



# XVII. The absorption of X-rays

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XVII. *The Absorption of X-Rays.*  
By TYCHO E:SON AURÉN, *Dr. phil.\**

I. *Method of Investigation.*

SINCE Moseley has ascertained that there is a simple relation between the frequency of X-ray spectra and atomic number, we may readily assume that there will be a similar relation when examining X-ray absorption in different elements. By way of ascertaining this kind of relation, I have made determinations of absorption in a number of elements. In so doing I have introduced a method of investigation which I have more particularly described in a preliminary paper†. This method has in view, by means of a procedure of compensation and by using a non-homogeneous radiation, the endeavour to determine the relation between the absorption coefficient of a certain element and the same coefficient of water. As materials for investigation I have preferably made use of chemical solutions, because a great number of elements are not obtainable in solid form, whereas they are easily obtainable in soluble compounds. As the method is adapted for determination of relative absorption coefficients, and these, only excepting the lightest elements, at least within a not too wide range,

\* Communicated by the Author.

† *Phil. Mag.* xxxiii. p. 471 (1917).

are independent of the wave-length, we have reason to believe that the fact that the radiation has not been quite homogeneous must be of less importance. Corrections can also easily be made for the absorption produced by scattering in the lighter elements, as will be shown below. In determining the absolute absorption coefficients by means of the method generally adopted, the irregularities in the action of the generator and the variations of the gas pressure in the bulb create appreciable difficulties by altering the composition of the radiation. Using homogeneous radiation obtained by reflexion on a crystal and using the ordinary method, Bragg and Peirce \* have made a series of experiments, but the authors represented them as being merely preliminary and announce that they intend to renew the experiments by the aid of a compensation method. These experiments recently have, however, been repeated by Owen †. In the following pages I shall revert to an experiment performed by Hull and Rice ‡ with the aid of very hard homogeneous rays, which research, however, only includes the elements Al, Cu, Pb. I shall also review a research recently published by Barkla and White §, which has also been worked out by using a homogeneous radiation and which likewise includes a few elements only.

My preliminary experiments, published in my paper above mentioned, have been continued, and I am now going to give the results obtained. In these experiments I have particularly endeavoured to make determinations with more accuracy and to perform them so as to make them comparable as far as possible. In order to increase the sensibility of the method I have in the later experiments used a more sensitive electrometer—a string-electrometer from A. B. Vetenskapliga Instrument, Lund, Sweden, which gave an indication of about 12 divisions on the scale for 1 volt, and the current in the bulb had amounted to 2 milliamperes and in this way the intensity of radiation appreciably increased. By way of obtaining fully comparable results I have tried, in all my experiments, to keep the composition of the radiation as constant as possible. The generator used, a high-tension transformer of 4 kilowatts, has been working very evenly. The generator was charged so as to keep a constant potential difference between the electrodes in

\* Bragg and Peirce, *Phil. Mag.* xxviii. p. 626 (1914).

† Owen, *Proc. Roy. Soc.* xciv. no. A 664, p. 510 (1918).

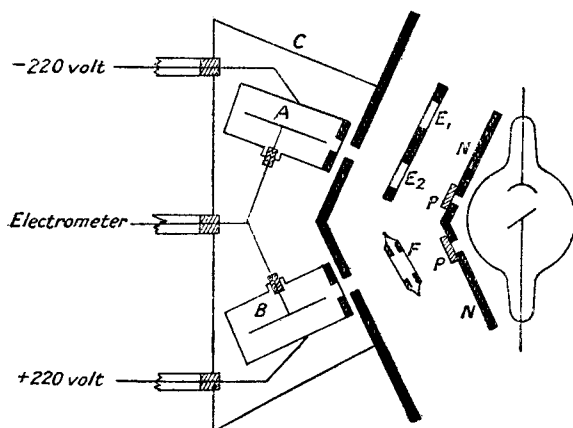
‡ Hull and Rice, *Phys. Rev.* ix. p. 326 (1916).

§ Barkla and White, *Phil. Mag.* xxxiv. p. 270 (1917).

the bulb. The same bulb, a Siemens' tungsten bulb of Grundelach type, with fin radiator for cooling the anticathode, has been employed in all experiments. But as the composition of radiation, in the case of an intermittent current, depends not only on the potential difference at the bulb but also on the gas-pressure in it, the greatest precaution has been taken to keep the gas-pressure as constant as possible. For this purpose the current in the bulb has been steadily controlled by means of a milliamperemeter, and by a careful and continual regeneration of the bulb it has been possible to keep the current very nearly constant. That the composition of the radiation has not undergone any alterations such as to have appreciably influenced the results is evidenced by the fact that different experiments repeated on different occasions with one and the same element have given very nearly the same results.

