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SPACE-DISTRIBUTION OF X-RAY PHOTOELECTRONS EJECTED FROM THE K AND L ATOMIC ENERGY-LEVELS

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ABSTRACT

A C.T.R. Wilson expansion-chamber was used to study the space-distribution of photoelectrons ejected from a gas by monochromatic x-rays. In agreement with Auger, and Watson and Van den Akker a more isotropic space-distribution was found for electrons ejected from the L energy-levels than for those ejected from the K energy-level. The distribution of the electrons from the L energy-levels became less isotropic with an increase in frequency of the incident radiation. For a given radiation, the average forward momentum of the electrons from the K energy-level was found to decrease with an increase in the binding energy of the parent atom. Within experimental error, however, for electrons from the K energy level, even for different binding energies, the average forward momentum remained the same for a given velocity of ejection of the electron. The average forward momentum of electrons from the L energy-level was greater than that for electrons from the K energy-level for a given velocity of ejection. The space-distribution of electrons from the K energy-level was in fair accord with the recent results of quantum mechanics.

THE longitudinal space-distribution of photoelectrons ejected from a gas by x-rays has been extensively studied by means of the C. T. R. Wilson expansion-chamber by several investigators.[1,2] The general shape of the distribution curve for electrons ejected from the K energy-level and the dependence on the frequency of the incident radiation has been determined, and are in approximate agreement with the recent quantum mechanical expressions.[3,4,5,6] Results so far published for the space-distribution of electrons ejected from the L energy-levels are rather meager. Auger[7] and Watson and Van den Akker[8] have shown, however, that a more isotropic

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[1] E. J. Williams, J. M. Nuttal and H. S. Barlow, Proc. Roy. Soc. **A121**, 611 (1928).

[2] M. P. Auger, C.R. **187**, 1141 (1928).

[3] A. Sommerfeld, Atombau und Spektrallinien, Wellenmechanischer Erganzungsband.

[4] G. Wentzel. (Communicated in Lecture Series of Norman Bridge Laboratory.)

[5] A. Carrelli, Zeits. f. Physik **56**, 694 (1929).

[6] S. E. Szczeniowski, Phys. Rev. **35**, 374 (1930).

[7] M. P. Auger, C.R. **188**, 447 (1929).

[8] E. C. Watson and J. A. Van den Akker, Proc. Roy. Soc. **A126**, 138 (1929).

space-distribution exists in this case. In the present work, the distribution of electrons ejected from the L energy-levels is found to become less isotropic as the frequency of the incident radiation is increased.

The C. T. R. Wilson expansion-chamber employed in this investigation was essentially that described by Simon and Loughridge.[9,10] Only minor refinements were effected to insure greater accuracy in the data obtained.

Simple filtering of the general radiation obtained from an x-ray tube was found to produce radiation not sufficiently monochromatic so other means of monochromatizing the x-rays were employed. Monochromatism was insured, in one instance, by the selection of the $K\alpha$ line of molybdenum by means of a calcite crystal spectrometer. For the other frequencies, the secondary fluorescence radiation from a metal plate, irradiated by primary x-rays from a tungsten-target Coolidge type tube, was collimated to a narrow beam and passed into the expansion chamber (Fig. 1). A. H. Compton[11] has shown the fluorescence radiation obtained in this manner to be very homogeneous, having 99 percent of its energy in the characteristic K line-radiation of the metal radiator.

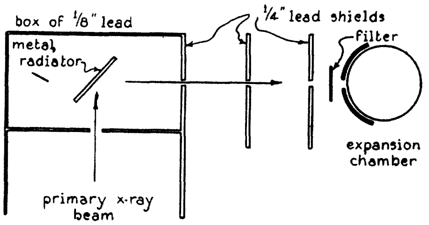

Fig. 1. Fluorescence radiator as source of monochromatic x-rays.

The wave-lengths of the x-rays used in this investigation are given in Table I together with the metal radiator employed in three cases.

TABLE I.

Source	Monochromatizer	λ
$\mathrm{M_o}$ target tube	Calcite spectrometer	0.71 A
W " "	Silver radiator	0.56 A
W " "	Palladium radiator	0.59 A
W " "	Tin radiator	0.49 A

The relatively faint $K\beta$ lines of palladium were filtered out by means of a ruthenium filter. The presence of the $K\beta$ lines in the other cases was not objectionable.

