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X-Ray Satellites of High Atomic Number Elements

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The x-ray lines $L\alpha_1$ and $L\alpha_2$ have been examined for accompanying satellites in the atomic number range from Ta(73) to U(92). $L\alpha$ is found to have two satellites, herein called $L\alpha^{ix}$ and $L\alpha^{x}$. The former (longer wave-length) extends from Au(79) to U(92); the latter from Os(76) to Bi(83). Even over the short range of atomic numbers over which they occur, these two satellites change rapidly as to relative intensity and appearance. They do not seem to be connected with the prominent group of satellites of $L\alpha$ which occur in the region $36<Z<54$. $L\beta_2$ is found to have two satellites, $L\beta_2'$ and $L\beta_2''$. $L\beta_2''$ extends from Ta(73) to U(92). $L\beta_2'$ begins several atomic numbers below Ta(73) and extends to U(92). The satellite structure accompanying $L\beta_2$ in this high atomic number range is somewhat similar to that found in the range $40<Z<54$. But the absence of any satellites of $L\beta_2$ in the range $54<Z<70$ suggests that these high atomic number satellites may be new lines.

ONE of the most significant characteristics of x-ray satellites is the fact their atomic number range is not at all coincident with that of the parent lines with which the satellites are respectively associated. For example, although $L\alpha$ is first observed at Va(23), the satellites of $L\alpha$ are not found until Ni(28)[1] or Cu(29)[2] is reached. For higher atomic numbers the satellites become more prominent, reaching a maximum of intensity, relative to the parent line for elements in the neighborhood of Rh(45). Beyond Rh(45) the satellite structure becomes less prominent. At Sn(50) only a broad, unresolved band remains.[3] This band is very faint at Te(52). No trace of satellite structure accompanying $L\alpha$ is observable for Ba(56).

Similarly it has been shown[4] that the prominent satellites of $L\beta_2$ are not observed for the elements immediately above I(53).

There have been reported in the literature,[5] however, numerous satellites of L lines in the spectra of the elements of higher atomic number, particularly from Ta(73) to U(92). Since there has been no systematic and searching study of satellites in this atomic number range, the present work was undertaken primarily to ascertain whether these high-atomic-number satellites are in fact, as has been assumed,[5] identical with the satellites found associated with elements of lower atomic number; or whether they are to be regarded as new lines.

The spectrometer used was of the Siegbahn-Thoraeus high-vacuum type,[6] the distance be-

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[1] A. Karlsson, Ark. Math. Astr. o. Fys. (Upsala) **22**, 1930.

[2] J. H. Van der Tuuk, *Dissertation*, Groningen, 1928.

[3] F. K. Richtmyer, J. Franklin Inst. **208**, 325 (1929).

[4] R. D. Richtmyer, Phys. Rev. **38**, 1802 (1931).

[5] These data are most readily found in tables in Siegbahn's *Spektroskopie der Röntgenstrahlen*, second edition, (1931), Siegbahn uses the term "spark lines" instead of "satellites."

[6] J. Opt. Soc. Am. and Rev. Sci. Inst. **13**, 235 (1926).

tween the entrance slit and the photographic plate being 54.9 cm for some of the plates; and 211.4 cm for others. The higher resolution attainable at the greater distance, with suitable slit widths, is an important factor in studying the satellite structure.

SATELLITES OF $L\alpha$

In the atomic number range $29<Z<50$, $L\alpha$ has five (in some elements more) satellites, which, beginning with In(49), decrease rapidly in intensity and are not observed above Xe(54). Contrary to the observations of Coster[7] and Dauvillier[8] no trace of satellites accompanying $L\alpha$ has been found by the senior author for Ba(56), although spectrum plates have been made and examined with great care. If satellites do accompany Ba $L\alpha$, they must be exceedingly faint. From La(57) to Yb(70) inclusive, *no observer has reported satellites of* $L\alpha$. Dauvillier[9] reports one satellite ($L\alpha_3$, Siegbahn's notation) for Lu(71), although no such line was found by Wennerlöf[10] or by Coster.[7] Two observers, namely Wennerlöf[10] and Auger and Dauvillier[11] report a satellite ($L\alpha_3$, Siegbahn) for Ta(73), in disagreement with Idei,[12] whose work appears to have been most carefully done. Of the 14 observers quoted by Siegbahn as having measured $L\alpha_{1,2}$ of W(74) only Rogers[13] reports a satellite for $L\alpha$. The present authors have made many plates of Ta(73) and of W(74) under a variety of different conditions, and have failed to find the slightest trace of a satellite of $L\alpha$ for either element. One concludes, therefore, either that no satellites exist for $L\alpha$ between Cs(55) and W(74) inclusive, or, if there is a satellite in this atomic number range, it is so very faint as to have escaped detection by most of the observers.

