \underline{13.6}$		
$L_{III} - O_{III}$	No data	
$L_{III} - O_{IV}$	$O_{IV} L_{II} - (L_{II} - L_{III})$	= 1225.3
	$O_{IV} M_{II} + L_{III} - M_{II}$	= <u>1225.6</u>
	Average	1225.5
$O_{IV} = \underline{7.0}$		

TABLE IV (CONTINUED)

$L_{III} - O_V$	$O_{IV}^{V_{III}}$	$= 1225.3$
	$O_V^{M_{III}} + L_{III} - M_{III}$	$= \underline{1225.5}$
		1225.4

$$O_V = \underline{7.1}$$

$$L_{III} = P_I$$

No data

$$L_{III} - P_{II,III}$$

$$P_{II,III} L_I - (L_I - L_{III}) = 1231.4$$

$$P_{II,III} = \underline{1.1}$$

REFERENCES TO TABLE IV

- L Absorption edges: V. Dobejšek and J. Marek, Zeit. F. Physik, 97, 97 (1935)
- M Absorption edges: V. Dobejšek and V. Kunzl, Nature, 138, 590 (1936)
- L Series: H. Bouthé and A. V. Grosse, Zeit. f. Physik, 61, 170 (1930)
- M Series: Pierce and A. V. Grosse, Phys. Rev., 47, 532 (1935)

TABLE V

$M_T - M_{II}$			$N_T - N_{II}$			$O_T - O_{II}$		
$\Delta(\nu/R)$	$\Delta\sqrt{\nu/R}$		$\Delta(\nu/R)$	$\Delta\sqrt{\nu/R}$		$\Delta(\nu/R)$	$\Delta\sqrt{\nu/R}$	
38 Sr	5.8	0.50	56 Ba	4.2	0.52	88 Ra	4.0	0.49
39 Y	6.1	.58	57 La	5.6	.67	89 Ac		
			58 Ce	4.7	.54	90 Th	4.9	.56
			59 Pr	5.2	.58	91 Pa		
			60 Nd	5.3	.58	92 U	5.0	.53
			61					
			62 Sm	5.7	.60			
			63 Eu	5.3	.54			
			64 Gd	6.3	.63			
			65 Tb	5.9	.57			
			66 Dy	5.9	.56			
			67 Ho	6.4	.60			
			68 Er	5.9	.54			
			69 Tm					
			70 Yb	7.8	.60			
			71 Lu	6.3	.54			
40 Zr	6.4	.60	72 Hf	7.4	.61			
41 Nb	6.6	.59	73 Ta	7.6	.62			
42 Mo	7.0	.60	74 W	7.3	.58			
43 Tc			75 Re	8.0	.61			
44 Ru	7.3	.59	76 Os					
45 Rh	7.7	.61	77 Ir	8.3	.61			
46 Pd	8.0	.59	78 Pt	8.3	.60			
47 Ag	8.6	.61	79 Au	8.5	.59			

REFERENCES FOR TABLE V.

All data are for Siegbahn, "Spectroskopie der Roentgenstrahlen", 2nd Ed., Springer, Berlin, 1931, except for the last row elements which are from Tables I and II, and rhenium which are from Y. Cauchois, J. Phys. Radium, 8, 267 (1937).

TABLE VI

DIFFERENCES BETWEEN OBSERVED AND CALCULATED M_{IV} AND M_V EDGES.Values of ν/R are listed.

Element	M_{IV} Edge observed	$[M_{IV}]$ Edge Calc. from L_{III} edge	$\Delta(\nu/R)$ $M_{IV} - [M_{IV}]$	M_V Edge observed	$[M_V]$ edge calc. from L_{III} edge	$\Delta(\nu/R)$ $M_V - [M_V]$
73 Ta				130.2	128.1	+2.1
74 W	140.5	137.5	3.0	136.0	132.9	3.1
75 Re				--	138.5	
76 Os	152.5			146.1	149.4	3.3
77 Ir	158.4	155.3	3.1	152.9	149.8	3.1
78 Pt	164.4	161.2	3.2	158.6	155.3	3.3
90 Th	256.7	256.9	-0.2	244.8	245.3	-0.5
91 Pa	265.8	266.0	-0.2	253.1	253.7	-0.6
92 U	273.9	274.5	-0.6	261.0	261.6	-0.6