The longitudinal space-distribution curves, representing the density of emission per unit angle of the photoelectrons as a function of the angle between the direction of ejection and the forward direction of the x-ray beam, were plotted in a number of cases to show the effect of the energy level from

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[9] A. W. Simon and D. H. Loughridge, Jour. Opt. Soc. **13,** 679 (1926).

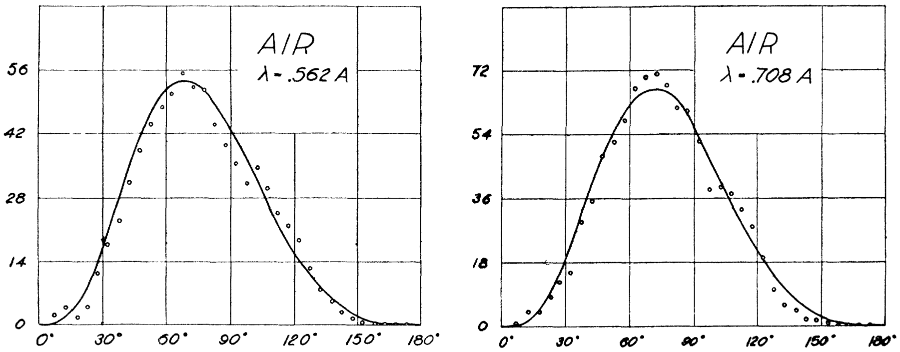
[10] D. H. Loughridge, Phys. Rev. **30,** 488 (1927).

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

which the electron is taken, and also the effect of a change in the frequency of the incident radiation.

In Figs. 2 and 3 are plotted the results obtained respectively from measurements on 272 tracks in air produced by radiation of 0.71A and on 200 tracks in air produced by radiation of 0.56A. Each small circle represents the number of electrons ejected in a 15° interval the point being plotted at an angle corresponding to the center of the interval. Points are plotted every 5° and therefore represent overlapping intervals.

In order to study the distribution where the binding energy was of appreciable magnitude, C_2H_5Br was introduced into the expansion-chamber in an atmosphere of hydrogen. The photoelectrons were produced by radiation of 0.59A, most of them being ejected from the *K* shell of the bromine atom. About 64 percent of the energy of the incident radiation was required to remove the electron from the atom, the remaining 36 percent appearing as kinetic energy. The secondary and tertiary photoelectrons could easily be distinguished from one another due to the difference in path length.* Photoelectrons ejected from levels other than the *K* level of bromine or from light atoms could be distinguished by their long path length and hence omitted in the measurements. Thus, only the photoelectrons having their origin in the *K* shell of bromine were included. Fig. 4 represents the distribution curve plotted as before for 233 tracks of electrons ejected from the *K* level of bromine by radiation of 0.59A.[12]



Figs. 2 and 3. Space distribution of photoelectrons ejected from air.

For the study of the distribution of electrons ejected from the *L* energy levels, CH_3I was introduced into the chamber in an atmosphere of hydrogen and photoelectrons produced by radiation of 0.71A and 0.49A emission, being from the *L* levels of iodine. The results of measurements on 200 tracks formed by radiation of 0.71A are shown in Fig. 5. In agreement with the work of Auger the curve is broader than that found for the *K* electrons indicating a

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* The ratio of the number of secondary to tertiary photoelectrons was found to be 2.5 in agreement with Auger [Ann. de Physique **6,** 229 (1926)] and Wentzel [Zeits. f. Physik **43,** 524 (1927)].

[12] C. D. Anderson, Phys. Rev. **34,** 547 (1929).

more isotropic distribution. The small circles as before represent the experimental points. Fig. 6 represents the distribution of 264 photoelectrons ejected from the L levels of iodine by radiation of 0.49A. The curve here is narrower than in Fig. 5, indicating a decrease in the isotropy of the distribution with an increase in the frequency of the incident radiation. Watson and Van den Akker[8] have shown that photoelectrons ejected from the $L_{\rm II}$ and $L_{\rm III}$ energy levels have a space-distribution more isotropic than those from the K and $L_{\rm I}$ energy levels, and Robinson and Cassie[13] have found the relative number of $L_{\rm I}$ electrons ejected to increase with an increase in the frequency of the incident radiation. The narrower distribution curve of Fig. 6 may then be explained by the presence of a greater proportion of $L_{\rm I}$ electrons than is the case for the curve of Fig. 6.