For atomic numbers higher than W(74) there is ample evidence that $L\alpha$ is accompanied by one (or more) satellites, except possibly in the case of Rh(75), for which Beuthe[14] alone reports $L\alpha_3$.

In the present work, in addition to the observations on Ta(73) and W(74) mentioned above, we have studied the satellite structure accompanying $L\alpha$ for the elements Os(76), Ir(77), Pt(78), Au(79), Tl(81), Pb(82), Bi(83), Th(90) and U(92). Two satellites were found which we shall call $L\alpha^{ix}$ and $L\alpha^{x}$.† $L\alpha^{x}$ is found in the atomic number range Os(76)[14] to Pb(83); $L\alpha^{ix}$ in the range of Au(79) to U(82), although we failed to find definite evidence of this line for Tl(81), since on our plates the $L\beta_9$ line of W(74), appearing because of our use of a tungsten filament in the x-ray tube, comes at exactly the same wave-length as would $L\alpha^{ix}$ of Tl(81). Data regarding these two satellites are given in Table I.

TABLE I. *Satellites of* $L\alpha$ *for the range Os(76) to U(93).*

	$L\alpha^{ix}$				$L\alpha^{x}$			
Element	λ(X.U.)*	$\Delta\lambda$ $(\alpha_1-\alpha^{ix})$	$\frac{\Delta\nu}{R}$	$\left(\frac{\Delta\nu}{R}\right)^{\frac{1}{2}}$	λ	$\Delta\lambda$ $(\alpha_1-\alpha^{x})$	$\frac{\Delta\nu}{R}$	$\left(\frac{\Delta\nu}{R}\right)^{\frac{1}{2}}$
Os 76					1383.07	5.52	2.62	1.62
Ir 77					1343.17	5.30	2.66	1.63
Pt 78					1305.13	5.20	2.77	1.66
Au 79	1270.54	3.23	1.82	1.35	1268.63	5.14	2.89	1.70
Tl 81	**				1200.00	4.93	3.10	1.76
Pb 82	1169.29	3.26	2.16	1.47	1167.85	4.73	3.13	1.77
Bi 83	1138.14	3.36	2.35	1.53	1136.95	4.55	3.18	1.78
Th 90	950.80	3.25	3.26	1.81				
U 92	905.35	3.39	3.72	1.93				

* Siegbahn's values of λ for $L\alpha_1$ for each element are taken as standard.

** Obscured by $L\beta_9$ of W(74).

The values of $(\Delta\nu/R)^{\frac{1}{2}}$ are shown graphically in Fig. 1 as a function of atomic number for these satellites, $L\alpha^{ix}$ and $L\alpha^{x}$. The circles represent the data of the present authors. The crosses are from the observations of Idei.[12] For comparison, there are plotted on the same graph the (six) satellites of $L\alpha$ in the atomic number range $36<Z<50$, from the measurements of Richtmyer and Richtmyer.[15]

If one relies solely upon the graphical relations shown in Fig. 1, one might conclude that the

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[7] Coster, Phil. Mag. **43**, 1070; **44**, 545 (1922).

[8] Dauvillier, C. R. **174**, 1347 (1922).

[9] Dauvillier, J. d. Physique et le Radium **3**, 230 (1922).

[10] Wennerlöf, Ark. Math. Astr. o. Fys. **22**, No. 8 (1930).

[11] Auger and Dauvillier, C. R. **176**, 1297 (1923).

[12] Idei, Tohoku Imp. Univ., Sci. Rep. **19**, 651 (1930).

[13] Rogers, Proc. Camb. Phil. Soc. **21**, 430 (1923).

