The Yield of Fluorescence X-Rays from the K-Shells of Thirteen Elements*

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(Received August 28, 1933)

The fluorescence yield w_K has been measured by the ionization method as developed by A. H. Compton for thirteen elements. The following results have been obtained:

Element	w_K	Element	w_K	Element	w_K
27 Co	0.38	33 As	0.53	47 Ag	0.72
28 Ni	.39	34 Se	.55	48 Cd	.70
29 Cu	.43	38 Sr	.72	50 Sn	.66
30 Zn	.45	42 Mo	.79	51 Sb	.64
				52 Te	.59

These results show that w_K reaches a maximum value of 0.79 for molybdenum. It then rapidly drops to lower values for the heavier elements.

INTRODUCTION

THE fluorescence yield w_K from the K-shells of an assemblage of atoms has been defined by Auger[1] as the ratio of the number of fluorescence K-quanta that leave the atoms in the group to the number of quanta that are photoelectrically absorbed in the K-shells of those atoms. The same definition can be applied *mutatis mutandis* to the yield from the L-shell. Auger[1, 2] and Locher[3] have measured the yield by counting the electron-tracks in cloud chambers. Values of the fluorescence yield based on ionization-chamber measurements have been reported by several investigators.[4–13] In spite of the number of investigations bearing on this subject, the amount of data is not large, for no one investigator worked with more than six elements, and some with only one. Furthermore, there is considerable divergence among the data.

The present investigation was undertaken in order to obtain data on a large number of elements with the same apparatus, and to determine the trend of the fluorescence yield with increase of atomic number.

THEORY

The fluorescence yield w_K is determined by comparing the intensities of the primary and the fluorescence beams by means of an ionization-chamber. Compton[9] used this method in his investigations and developed the appropriate equations. He found

$$w_K=\frac{4\pi r^2}{A''(\delta-1)/\delta}=\frac{\mu'+\mu''}{\mu'}\times\frac{\lambda''}{\lambda'}\times\frac{i''}{i'}\times\frac{f'}{f''}\times\frac{S'}{S''}\times\frac{R'}{R''}, \quad (1)$$

* From a thesis presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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1 P. Auger, Ann. d. Physik **6**, 183 (1926).
2 P. Auger, Comptes Rendus **180**, 65 (1925).
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3 Gordon L. Locher, Phys. Rev. **40**, 484 (1932).
4 W. Kossel, Zeits. f. Physik **19**, 333 (1923).
5 W. Bothe, Phys. Zeits. **26**, 410 (1925).
6 G. E. M. Jauncey and O. K. De Foe, Proc. Nat. Acad. Sci. **11**, 520 (1925).
7 L. Balderston, Phys. Rev. **27**, 695 (1926).
8 M. I. Harms, Ann. d. Physik **82**, 87 (1926).
9 A. H. Compton, Phil. Mag. **8**, 961 (1929).
10 L. H. Martin, Proc. Roy. Soc. **A115**, 420 (1927).
11 R. J. Stephenson, Phys. Rev. **43**, 527 (1933).
12 W. Stockmeyer, Ann. d. Physik [5] **12**, 71 (1932).
13 M. Haas, Ann. d. Physik [5] **16**, 473 (1932).

where the symbols* have the same meanings as in his paper. The primed and double-primed quantities refer to the primary and secondary radiations, respectively. Compton used the approximation 85 percent for the fraction of the primary quanta absorbed in the K-shells, instead of the more exact value $(\delta-1)/\delta$ obtained from the measurements of the K-absorption jump δ. The symbol R designates the ratio of the energy spent in producing ionization to the absorbed energy.

$$R=1-\frac{\delta-1}{\delta}\times e^{-\mu''x}\times\left(w_K\times\frac{\tau}{\mu}\times\frac{\lambda}{\lambda''}\right)_{\text{Argon}}-\frac{\sigma}{\mu}\times e^{-\mu'x}. \quad (2)$$

The second term of Eq. (2) takes account of the loss of fluorescence energy excited in the gas in the ionization-chamber, while the third term takes account of the loss by scattering. In the present work, argon at atmospheric pressure was used in the chamber. This has two advantages. In the first place, it has such a high atomic number that for the wave-lengths used here the scattering is negligible in comparison to the photoelectric absorption. Thus the third term of Eq. (2) vanishes. In the second place, the fluorescence rays of argon are so soft that they will be absorbed before reaching the walls of the ionization-chamber. There will not even *be* much fluorescence, because w_K for argon is small. Thus the second term in Eq. (2) reduces (nearly) to zero,[14] and we have[15]

$$R \doteq 1.$$

A geometrical constant of the apparatus is

$$M\equiv(4\pi r^2/A'')(S'/S''). \quad (3)$$

After f' and f'' have been determined (from the values of the absorption-coefficients of argon), there is a constant C_Z for each element under investigation:

$$C_Z\equiv\frac{M}{(\delta-1)/\delta}\times\frac{\mu'+\mu''}{\mu'}\times\frac{\lambda''}{\lambda'}\times\frac{f'}{f''}. \quad (4)$$

