The Compound Photoelectric Effect of X-rays in Light Elements*

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The K fluorescence yields of oxygen, neon, and argon have been found from the numbers of double photoelectron tracks (produced by auto-ionization), and the numbers of single tracks, on 1950 stereopictures made in a Wilson cloud chamber, with atmospheres containing small amounts of the gases under investigation. From the data of this experiment and the K absorption data collected by Wien and Harms, the yields are: oxygen 8.2 percent, neon 8.3 percent, and argon 14.9 percent, for 0.709A x-rays. The K yields previously found for heavier elements by A. H. Compton, M. I. Harms, and L. H. Martin, and those given here, mostly lie on a smooth curve. Auger's value for krypton seems to be 13 percent to low, and that for argon, at least 45 percent too low. The most probable values of the K yields of 47 elements are considered to be, at present, as follows: O 8.2, F 8.5, Ne 8.8, Na 9.3, Mg 9.9, Al 10.5, Si 11.2, P 12.0, S 12.8, Cl 13.8, A 14.9, K 16.0, Ca 17.2, Sc 18.5, Ti 20.0, Va 21.7, Cr 23.6, Mn 25.5, Fe 28.4, Co 31.2, Ni 34.4, Cu 37.8, Zn 41.2, Ga 44.3, Ge 47.4, As 50 5, Se 55.3, Br 55.8, Kr 58.2, Rb 60.2, Sr 62.2, Y 64.0, Zr 65.5, Nb 67.0, Mo 68.0, Ma 69.1, Ru 70.0, Rh 70.8, Pa 71.7, Ag 72.5, Cd 73.0, In 73.5, Sn 74.0, Sb 74.5, Te 74.8, I 75.0, Xe 75.3, expressed as percentages of the K quanta that escape from K ionized atoms. The L yield of argon is estimated to be between zero and 20 percent, on the basis of the numbers of tracks counted. A new type of double track has been observed; its components are of similar energy, but produce very unequal ionization. They are believed to be due to krypton atoms with metastable lives of the order of 0.01 second. The cloud method can be used for detecting heavy gases in light ones. It is shown that 15 parts of krypton in 10^5 of oxygen, or 50 parts of xenon in 10^6 of oxygen, will give 2 percent of characteristic double tracks due to the heavy element.

INTRODUCTION

THE compound photoelectric effect consists in the almost simultaneous ejection of two or more electrons from an atom by a single photon, as a result of the atom's absorption of its own fluorescent radiation. Using the Bohr atom model, the mechanism of this phenomenon is as follows: when a K electron is ejected by x-rays, an outer one drops into the vacant orbit, accompanied by the emission of a K quantum characteristic of the atom. But this fluorescence quantum is in the interior of the atom and has a considerable chance of being absorbed by one of the outer electrons before emerging, thereby ejecting it with energy characteristic of the atom and level concerned. The net result is that two electrons are set free by one photon. In sufficiently heavy elements, three or more may be successively liberated by similar action in the several electronic shells. This effect was recognized in 1925 by Auger[1] as the explanation of certain types of multiple photoelectron

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[1] P. Auger, Comptes Rendus **180**, 65 (1925); Jour. de Physique et Radium **6**, 205 (1925); also Ann. de Physique **6**, 183 (1926).

tracks that he found in a Wilson cloud chamber. C. T. R. Wilson[2] had previously observed similar tracks and commented on them at some length, but it appears that he did not fully understand their origin.

Compound action does not follow every K ionization, else fluorescent x-rays would never be observed, but it greatly reduces x-ray fluorescence, especially from elements of low atomic number. In this connection, the "K fluorescence yield" is conveniently defined as the fraction of all K quanta that escape from the atoms in which they originate, without producing compound action. Similarly, the L fluorescence yield is the fraction of the fluorescent L quanta that escape, and so on. The K yield is the most important of these, particularly for hard x-rays and light elements, because 85 percent or more of all primary photoelectrons come from K levels. It might be supposed that a quantum of fluorescent radiation would have a greater chance to escape if there were but few peripheral electrons between it and the outside of the atom, but the opposite is true: the K yield *increases* with atomic number, instead of decreasing. It seems desirable to determine the fluorescence yields of as many elements as possible, for it is only by knowing these and the relative absorption of the incident radiation by the K L, M, and N rings that one can predict the number of photoelectrons liberated by any given number of quanta, and the ionization resulting therefrom.

Auger[1] deduced values for the K yields of argon, krypton, and xenon, by counting the numbers of single and double tracks formed in cloud-chamber atmospheres containing these gases. The double tracks originate from compound action, while the single ones are made by electrons ejected (from any orbit) by the ordinary process. His measurements were followed by those of Harms[3] and A. H. Compton,[4] who determined the K yields of 8 elements between 26 and 42 by measuring the relative intensities of incident and the corresponding fluorescent x-rays from solid fluorescers, using ionization chambers. Martin[5] explored the same range and also found the K yield of iodine, with a special ionization method. The approximate agreement of the results of these careful experiments, seems to fix the values for elements between 26 and 42, with considerable certainty. The present paper describes cloud-method determinations of the yields of oxygen, neon, and argon, and a correlation of the results with previous ones. In this way, a continuous range is made available for elements 8 to 54. The cloud method is somewhat more direct than those using ionization chambers, and seems preferable when the material investigated is a suitable gas or vapor. On the other had, it is much slower because it involves the collection and minute examination of large numbers of stereoscopic pictures.