Both absorption vessels (E and F in fig. 1) having a

Fig. 1.



diameter of 3 cm. are placed at a distance of 12 cm. from their respective ionization chambers, whose front is made of lead plates, in which there are round openings of a radius of 2.5 cm. covered with mica. The position of the bulb has been adjusted so that with the same thickness of the layer and the same liquid in the two absorption vessels the intensity of both the ray-pencils penetrating into the ionization chambers should be as nearly alike as possible. The distance from the focus to the ionization chambers is 42 cm. Between the absorption vessels and the bulb there

is a leaden screen (N) at a distance of 20 cm. from the focus. In the screen there are also made two round openings of a radius of 2 cm., through which are admitted the ray-pencils that are to pass through the absorption vessels. In front of the openings are placed aluminium plates (P), which in the experiments have been used as filters for the rays. These filters were of four thicknesses—*i. e.* 1.25, 2.5, 5.0, and 10.0 mm.—and are marked, in the following, by I., II., III., IV. The mean wave-length of the four different compositions of radiation when using these filters is indicated in Table I.

Concerning the  $\gamma$ -rays Keetman \* has shown that, in order to obtain reliable values of the absorption coefficients, two conditions must be fulfilled. First, the absorbing layer should be exposed as little as possible to oblique radiation; secondly, the rays coming out of the absorbing layer in such a direction should, as much as possible, be excluded from the ionization chamber. There can be no doubt but that experiments for the purpose of determining the absorption coefficient in the case of hard X-rays give more or less inaccurate results if the said conditions are not approximately fulfilled. As in the experimental arrangements above mentioned the ray-pencil entering the ionization chamber seen from the focus and the absorbing layer has not had greater opening angles than  $3^{\circ}.5$  and  $12^{\circ}$  respectively, and as the diameter of the absorbing layer has not been more than 3 cm., the conditions mentioned may safely be considered as very nearly fulfilled. To be sure that no error might arise from the possible admission of scattered rays from the absorbing layer into the ionization chamber, special experiments were undertaken, in which the absorption vessel ( $E_1$  and  $E_2$ ) when being irradiated was displaced so that the distance to the ionization chamber was diminished from 12 to 1.5 cm. without the direction of the incident rays being changed in relation to the vessel. The experiments have shown that when the distance is greater than 3 or 4 cm. the position of the absorption vessel has scarcely any measurable influence on the results. In regard to this fact, O. Klein † has undertaken a mathematical explanation, to which I here beg to refer. The same problem has also recently been discussed by Glocher ‡, and his results agree very well with those found by Klein.

The relation between the intensity of both the ray-pencils

\* Keetmann, *Ann. der Ph.* lii. p. 720 (1917).

† O. Klein, *infra*, p. 207.

‡ Glocher, *Phys. Z.* xix. p. 251 (1918).

sometimes happened to undergo small changes, which have had a disturbing effect on the measurements. These changes seem likely to depend on the position of the focus being changed. To be independent, in the highest degree possible, of this source of errors I have used two cuvettes beside each other ( $E_1$  and  $E_2$ ), which have been so arranged as to be pushed alternately into the path of the rays. One of the cuvettes has always been filled with water, while the other has been filled with the liquid whose absorption was to be determined. When solid elements were examined the latter cuvette was emptied and in front of it a plate of the element in question was placed.

The procedure of measuring has been as follows :—When the cuvette filled with water had at first been placed in the path of the rays and the thickness of the water layer in comparator (cuvette F, fig 1) had been adjusted so that the electrometer gave no indication, the other cuvette, containing the liquid whose absorption was to be determined, was immediately pushed into the same position ; whereupon a new adjustment was effected. The difference between the two adjustments then indicates the difference of absorption in the two cuvettes. As a rule several such adjustments have been made, which, however, have seldom differed by more than *in maximo* 5 per cent. The absorption coefficients given in the following pages are calculated from the mean values of the experimental observations. The thickness of the liquid layers contained in both the cuvettes was about 1 cm. By special observations the thicknesses of the layers have been accurately determined. From these determinations I could measure the thickness of a water layer that absorbed just as much as a layer of the thickness of 1 cm. of a liquid or a layer of known thickness of the solid substance in question.

If the thickness of the water layer whose absorption is equal to a layer of the thickness of 1 cm. of a certain substance be supposed to be  $d$  cm., and the respective absorption coefficients of the water and of the liquid in question to be  $\mu_w$  and  $\mu_s$ , then by means of the absorption law  $I = I_0 e^{-\mu d}$ , where  $I$  stands for the intensity of transmitted radiation and  $I_0$  for the intensity of incident radiation, we obtain the equation :—

$$I_0 e^{-\mu_w d} = I_0 e^{-\mu_s d},$$

from which follows that

$$\frac{\mu_s}{\mu_w} = d.$$

If  $\kappa_{A/H_2O}$  designates the molecular absorption coefficient of a certain substance (A) in relation to the molecular coefficient of water, then when the said substance is supposed to contain  $m$  and water 55.5 mols per litre, we obtain the following formula for the calculation of this coefficient :