[14] Beuthe, Zeits. f. Physik **46**, 873 (1928).

† Idei (reference 12) recognizes the existence of these two lines, although he did not find both of them for any one element. He designates them $L\alpha'$ and $L\alpha''$, respectively. Since it is obvious from Fig. 1 that these lines are *not* to be identified with the satellites $L\alpha'$ and $L\alpha''$ which occur in the atomic number range Rb(37)–Te(52), we have adopted the symbols $L\alpha^{ix}$ and $L\alpha^{x}$ to avoid confusion. Siegbahn (reference 5) does not distinguish between these two lines and calls them $L\alpha_3$.

[15] Richtmyer and Richtmyer, Phys. Rev. **34**, 574 (1929).

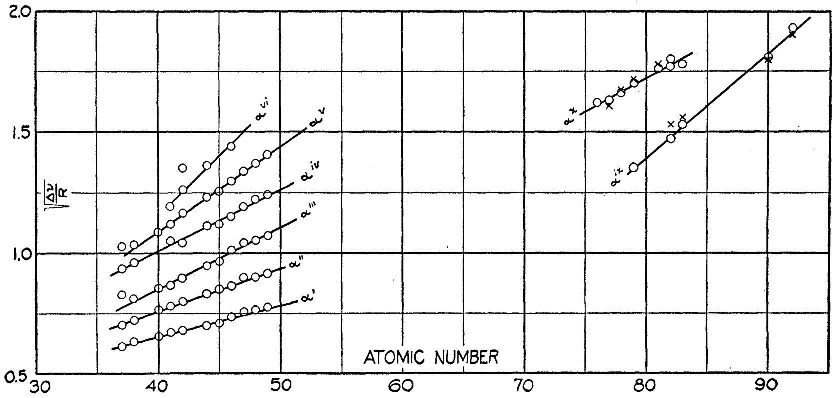

FIG. 1. $(\Delta\nu/R)^{\frac{1}{2}}$ as a function of atomic number for satellites of $L\alpha$. ($\Delta\nu \equiv$ difference in frequency between satellite and parent line.) The crosses are from the measurements of Idei.[12] The circles, for elements 76–92, are from data by present authors; for elements 37–50, from data by Richtmyer and Richtmyer.[15]

satellite designated $L\alpha^x$ is to be identified with $L\alpha''$ and $L\alpha'''$, perhaps unresolved for these high atomic number elements, which latter are the most intense satellites of the lower atomic number range.

There are, however, weighty arguments against this conclusion. First of all, there is no evidence that additional satellites accompany $L\alpha^{ix}$ and $L\alpha^x$, similar to $L\alpha^{iv}$ and $L\alpha^v$ which are associated with $L\alpha''$ and $L\alpha'''$ in the lower range. The intensities of $L\alpha^{iv}$ and $L\alpha^v$ are such that, if present with $L\alpha^x$, they should be readily detected. Second, the combination $L\alpha^{ix}$ and $L\alpha^x$ presents a structure very different from $L\alpha' - L\alpha^{vi}$, as may be seen from Fig. 1. Third, and most important, $L\alpha^x$ appears very abruptly at Os(76), and can therefore hardly be regarded as an extension of $L\alpha''^{+'''}$, which, as above noted, are not found above I(53).

Of greater importance than the wave-length and atomic number range of $L\alpha^{ix}$ and $L\alpha^x$, is the rapid change in character of these lines as one advances up the atomic number scale above Os(76). At Os(76) $L\alpha^x$ is a sharp, fairly prominent line, well separated from $L\alpha_1$. At Ir(77) the satellite is still sharp, but the "valley" between it and the parent line is less pronounced. At Pt(78) this "valley" has become almost as intense as the satellite itself, which now appears almost like a sharp, prominent edge to a narrow band. At Au(79) there is unmistakable evidence of the presence of *two* lines, the new line, $L\alpha^{ix}$, appearing in what was formerly the valley between $L\alpha^x$ and $L\alpha_1$. Very likely the "filling up" of this valley in Ir(77) and Pt(78) foreshadows the appearance of $L\alpha^{ix}$. For Tl(81), Pb(82) and Bi(83) there is clear evidence of the presence of both $L\alpha^{ix}$ and $L\alpha^x$, although, as above noted, $L\alpha^{ix}$ for Tl(81) is probably covered up by $L\beta_9$ of W(74). For Th(90) and U(92) our plates are not as intense as they should be for best observation, but unmistakably there is only one satellite present, namely $L\alpha^{ix}$.