Then Eq. (1) reduces to

$$w_K=C_Z(i''/i'). \quad (5)$$

Apparatus and Procedure

The radiator L of barium nitrate[16] is placed at an angle of 45° directly above the tungsten-target x-ray tube (Fig. 1). Fluorescence x-rays

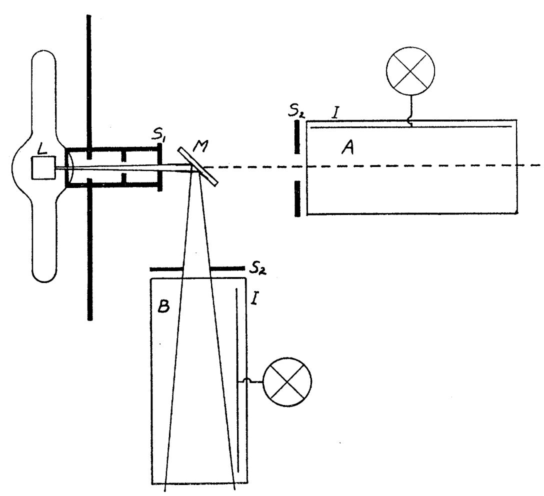

Fig. 1. Arrangement of apparatus.

* r = distance between secondary radiator M and diaphragm S_2. A'' = area of the hole in diaphragm S_2. δ = K-absorption jump. μ' = absorption coefficient of the material of the radiator M for the primary radiation falling on it from L. μ'' = absorption coefficient of the material of the radiator M for its own characteristic K-radiation. λ' and λ'' = wave-lengths of the K-radiations characteristic of the radiators L and M, respectively. i' and i'' = corrected ionization-currents obtained with the ionization-chamber in the positions A and B, respectively. S' and S'' = areas of the diaphragm S_1 when measuring the primary and secondary rays, respectively. f' and f'' = fractions of the x-ray beams absorbed in the ionization-chamber when in the positions A and B, respectively. R' and R'' = ratios of the energy spent in producing ionization to the absorbed energy, for the primary and secondary rays, respectively.

[14] S. K. Allison and V. J. Andrew, Phys. Rev. **38**, 441 (1931). These investigators have studied this phenomenon and report deviations of the order of 1–2 percent from unity. This is of the same order as the experimental error, and so is here neglected.

[15] The author is indebted to A. H. Compton for suggesting the use of argon in the chamber, as well as for several other helpful details.

[16] This is used merely as a convenient source of monochromatic x-rays.

TABLE I. *Values of C_Z.*

Element	$(\delta-1)/\delta$	μ'/ρ	μ''/ρ	$(\mu'+\mu'')/\mu'$	λ''	λ''/λ'	f''	f'/f''	C_Z
27 Co	0.886	7.0	61.	9.7	1.77	4.68	1.00	0.075	6.58
28 Ni	.884	7.7	54.	8.0	1.63	4.32	0.99	.076	5.04
29 Cu	.882	8.8	49.	6.6	1.51	4.00	.98	.077	3.88
30 Zn	.880	9.9	47.0	5.76	1.41	3.73	.96	.078	3.24
33 As	.874	12.7	37.3	3.94	1.16	3.06	.85	.088	2.07
34 Se	.872	13.9	34.0	3.45	1.09	2.87	.78	.096	1.85
38 $SrCO_3$	.865	11.3	15.6	2.38	0.859	2.27	.52	.144	1.53
42 Mo	.858	23.0	18.7	1.81	.696	1.84	.345	.217	1.43
47 Ag	.850	31.0	12.6	1.41	.549	1.45	.205	.366	1.49
48 Cd	.849	31.9	11.7	1.37	.525	1.39	.178	.406	1.54
50 Sn	.847	34.5	10.0	1.29	.482	1.28	.155	.484	1.60
51 Sb	.844	36.5	9.4	1.26	.462	1.22	.140	.536	1.66
52 Te	.843	38.2	8.4	1.22	.443	1.17	.125	.600	1.73
56 Ba	—	—	—	—	.378	—	.075	—	—

from L pass through holes in a series of baffles and finally through the diaphragm S_1, falling upon M set at 45° to the beam. The fluorescence radiation from M (the sample under investigation) is measured by the ionization-chamber I in the position B through the diaphragm S_2. The ionization-current i'' thus measured is compared with that i' caused by the direct beam with I in the position A, M being then removed and a much smaller diaphragm placed in the position S_1.