Apparatus and Procedure

Fig. 1 shows the general arrangement of the apparatus. X-rays generated in a tube A, pass through filters into the expansion chamber of a Wilson cloud

[2] C. T. R. Wilson, Proc. Roy. Soc. **A104,** 1 (1923).

[3] M. I. Harms, Ann. d. Physik **82,** 87 (1926).

[4] A. H. Compton, Phil. Mag. **8,** 961 (1929). This paper contains a good summary of preceding work on this subject, and makes some necessary corrections of Harms' data.

[5] L. H. Martin, Proc. Roy. Soc. **A115,** 420 (1927).

machine B, producing photoelectron tracks that are photographed by a pair of cameras C, while illuminated by the arc D.

The x-rays were taken from a water-cooled molybdenum Coolidge tube, operated for 0.04 sec. at 25 m.a. and 37 k.v.p., at each expansion. A Seeman spectrogram of the radiation showed intense K lines and negligible background. The rays were filtered through 0.2 mm of aluminum, a "balanced filter"[6] containing strontium carbonate and zirconium oxide in equal atomic concentrations of the metals, and 5 mm of Pyrex glass; the wave-length transmitted is taken as 0.709A. The work of Compton,[4] Martin,[5] and Auger[1] indicates that the K yield is independent of the wave-length of the exciting rays, so that small variations in this should certainly have no effect. Intensity requirements of the experiments were met by varying the diameter of the x-ray beam through the chamber from 1 to 3 mm.

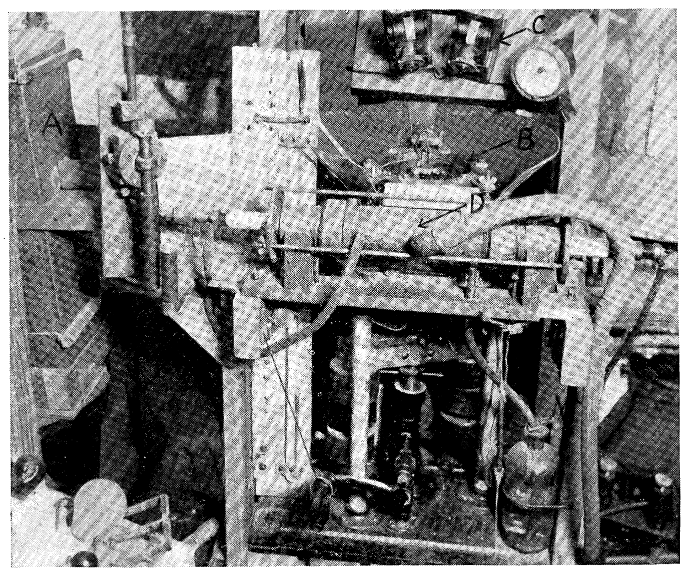

Fig. 1. Experimental arrangement.

Details of the cloud machine have already been published,[7] although some improvements have since been made. The apparatus is operated by turning a crank that mechanically drives the expansion mechanism and times the events connected with the cycle of operation. Once adjusted, hundreds of pictures may be taken without any appreciable change in the quality of the tracks. About 9000 pairs of pictures have been made with this outfit, including tracks originating from x-rays, cosmic-rays, and radioactive γ-rays.

Matched "Leica" cameras, mounted with their optic axes intersecting at 22° in the cloud chamber, served as a stereoscopic camera. Their regular

[6] Similar to that of P. A. Ross, J.O.S.A. and R.S.I. **16,** 433 (1928).

[7] G. L Locher, J.O.S.A. and R.S.I. **19,** 58 (1929). The chamber is 15.6 cm across; a flexible diaphragm replaces the customary cylinder and piston arrangement.

lenses which have an aperture of f. 3.5, were supplemented with auxiliary ones for close photography. The developed negatives (2.5 by 3.5 cm, each) were viewed in a Zeiss stereoscope equipped with achromatic lenses of 8 cm local length. It was found that the gain in contrast resulting from the use of "positive" motion picture film, instead of the customary negative film, much more than compensates for the smaller sensitivity of the former, which was used in this work.

A convenient high-intensity mercury arc has been invented by the author to meet the unusual intensity requirements of cloud-track photography. Details of the arc, including its optical and electrical characteristics, will presently be submitted for publication in The Review of Scientific Instruments. In this machine, a fine stream of mercury, issuing from a small hole in one electrode and impinging on the other, is continuously exploded in an iron chamber for 1/60 to 1/30 sec., at the time of photographing the tracks, with power consumption estimated at 10 to 15 k.w. The luminosity of this source is enormous, greatly exceeding that got from any of the high-intensity carbon arcs, or by exploding tungsten wires, or mercury vapor, previously tried.