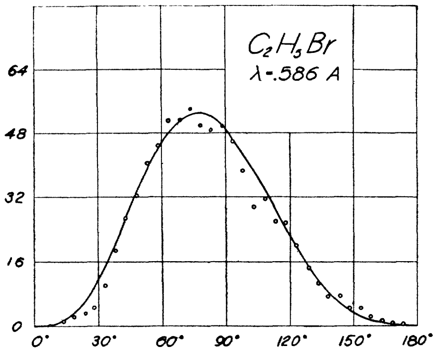
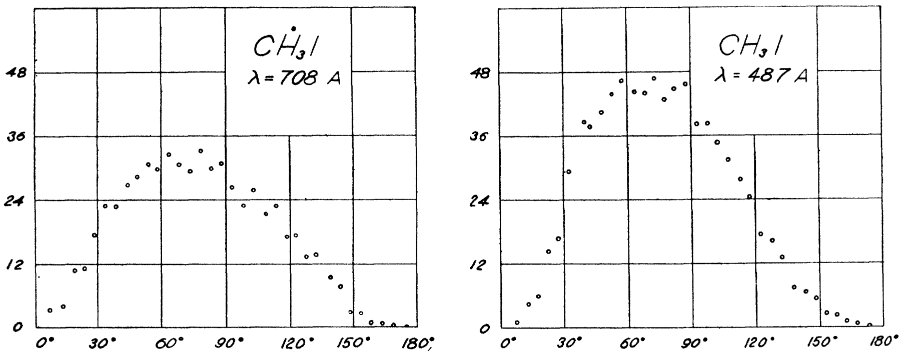


Fig. 4. Space distribution of photoelectrons ejected from K energy-level of bromine.



Figs. 5 and 6. Space distribution of photoelectrons ejected from L energy-levels of iodine.

A theoretical expression derived recently by Wentzel[14] on the basis of quantum mechanics,

$$P(\theta) \propto \frac{\sin^3 \theta}{\left[1 - \frac{v}{c} \cos \theta + \frac{h\nu}{2mc^2}\right]^4} \qquad (1)$$

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[13] H. R. Robinson and A. M. Cassie, Proc. Roy. Soc. **A113,** 296 (1926–27).

[14] G. Wentzel, reference 4.

gives the probability of ejection per unit angle of a photoelectron from the K energy level as a function of the angle, θ, between the direction of ejection and the forward direction of the x-ray beam, where v represents the velocity of ejection, ν the frequency of the incident radiation, and h, m, and c are the customary physical constants.

The solid-line curves of Figs. 2, 3 and 4 represent $P(\theta)$ with the proper values of v and ν inserted, the curves being plotted on a scale to conform to the experimental points. No analogous theoretical expression has as yet been published for the probability of ejection of a photoelectron from the L levels.

The observed asymmetry of the distribution about a plane normal to the x-ray beam may be compared with the theory in several ways.[15] The value of cos θ averaged over all the photoelectron tracks, a quantity proportional to the average forward momentum of the photoelectrons may be computed as follows

$$\overline{\cos\theta} = \frac{\int_0^\pi P(\theta)\cos\theta d\theta}{\int_0^\pi P(\theta)d\theta} = \frac{4}{5}\frac{v}{c} + \cdots \qquad (2)$$

if only first order terms in v/c are retained. The observed and calculated values of the mean of cos θ are listed in Table II.

Table II.

Energy Level	Gas	λ	$\overline{\cos\theta}$ (obs.)	$\overline{\cos\theta}$ (calc.)
K	Air	0.71 A	0.182	0.210
K	Air	0.56 A	0.210	0.235
K	C_2H_5Br	0.59 A	0.133	0.138
L	CH_3I	0.71 A	0.230	
L	CH_3I	0.49 A	0.255	

The average forward momentum of the K electrons for a given radiation decreases with an increase of the binding energy of the parent atom. Within experimental error, however, K electrons of the same initial velocity have the same average forward momentum. It is to be noted, moreover, that in accord with the results of Auger and Watson and Van den Akker for a given velocity of ejection, the L electrons have an average forward momentum greater than that of the K electrons. The difference in behavior of the K and L electrons is more marked for the lower frequencies of incident radiation. The asymmetry to be expected on theoretical grounds for the L electrons has not as yet been brought to light.