The x-ray tube was operated at 60 peak kilovolts and 34 milliamperes from a supply giving half-wave rectification by means of a kenotron. The power was supplied by a motor-generator set, with a large induction motor. This minimized fluctuations in the input voltage to the high-tension transformer, which could thus be held constant to one-tenth of a volt by means of the field rheostat. The voltage was controlled continuously during a reading. The ionization-chamber was 24 cm long, 7 cm in diameter and filled with argon at atmospheric pressure. Diaphragms were so disposed that no rays ever struck the walls. The x-rays emerged from the rear of the chamber through a cellophane window. The Compton electrometer was operated at 3000–4000 mm per volt at a scale distance of 140 cm.

AUXILIARY DATA

In order to calculate w_K, the factor C_Z (see Eq. (4)) must be calculated separately for each element used. The values of $(\delta-1)/\delta$ were obtained from a table compiled by F. Kirchner.[17] It is calculated from published data on absorption-jumps. This was plotted and a smooth curve drawn through the points. From this curve the values of $(\delta-1)/\delta$ for the elements used were read off. The values of μ' and μ'' were interpolated from tables collected by Professor S. J. M. Allen and kindly furnished to the author.

The wave-lengths λ' and λ'' were calculated from those given in the Wien-Harms *Handbuch der Experimental Physik*, Vol. 24, part 2. The values used are the weighted means wave-lengths of the α and β-lines,[18, 19] the α-line being given five times the weight of the β-line, in accordance with the work of Unnewehr and Compton.

The fractions f' and f'' of the beams absorbed in the ionization-chamber were calculated from the published absorption-coefficients of argon and nitrogen. It was necessary to take account of the nitrogen, as the argon used was the commercial grade containing 14 percent by volume of nitrogen.

Table I shows the values of C_Z for the various samples used, as well as the auxiliary data used in calculating them. Throughout the course of the investigation barium was used as the source of the primary radiation. We have

$$M=(4\pi r^2/A'')(S'/S'')=1.697,$$

[17] Wien-Harms, *Handbuch der Experimental Physik*, Vol. 24, part 1, p. 256.

[18] Unnewehr, Phys. Rev. **22**, 529 (1923).

[19] A. H. Compton, Proc. Nat. Acad. Sci. **14**, 549 (1928).

where $r = 11.4$ cm, $A'' = 3.19$ cm^2, and $S'/S'' = 0.003305$.

It will be noticed that the strontium used was in the form of the carbonate. Therefore it was necessary to compute values of μ/ρ for the compound at the wave-lengths λ' and λ'' by the additive law.

Discussion of Results

The ratios of the ionization-currents caused by the primary and fluorescence beams are shown in Table II, together with the values of the fluorescence yield w_K deduced from Eq. (5).

Table II. *Ratios of currents due to primary and fluorescence radiation and values of w_K.*

Element	i''/i'	w_K	Element	i''/i'	w_K
27 Co	0.058	0.38	38 Sr	0.469	0.72
28 Ni	.077	.39	42 Mo	.549	.79
29 Cu	.111	.43	47 Ag	.480	.72
30 Zn	.140	.45	48 Cd	.452	.70
33 As	.255	.53	50 Sn	.414	.66
34 Se	.300	.55	51 Sb	.383	.64
			52 Te	.344	.59

The values given in Table II are plotted in Fig. 2. They show that there is a distinct maximum in the K-fluorescence yield at $Z = 42$, molybdenum. Beyond molybdenum the yield decreases again. So far as the author is aware, this is the first investigation of the K-yields of elements of high enough atomic number to show this decrease. Heretofore many have tacitly supposed that the K-yields kept on increasing up to uranium. The work of Balderston[7] gives the only hint available that such may not be the case.

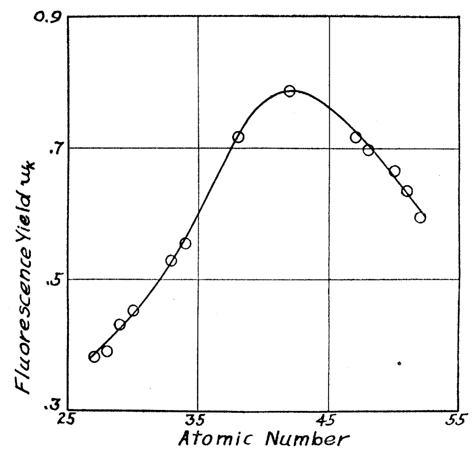

Fig. 2. Fluorescence yield as a function of atomic number.

Why does the K-fluorescence yield decrease beyond element number 42? Does it continue to decrease for the elements heavier than tellurium? These questions cannot as yet be answered, for there is at present no satisfactory theory of this effect. The wave-mechanical treatment of this subject given by Wentzel[20] contains no hint of a drop in the efficiency of production of fluorescence x-rays from the K-shells of the heavy elements.

The author is glad to acknowledge his indebtedness to Professor S. M. J. Allen for suggesting this problem, and for much helpful advice given during the course of this investigation.

[20] G. Wentzel, Zeits. f. Physik **43**, 524 (1927).