In order that the low-energy components of the compound action tracks should be as long as possible, the atmospheres used in the cloud-chamber were mainly composed of hydrogen. Tracks in hydrogen are much thinner and less persistant than in air, because of the lower density and viscosity of hydrogen, so the photographic exposure has to be short and the illumination strong. The expansion ratio that gave best results was found by trial to be about 1.25, at 33°C. Recoil electrons from hard γ-rays were found convenient for such adjustment, since their tracks are very thin.

Results for Oxygen, Neon and Argon

In these experiments the temperature of the cloud chamber was kept at 33° and the total pressure at 68 cm. It might be supposed that the increased lengths of the low-energy tracks, got by using lower gas pressure, would make their identification easier, but this apparent advantage is offset by increased diffuseness and thinness of the tracks formed at reduced pressures, especially in hydrogen.

It was often difficult or impossible to identify the short tracks from oxygen and neon. (Their energies are respectively $528-50=478$ volts, and $864-22=842$ volts; track lengths <0.5 mm).[8] All tracks were discarded that could not be definitely classified as single or double, or in connection with which there was any other uncertainty. About as many were lost for various reasons as were kept.

Oxygen

The source of oxygen was the water vapor of the cloud chamber; pure hydrogen constituted the remainder of the atmosphere. Calculation of the relative amounts of the incident radiation absorbed by these two elements was

[8] F. Holweck, "De la Lumiere aux Rayons X" 134 (1927); also Compton and Mohler, "Critical Potentials," 103 and 87 (1924).

based on the assumption that the vapor was saturated, although no appreciable error arises if this was not the case. The atomic fluorescence absorption coefficient of oxygen is 410 times that of hydrogen, which makes the hydrogen absorption almost negligible. The data for oxygen are as follows:

Atmosphere	Oxygen	2.72 percent
	Hydrogen	97.28 percent, of the total number of atoms

Number of tracks identified	644, on 900 pairs of pictures
Single tracks	93 or 14.5 percent
Double tracks	551 or 85.5 percent

Absorption of incident x-rays[9] oxygen 99.3 percent, hydrogen 0.7 percent

Neon

In this case it was desirable to know the exact composition of the atmosphere, because the tracks due to oxygen are indistinguishable from those due to neon. The numbers of single and double tracks due to neon alone had to be deduced from the total numbers counted, by means of simple calculations based on the relative absorption coefficients of neon and oxygen, the relative numbers of atoms present, and the relative numbers of single and double tracks formed in oxygen alone. The last mentioned are 14.5 percent and 85.5 percent, as shown above. Although the accuracy possible in this experiment is thought to be somewhat less than in the other two, because of the uncertainty about the saturation of the water vapor, the error is diminished by the proximity of neon to oxygen in the periodic table. The similarity of their K yields, which this suggests, is borne out by the results given later on in this paper. The principal data for neon are as follows:

Atmosphere	Neon	7.36 percent
	Water vapor	5.5 percent
	Hydrogen	87.14 percent, of the total pressure

Number of tracks identified	1018, on 603 pairs of pictures
Single tracks	182 or 17.88 percent
Double tracks	836 or 82.12 percent

Double tracks due to compound action in krypton, about 35

Absorption of incident x-rays[9] neon 72.0 percent, oxygen 28.0 percent (hydrogen <0.4 percent)

Argon

The short components of the double tracks counted in this case come from three sources: argon K photons (energy about 2930 volts), argon L photons (230 volts), and oxygen K photons (480 volts). The first are listed as "tracks with long companions", and the other two as "tracks with short companions". The data for argon are:

Atmosphere	Argon	5.1 percent
	Water vapor	5.5 percent
	Hydrogen	89.4 percent, of the total pressure

[9] Calculated from Owen's formula, Proc. Roy. Soc. **A94,** 510 (1918), as modified by Richtmyer and Warburton, Phys. Rev. **22,** 539 (1923).

Number of tracks identified	1828, on 450 pairs of pictures
Tracks with long companions	1334 or 73.0 percent
Tracks with short companions	224 or 12.2 percent
Tracks with no companions	270 or 14.8 percent
Sum of last two classes	494 or 27.0 percent
Double tracks due to compound action in krypton, about 37	

Absorption of incident x-rays[9] argon 96.0 percent, oxygen 4.0 percent (hydrogen <0.05 percent)

To find the K yields, one must also know the relative absorption of the incident x-rays by the K, L, and M electrons of the atoms concerned. Unfortunately, adaquate data are not available on this subject, probably because of the experimental difficulties involved in determining them. So it has been found necessary to extrapolate the relative absorption data found for heavier elements, to get values for the light ones. This is, evidently, not very satisfactory procedure, but there is reasonably good agreement of the values of the yields found by applying three sets of these data. Two of the sources were the atomic fluorescent absorption coefficients found by Richtmyer and Warburton[10] and by Gray.[11] The former are expressed by the formulae

$$\tau_a = 2.24Z^4\lambda^3 \times 10^{-26} \cdots 0.1A < \lambda < \lambda_K \qquad (1)$$

$$\tau_a = 0.33Z^4\lambda^3 \times 10^{-26} \cdots \quad \lambda_K < \lambda < \lambda_{L3}. \qquad (2)$$