The bi-partition angle, θ_b, the half-angle at the apex of a cone which divides the photoelectrons into two groups of equal numbers, is defined by Eq. (3). Calculation of cos θ_b shows it to be equal to v/c to a first approximation. The experimental and calculated values of cos θ_b are given in Table III.

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[15] Williams, Nuttall and Barlow, reference 1.

$$\int_0^{\theta_b} P(\theta)d\theta = \int_{\theta_b}^{\pi} P(\theta)d\theta. \tag{3}$$

TABLE III.

Energy Level	Gas	λ	$\cos\theta_b$ (obs.)	$\cos\theta_b$ (calc.)
K	Air	0.71 A	0.242	0.262
K	Air	0.56 A	0.292	0.294
K	C_2H_5Br	0.59 A	0.191	0.173
L	CH_3I	0.71 A	0.174	
L	CH_3I	0.49 A	0.242	

For a given value of v/c the bi-partition angle for electrons ejected from the L energy-levels seems to occur nearer 90° than for those from the K energy-level, in agreement with the conclusions of Auger.[2,7]

The ratio, of the number of electrons ejected forward of the plane normal to the x-ray beam, to the number ejected backward, ρ, is given by Eq. (4):

$$\rho = \frac{\int_0^{\pi/2} P(\theta)d\theta}{\int_{\pi/2}^{\pi} P(\theta)d\theta} = \frac{2+3\frac{v}{c}}{2-3\frac{v}{c}} + \cdots \tag{4}$$

The observed and calculated values of ρ are given in Table IV.

It is to be noted that no marked difference was found in the behavior of ρ for the K and L electrons.

TABLE IV.

Energy Level	Gas	λ	ρ (obs.)	ρ (calc.)
K	Air	0.71 A	2.17	2.30
K	Air	0.56 A	2.39	2.58
K	C_2H_5Br	0.59 A	1.74	1.70
L	CH_3I	0.71 A	2.00	
L	CH_3I	0.49 A	2.30	

In conclusion I wish to express my gratitude to Professor R. A. Millikan and Professor E. C. Watson for their interest in this work.

Note added in proof:

Since this article was written, G. Schur [Ann. d. Physik, **4,** 441, (1930)] has published a theoretical expression for the space-distribution of photo-electrons ejected from the L energy-levels of an atom. For the longitudinal space-distribution he finds,

$$P(\theta)\alpha\ \sin^3\theta + \frac{4\nu}{c}\sin^3\theta\cos\theta\left(1-\frac{I_L}{h\nu}\right) + \frac{I_L\sin\theta}{h\nu+3I_L}\left\{1+\frac{8I_L}{h\nu}\sin^2\theta + \frac{2\nu}{c}\cos\theta\left(1+2\sin^2\theta\left(1+\frac{11I_L}{h\nu}\right)\right)\right\} \tag{5}$$

where I_L represents the mean value of the binding energy of the L energy-levels, and the other quantities remain as defined above.

Calculation of the average value of cos θ for L electrons, in the manner carried out above for K electrons, leads to the following results:

TABLE V.

Energy level	Gas	λ	$\overline{\cos\theta}$ (obs.)	$\overline{\cos\theta}$ (calc.)
L	CH_3I	0.71 A	.23	.17
L	CH_3I	0.49 A	.25	.22

The agreement here is not satisfactory, the observations seeming to indicate a greater average forward momentum of the photoelectrons than the theory.

Calculation of ρ, defined as above, leads to the following results:

TABLE VI.

Energy level	Gas	λ	ρ (obs.)	ρ (calc.)
L	CH_3I	0.71 A	2.0	1.9
L	CH_3I	0.49 A	2.3	2.4

With regard to ρ, experiment and theory are in fair accord.

A decrease in the isotropy of the space-distribution curve for L electrons, with an increase in the frequency of the incident radiation, as was found above, is also to be expected from the theory. The ratio of the number of L_{II} and L_{III} electrons to the L_I electrons is given by

$$\frac{L_{II}+L_{III}}{L_I} = \frac{I_L}{h\nu + 3I_L}\left(3 + 8\frac{I_L}{h\nu}\right) \qquad (6)$$

which for this case, leads to:

TABLE VII.

Energy level	Gas	λ	Relative proportion of	
			L_I Electrons	L_{II} and L_{III} Electrons
L	CH_3I	0.71 A	67%	33%
L	CH_3I	0.49 A	72%	28%

For the harder radiation then, due to the greater proportion of L_I electrons ejected, a slightly less isotropic distribution is to be expected.