One concludes tentatively, therefore, that $L\alpha^{ix}$ and $L\alpha^x$ are *new* satellites, having a different origin from the group of satellites $L\alpha' - L\alpha^{vi}$. Furthermore, the rapid change in the character of these two satellites with atomic number after passing Os(76) suggests that their origin is in some way connected with the changes which take place in the O_{IV} and the several P electron shells in the region of Os(76) to U(92), *there being over this atomic number range no change in the L and M shells in which* $L\alpha_{1,2}$ *originates.*

It is not easy to reconcile these data with the Wentzel-Druyvesteyn theory, according to which satellites have their origin in atoms which are doubly ionized as to their *inner* electron shells. W(74) differs from Os(76) *only* as regards the number of electrons in the O_{IV} shell: W(74) has no electrons in this shell while Os(76) has two. Yet in Os(76) there is a prominent satellite while in W(74) there is none.

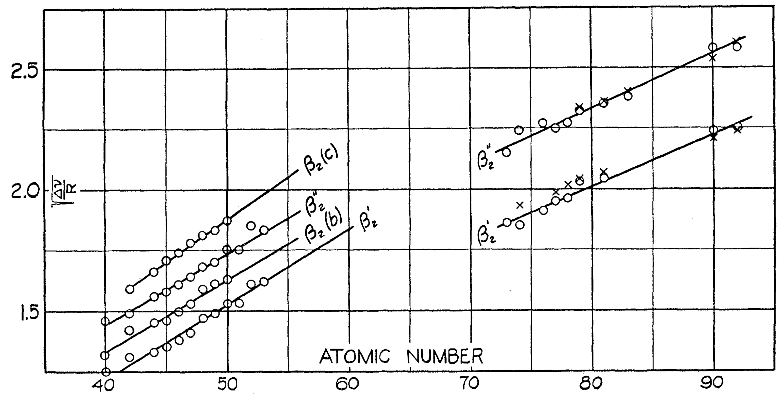

FIG. 2. $(\Delta\nu/R)^{\frac{1}{2}}$ as a function of atomic number for satellites of $L\beta_2$. The crosses are from the measurements of Idei.[12] The circles, for elements 73–92, are from data by present authors; for elements 40–54, from data by Richtmyer and Richtmyer.[15]

SATELLITES FOR $L\beta_2$

In the atomic number range $40<Z<54$, $L\beta_2$ has four satellites, well separated from the parent line. Two of these, $L\beta_2'$ and $L\beta_2''$ are quite sharp and, for satellites, are relatively intense. Associated with these two lines is a short continuous spectrum extending toward shorter wave-lengths from $L\beta_2'$ well past $L\beta_2''$. Midway between $L\beta_2'$ and $L\beta_2''$ is a faint, diffuse satellite[15] called $L\beta_2$(c); beyond $L\beta_2''$ is a fourth line, similarly faint and diffuse, called[15] $L\beta_2$(d). This type of structure persists substantially unchanged, except as to intensity relative to parent line, over the above atomic number range.

These satellites disappear, abruptly, at I(53), as has been shown by R. D. Richtmyer,[4] who pointed out that the lines designated by Coster[16] as satellites, in the spectrum of Ba(56) are, in reality, diagram lines ($L\beta_7$ and $L\beta_{10}$ respectively). *There are no other satellites of $L\beta_2$ reported in the literature for elements above Ba(56) until Er(68) is reached.* For this element Coster[17] reports a single satellite, $L\beta_2'$. This one line is reported by various observers for the elements Yb(70) to Ir(77). For the remaining elements two satellites $L\beta_2'$ and $L\beta_2''$ are reported.