Gray's formulae are derived by comparing (1) and (2) with similar ones given by Allen,[12] and are as follows

$$\tau_a = 1.92(1 + 0.008Z)(1 - \lambda/4\lambda_K - \lambda/50\lambda_K{}^2)Z^4\lambda^3 \times 10^{-26} \cdots 0.1A < \lambda < \lambda_K \qquad (3)$$

$$\tau_a = 0.255Z^4\lambda^{2.7} \times 10^{-26} \cdots \quad \lambda_K < \lambda < \lambda_{L3} \qquad (4)$$

$$\tau_a = 0.058Z^4\lambda^{2.6} \times 10^{-26} \cdots \quad \lambda_{L_1} < \lambda < \lambda_{M5}. \qquad (5)$$

A third set of values, which are probably the best ones, were got by interpolation (for argon), and by a very reasonable extrapolation (for oxygen and neon), of values collected in Wien and Harms' Handbuch.[13]

On the basis of these, Table I was prepared:

TABLE I. *Relative absorption of 0.709A x-rays by K, L, and M electrons.*

<table>
<tr><th>Source</th><th colspan="2">Absorption, percent</th><th colspan="2">Absorption, percent</th></tr>
<tr><td></td><td>Oxygen K</td><td>Oxygen L</td><td>Neon K</td><td>Neon L</td></tr>
<tr><td>(a)</td><td>87.8</td><td>12.3</td><td>86.2</td><td>13.8</td></tr>
<tr><td>(b)</td><td>93.3</td><td>6.7</td><td>92.8</td><td>7.2</td></tr>
<tr><td>(c)</td><td>85.3</td><td>14.7</td><td>85.3</td><td>14.7</td></tr>
<tr><td></td><td>Argon K</td><td>Argon L</td><td>Argon M</td><td></td></tr>
<tr><td>(a)</td><td>88.6</td><td>8.3</td><td>3.1</td><td></td></tr>
<tr><td>(b)</td><td>90.8</td><td colspan="2">9.2</td><td></td></tr>
<tr><td>(c)</td><td>85.3</td><td colspan="2">14.7</td><td></td></tr>
</table>

(a) Calculated from Gray's formulae.
(b) Interpolated and extrapolated from Wien and Harms' collected data
(c) Calculated from Richtmyer and Warburton's formulae

[10] F. K. Richtmyer and F. W. Warburton, Phys. Rev. **22**, 539 (1923).
[11] J. A. Gray, Trans. Roy. Soc. of Canada **21**, 179 (1927).
[12] S. J. M. Allen, Phys. Rev. **27**, 226 and **28**, 907 (1926).
[13] "Handbuch der Experimentalphysik", 24, part 1, 256 (1930).

From these and the data previously given, we get the following values for the K fluorescence yields of oxygen, neon, and argon, expressed as percentages of K quanta that escape from K ionized atoms:

	Oxygen	Neon	Argon
(a)	2.34	2.84	12.75
(b)	8.21	8.29	14.88
(c)	0	1.82	9.40

Calculation of the K yield of neon, from (a), above, is given as an illustration of the method used.

Let S_n and S_0 = number single tracks from neon and oxygen; C_n and C_0 = number double tracks from neon and oxygen; S = total number single tracks observed; S_1 = total number single tracks due to oxygen and neon; C = total number double tracks due to oxygen and neon; $S_1 = S - 35$ (estimated number of single tracks due to krypton, on the basis of the number of double tracks)

$$S_1 = 147 \quad S_n + S_0 = 147 \quad S_n + C_n = 0.72(836 + 147) = 707.8$$

$$C = 836 \quad C_n + C_0 = 836 \qquad S_0 = 0.145(S_0 + C_0).$$

These give $S_n = 115$, $C_n = 593$, $S_0 = 32$, $C_0 = 243$. Of the 708 neon tracks, 13.8 percent should come from the L shells, so the number of single tracks from the K shells, S_k, is $S_n - 0.138\ (S_n + C_n) = 17.3$. The total number of tracks from the K shell is $S_k + C$, so the K yield is

$$W_K = S_K/(S_K + C) = (S_n - 0.138(S_n + C_n))/(S_n - 0.138(S_n + C_n) + C_n)$$

$$W_K = 0.0284, \text{ or } 2.84 \textit{ percent}.$$

Equivalent procedure is followed for getting the yields of oxygen and argon. It is somewhat more complex in the case of argon, because the M electrons have to be dealt with.

TABLE II. *K fluorescence yields, collected data.*

Element	Observer	Method	K yield, percent	
8 O	Locher	Cloud	(a) 2.3	(b) 8.2†
10 Ne	Locher	Cloud	(a) 2.8	(b) 8.3
18 A	Locher	Cloud	(a) 12.8	(b) 14.9
18 A	Auger	Cloud	7.	
26 Fe	Harms*	Ioniz.	28.2	
26 Fe	Martin	Ioniz.	29.	
28 Ni	Compton	Ioniz.	37.	
28 Ni	Martin	Ioniz.	35.	
29 Cu	Harms	Ioniz.	37.8	
29 Cu	Martin	Ioniz.	40.	
30 Zn	Harms	Ioniz.	40.3	
30 Zn	Martin	Ioniz.	46.	
34 Se	Compton	Ioniz.	54.	
34 Se	Harms	Ioniz.	51.7	
34 Se	Martin	Ioniz.	59.	
35 Br	Compton	Ioniz.	56.	
35 Br	Martin	Ioniz.	59.	
36 Kr	Auger	Cloud	50. } 51. }	
38 Sr	Harms	Ioniz.	61.5	
42 Mo	Compton	Ioniz.	68.	
53 I	Martin	Ioniz.	75.	
54 Xe	Auger	Cloud	71.	

* Harms' values are corrected by Compton.
† The values (*b*) are preferred.

Variation with Atomic Number

Table II is a collection of the experimental values of the K yields of 14 elements, that seem to be the most reliable data now available. Fig. 2 shows

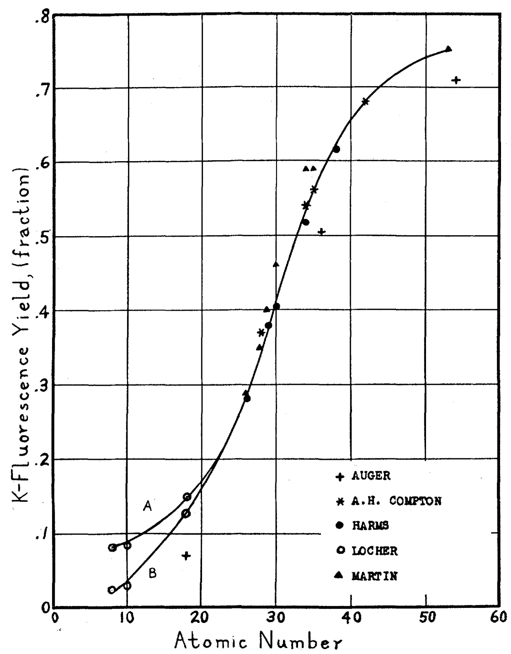

Fig. 2.

Table III. *K fluorescence yields, interpolated values.*

Element	K yield, percent (a)	(b)	Element	K yield, percent
8 O	2.3	8.2	33 As	50.5
9 F	2.9	8.5	34 Se	53.3
10 Ne	3.6	8.8	35 Br	55.8
11 Na	4.5	9.3	36 Kr	58.2
12 Mg	5.4	9.9	37 Rb	60.2
13 Al	6.4	10.5	38 Sr	62.2
14 Si	7.6	11.2	39 Y	64.0
15 P	8.8	12.0	40 Zr	65.5
16 S	10.1	12.8	41 Nb	67.0
17 Cl	11.4	13.8	42 Mo	68.0
18 A	12.8	14.9	43 Ma	69.1
19 K	14.3	16.0	44 Ru	70.0
20 Ca	16.0	17.2	45 Rh	70.8
21 Sc	17.8	18.5	46 Pa	71.7
22 Ti	19.7	20.0	47 Ag	72.5
23 Va	21.6	21.7	48 Cd	73.0
24 Cr	23.7	23.6	49 In	73.5
25 Mn	26.0	25.5	50 Sn	74.0
26 Fe	28.4	28.4	51 Sb	74.5
27 Co	31.2		52 Te	74.8
28 Ni	34.4		53 I	75.0
29 Cu	37.8		54 Xe	75.3
30 Zn	41.2			
31 Ga	44.3			
32 Ge	47.4			

that they mostly lie on a smooth curve. In plotting this curve, a little more weight has been given to the data of Harms and Compton than to those of Martin, because of the difference in their experimental methods. The lower branch (B), corresponds to the data (a), of Table II, while the upper branch