Our own measurements begin at Ta(73) and include all elements readily available up to U(92). For each element studied, two satellites, $L\beta_2'$ and $L\beta_2''$ have been found,† as is shown in Table II. $(\Delta\nu/R)^{\frac{1}{2}}$ as a function of Z is shown in Fig. 2, in which, for comparison there is also shown the four satellites of $L\beta_2$ in the lower atomic number range. The circles are the observations of the present authors. The crosses are from the work of Idei.[12]

TABLE II. *Satellites of $L\beta_2$ for the range Ta(73) to U(92).*

Element	$L\beta_2'$				$L\beta_2''$			
	λ(X.U.)*	$\Delta\lambda$ $(\beta_2-\beta_2')$	$\frac{\Delta\nu}{R}$	$\left(\frac{\Delta\nu}{R}\right)^{\frac{1}{2}}$	λ(X.U.)	$\Delta\lambda$ $(\beta_2-\beta_2'')$	$\frac{\Delta\nu}{R}$	$\left(\frac{\Delta\nu}{R}\right)^{\frac{1}{2}}$
Ta(73)	1275.68	6.22	3.46	1.86	1273.57	8.33	4.62	2.15
W(74)	1236.21	5.82	3.43	1.85	1233.53	8.50	5.02	2.24
Os(76)	1163.38	5.46	3.65	1.91	1161.13	7.71	5.15	2.27
Ir(77)	1127.61	5.36	3.80	1.95	1125.85	7.12	5.07	2.25
Pt(78)	1094.64	5.10	3.86	1.96	1092.93	6.81	5.15	2.27
Au(79)	1062.86	5.15	4.12	2.03	1061.28	6.73	5.39	2.32
Tl(81)	1003.58	4.64	4.17	2.04	1002.07	6.15	5.53	2.35
Pb(82)	976.09				974.50			
Bi(83)	(masked by $L\beta_1$)				947.62	5.62	5.67	2.38
Th(90)	788.47	3.45	5.02	2.24	787.36	4.56	6.66	2.58
U(92)	749.92	3.15	5.07	2.25	748.93	4.14	6.66	2.58

* Siegbahn's values for $L\beta_2$ for each element taken as standard.

As in the case of the satellites of $L\alpha_1$, the wave-length data, either in tabular or graphical form, do not tell the whole story. There is no doubt concerning the absence of both β_2' and β_2'' over a considerable range of atomic numbers in the rare earth region. There is agreement in the literature that β_2' is the first to reappear. It seems to increase in intensity until Os(76) is reached,

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[16] Coster, Phil. Mag. **44**, 545 (1922).

[17] Coster, Phil. Mag. **43**, 1070 (1922).

† To save confusion in terminology Siegbahn's designation of these high atomic number satellites of $L\beta_2$, namely $L\beta_2'$ and $L\beta_2''$, has been retained, although it is by no means certain that these lines are to be identified with those similarly designated in the lower atomic number range.

beyond which its intensity seems to be constant. Our plates show clearly that, although β_2'' is unmistakably present at Ta(73) it is much weaker than β_2', and it grows in intensity less rapidly than does β_2'. Not until Tl(81) or Pb(82) is reached do the two lines have the same intensity, which equality is maintained up to U(92).

The behavior of these two satellites in the high-atomic number range is thus, as was found to be the case with the satellites of $L\alpha$, quite different from that observed in the lower range in which the two lines maintained the same intensity relative to each other throughout.

A further point of difference is that while $L\beta_2'$ and $L\beta_2''$ are equally sharp for the range $40<Z<54$, $L\beta_2''$ is noticeably "fuzzy" for the elements Ta(73) to Pt(78).

Again, as in the case of $L\alpha$, there is no change in the electron configurations in the shells which give rise to $L\beta_2$ over the atomic number range for which the satellites are observed.

The following two conclusions therefore, seem to be justified by the data above reported: First, the high atomic number satellites of $L\alpha$ and $L\beta_2$ are not to be identified with the satellites which accompany these lines at the lower atomic number range. Second, the peculiar behavior of these satellites in passing from element to element in this high atomic number region, seems to indicate a close connection of some kind between the satellites and the peripheral electron structures of the atom.

Since it is the purpose of this paper to present experimental results, no further comments will be made concerning the bearing of these data on current theories of the origin of satellites, beyond the obvious remark that any acceptable theory must be in agreement with the observations herein reported!