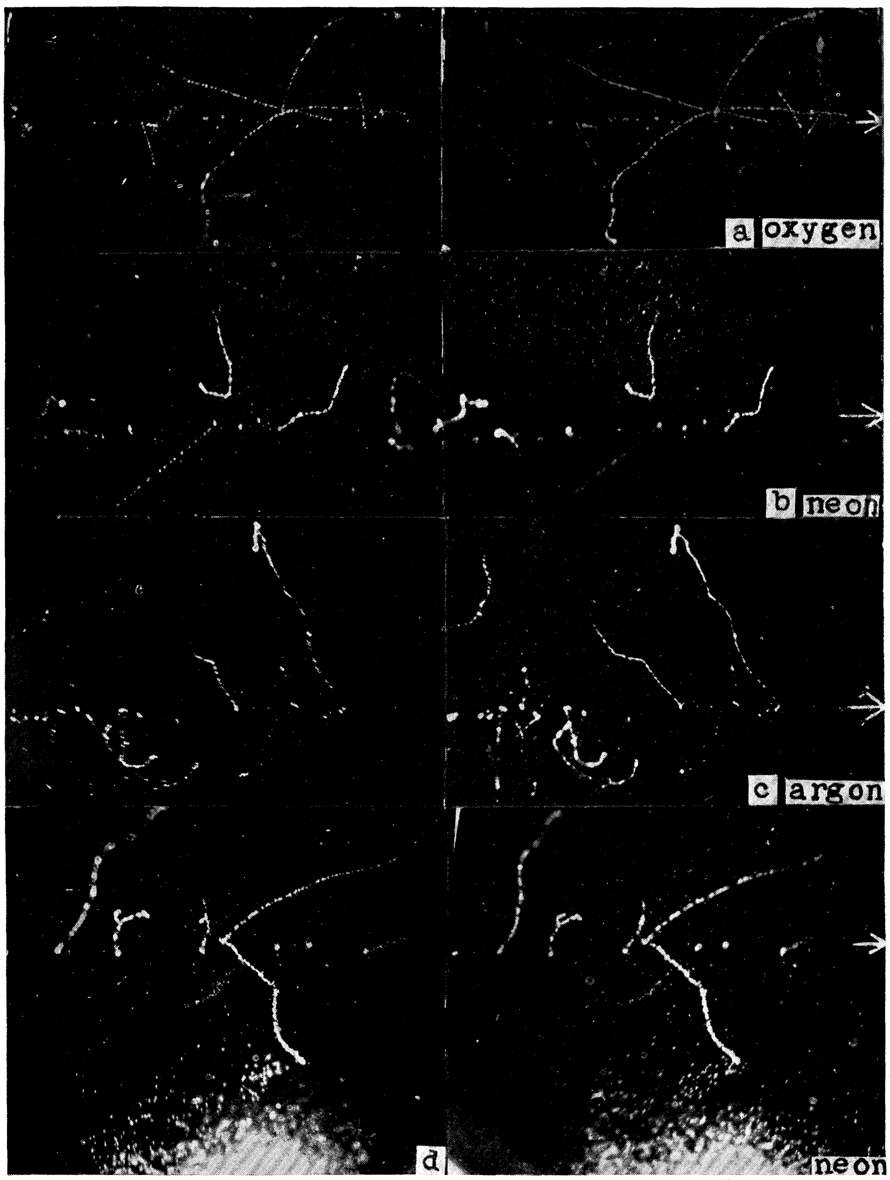

Fig. 3. a, b, and c. Cloud tracks showing compound photoelectric action of x-rays in oxygen neon, and argon, respectively. d, also shows a diffuse track of an α-particle and a compound track, due to krypton. The arrows indicate the direction of the x-ray beam. Mag. $\times 0.73$.

(A), which corresponds to the data (b), is believed to give the best representation of the actual variation. Auger's values were the first determined, and seem to be too low.

It is interesting to notice that there is still an appreciable yield for very light elements, contrary to the expectation of Martin, whose extrapolated curve intersected the axis at $Z=21$. There is no evidence for believing that discontinuities exist in this curve, although the possibility of their existance makes interpolation between experimental points a little uncertain, and prohibits extrapolation to elements of lower atomic number.

Experimental work might well be extended to heavier elements, in which the auto-ionization is less conspicuous, by the use of ionization methods, or Geiger counters. The small x-ray absorption of very light elements, and the smallness of the energies of the short components of their compound tracks, casts much doubt on the feasibility of attempting to extend the measurements to lighter elements, except, perhaps, by spectroscopic methods. It seems possible, however, that the yields might be deduced by measuring the intensities of spark lines, since these intensities are believed to be altered by auto-ionization.

Discussion

Fig. 3, a, b, and c, are typical pictures taken in atmospheres containing oxygen, neon, and argon, respectively. Fig. 3, d, taken in neon, shows 4 compound tracks due to neon or oxygen, 1 single track (very diffuse), 3 recoil electrons, 1 compound track due to krypton (with the long branch), and 1 very diffuse α-particle track; two of the tracks are branched, and two others have spiral paths.

The formation of compound tracks in a gaseous mixture provides a sensitive way of detecting small amounts of heavy gases, such as krypton, among light ones. One can rather easily identify the double tracks that hard x-ray produce under such circumstances, by the low-energy components whose lengths are characteristic of the parent atoms. Their relative numbers are simple functions of the absorption coefficients and the fluorescence yields. As an example, consider how the relative numbers of krypton and oxygen atoms, n_k and n_0, can be found from the total number of tracks, N, in a krypton-oxygen atmosphere, by using total number of double krypton tracks, N_d, (which is p percent of N), and the K yield of krypton, W_k, the fraction of the krypton-absorbed incident x-rays, f_k, that are absorbed by K-electrons,the atomic fluroescent absorption coefficients, τ_k and τ_0, and the atomic numbers, Z_k and Z_0, all of which are known. If the total numbers of krypton and oxygen tracks are N_k and N_0, we may write

$$N_d = N_K f_K(1 - W_K). \tag{1}$$

From Owen's law

$$\tau_K/\tau_0 = Z_K{}^4/Z_0{}^4, \text{ whence}$$
$$N_K/N_0 = n_K Z_K{}^4/n_0 Z_0{}^4. \tag{2}$$

Also,

$$N_d/N = p\% = 0.0p = N_K f_K(1 - W_K)/(N_0 + K_K), \text{ or}$$
$$N_K/N_0 = 0.0p/(f_K - f_K W_K - 0.0p). \tag{3}$$

From (2) and (3)

$$n_K/n_0 = 0.0pZ_0^4/(f_K - f_KW_K = 0.0p)Z_K^4. \quad (4)$$

If, for example, $p=2$ percent,

$$n_K/n_0 = \frac{0.02 \times 8^4}{(0.85 - 0.85 \times 0.58 - 0.02)36^4} = 0.000145 = 0.015 \text{ percent.}$$

The neon and argon used in the present experiment were contaminated with about 0.02 percent of krypton, as found by similar calculations. Using Auger's value for the K yield of xenon, we see that $n_x/n_0 = 0.000044$, or 0.0044 percent of xenon atoms in oxygen will give 2 percent double xenon tracks, if sufficiently hard x-rays are used. The existence of this percentage would be readily noticed.

Several curious types of tracks were found on the pictures taken in this experiment. Perhaps the most interesting that are not known to have been

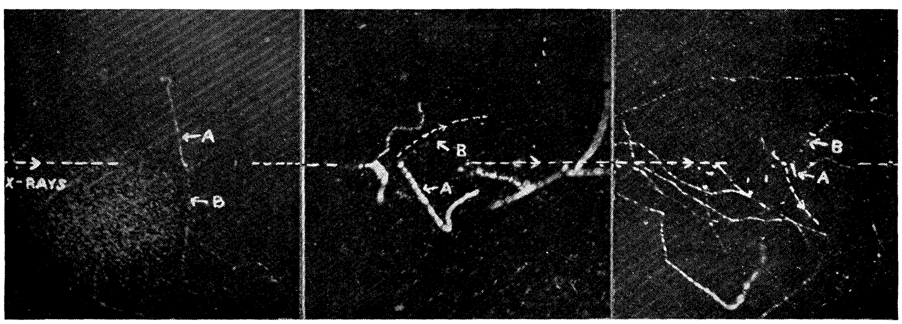

Fig. 4. Compound tracks whose components are of similar energy but very unequal density. Mag. ×0.73.

previously described, are double tracks resembling compound krypton tracks in all respects except that the two components are of unequal density. At first, these were regarded as cases of accidental coincidence of the starting points of two ordinary tracks, but their frequent occurrence presently made this improbable. A possible explanation is that they are due to K ionized krypton atoms that have a metastable life comparable with the time of sensitivity of the cloud chamber (0.01 to 0.04 sec.), so that the formation of the second component took place after the sensitivity of the atmosphere had appreciably diminished. Fig. 4 shows the beginnings of three tracks of this type; the density differences of the components vary considerably. In case the proposed explanation should prove correct, the approximate lives of individual excited krypton atoms could be found by measuring the displacements of the charged drops in the two tracks, resulting from the application of a suitable horizontal electric field in the chamber. The performance of this experiment is contemplated. Another possibility in this connection, is that two fast electrons that have about the same velocity may produce very different amounts of ionization per cm path. This might be explained by supposing that one was spinning and the other not, or that some other abnormal condition affected the production of ions by one of them. Evidence for an effect of this type was seen in connection with the pictures recently examined: tracks of definitely established origin were occasionally observed, along which the ionization *suddenly diminished*, accompanying a sharp bend in the track, and later increased in the normal manner as the electron slowed down.

A rough determination of the L yield of argon places it between zero and 20 percent. This is not of much value, because the number of L tracks dealt with is small, and especially because the numbers of oxygen K compound tracks and argon L compound tracks have to be separately counted. Their short components have energies that differ only by 100 percent, whereas in getting the K yield, the smallest energy difference is about 600 percent. However, the accuracy seems good enough to show that the L yield is small.

When γ-rays are scattered by K electrons, compound action may follow. This is shown by the fact that most recoil electron tracks from hard γ-rays scattered in the gas of the cloud chamber, were double, just as the x-ray tracks were. Likewise, tracks produced by scattered x-ray quanta were observed to be double, usually. Neither of these observations is in the least surprising, because the auto-ionization that follows K ionization is an atomic phenomenon that should be independent of the particular type of radiation that sets it in motion.

The author wishes to express his best thanks to Professor H. A.Wilson for his interest and advice throughout the course of this investigation.

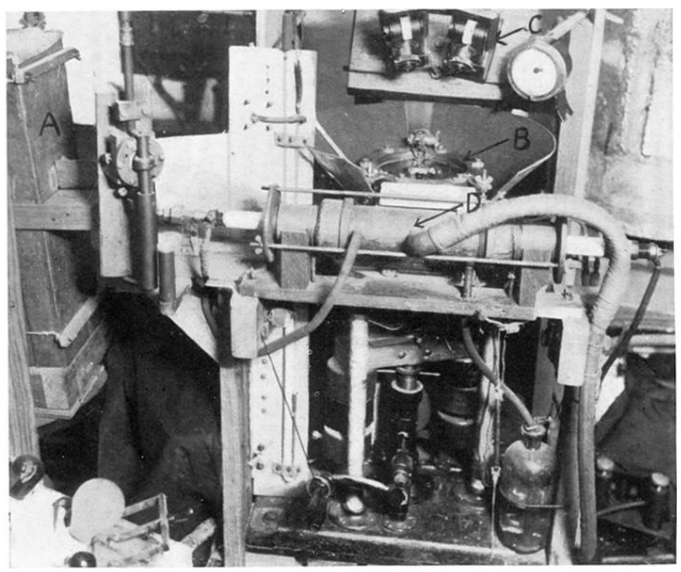

Fig. 1. Experimental arrangement.

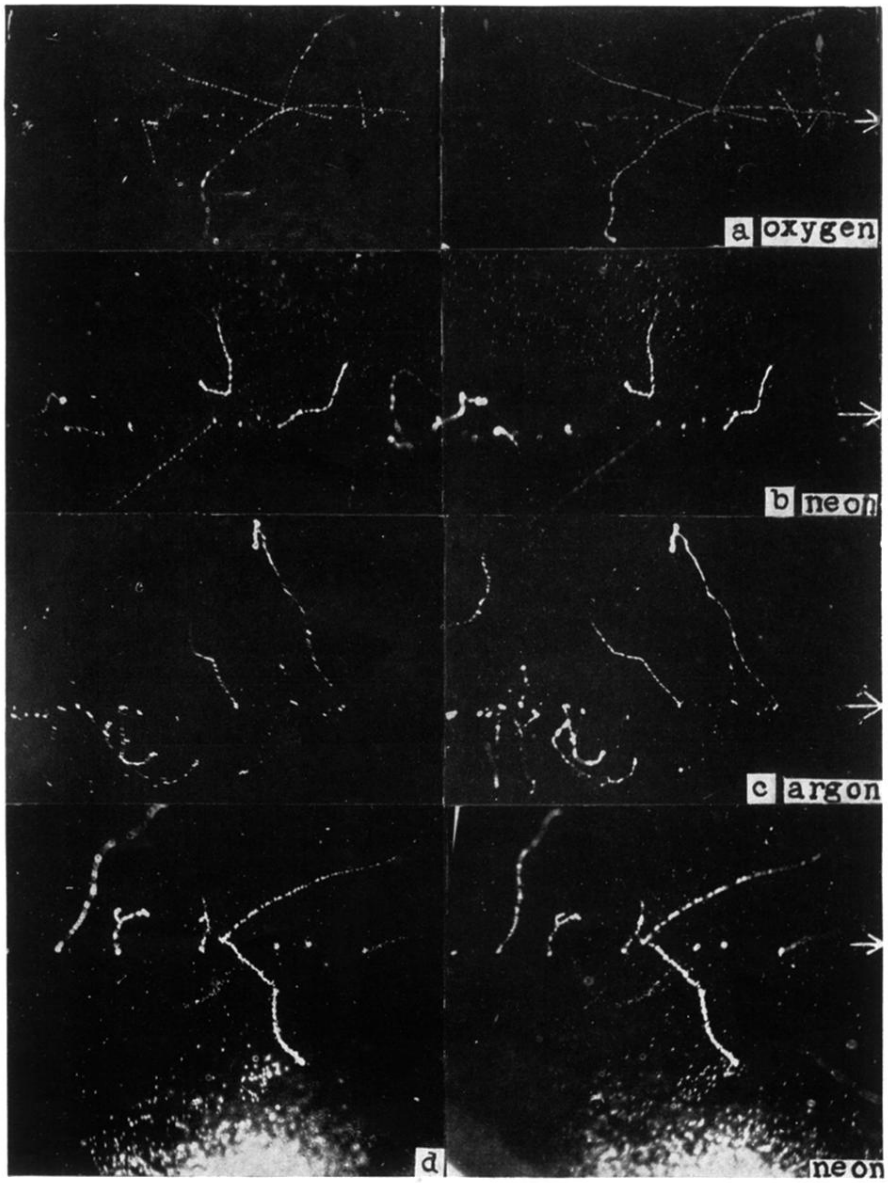

Fig. 3. *a*, *b*, and *c*. Cloud tracks showing compound photoelectric action of x-rays in oxygen neon, and argon, respectively. *d*, also shows a diffuse track of an α-particle and a compound track, due to krypton. The arrows indicate the direction of the x-ray beam. Mag. $\times 0.73$.

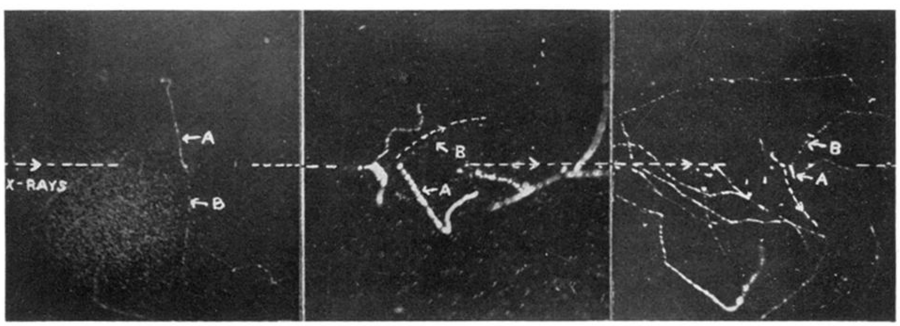

Fig. 4. Compound tracks whose components are of similar energy but very unequal density. Mag. $\times 0.73$.