$$\kappa_{A/H_2O} = \frac{55.5d}{m} \dots \dots \dots (1)$$

As shown by researches by Winaver and Sachs\*, Glocker†, Barkla and White‡, etc., the absorption coefficient of water increases with increasing wave-length much more slowly than is the case with absorption coefficients of substances containing elements of higher atomic weight. In section IV. I shall give a detailed account of the matter and its cause. For that reason it is less suitable, in values obtained when the composition of radiation has been varied, to use the molecular absorption coefficient of water as a unit. The coefficients calculated after formula (1) have therefore been recalculated so as to give values corresponding to the atomic absorption coefficient of copper. If  $\kappa_{Cu/H_2O}$  designates the atomic absorption coefficient of copper in relation to the molecular absorption coefficient of water, we thus obtain

$$\kappa_{A/Cu} = \frac{\kappa_{A/H_2O}}{\kappa_{Cu/H_2O}} \dots \dots \dots (2)$$

Benoist was the first to advance the hypothesis that in chemical compounds, as well as what has been ascertained in regard to mixtures, the total absorption can be calculated from the absorption of the respective components by simple addition. This assumption has later on been regarded as satisfactory, a fact which is also in accordance with my former experiments. If in a molecule of a certain substance (A) there are  $n_1$  atoms of the element  $a_1$ ,  $n_2$  atoms of the element  $a_2$ , &c., we consequently suppose that

$$\kappa_{A/Cu} = n_1\kappa_{a_1/Cu} + n_2\kappa_{a_2/Cu} + n_3\kappa_{a_3/Cu} + \dots \dots (3)$$

When chemical compounds are used it is evidently most profitable for attaining a greater accuracy to choose

\* Winaver and Sachs, *Phys. Z.* xvi. p. 258 (1915).

† Glocker, *Phys. Z.* xviii. p. 332 (1917).

‡ Barkla and White, *Phil. Mag.* xxxiv. p. 270 (1917).

compounds in which absorption is dependent as much as possible on the element examined. When we calculate absorption of substances in solutions we have to correct the observed values in respect to the influence of the solvent. All the values below are corrected in this manner.

In calculating  $\kappa_{A/Cu}$  I have made use of the mean values of  $\kappa_{Cu/H_2O}$  obtained when examining Cu in metal form and in water solutions of  $CuCl_2$ ,  $CuSO_4$ ,  $CuNO_3$  (Table VII.). By the aid of the values exhibited in Barkla and White's paper on the mass absorption coefficient of copper and water in case of different wave-lengths  $\kappa_{Cu/H_2O}$  can be calculated, and by interpolation one can readily find the wave-lengths corresponding to the values found by the writer for  $\kappa_{Cu/H_2O}$ . In the Table below I have given the values obtained for the mean wave-lengths ( $\lambda_m$ ) in the four cases with different compositions of radiation. Likewise I have indicated the values of the mass-absorption coefficients of Cu ( $\frac{\mu}{\rho}_{Cu}$ ) corresponding to these wave-lengths, which values have been obtained by interpolation between the values given by Barkla and White.

TABLE I.

Notation.	Filter. Thickness in mm.	$\kappa_{Cu/H_2O}$ .	$\lambda_m$ .	$\frac{\mu}{\rho}_{Cu}$ .
I.....	1.12	78.9	0.38	7.10
II.....	2.50	67.8	0.36	5.92
III.....	5.00	57.6	0.34	4.89
IV.....	10.00	48.4	0.30	3.73

In the table, as well as in the following demonstration, the wave-lengths are denoted by the Ångström units (1 A.E. =  $10^{-8}$  cm.).

By filtering, most of the waves of greater wave-lengths in proportion are done away with, by which means radiation for an increasing thickness of filter is more and more apt to be homogeneous. Of course the range in which the wave-lengths fall has had an appreciable extension on both sides of the above-mentioned mean wave-lengths. Among the substances examined, certainly the characteristic wave-lengths of K-radiation for Sn, I, and Ba have fallen within the range mentioned. This is evident from the



strong increase of  $\kappa_{a/H_2O}$  (see Table VII.) for these elements; while there is decrease in intensity of rays of a greater wave-length on increasing the thickness of the filter. Values for elements that fall within what is called selective absorption range are not comparable with the other values. No doubt this range has also extended to substances whose atomic numbers lie next below the numbers of these elements, but probably the intensity of radiation within this section of the wave-length range must have been much less. In order, as much as possible, to do away with errors that would arise from this cause, it does not seem to be advisable to include the values obtained when using filter I. for the substances Sr ( $\lambda_{\kappa_{\beta_1}} = 0.767$ ), Mo ( $\lambda_{\kappa_{\beta_2}} = 0.633$ ), Rh ( $\lambda_{\kappa_{\beta_1}} = 0.537$ ), and for the substances Pd ( $\lambda_{\kappa_{\beta_2}} = 0.521$ ) and Ag ( $\lambda_{\kappa_{\beta_1}} = 0.491$ ) when filtering with I. and II.

## II. *Experimental Results.*

By comparing the absorption coefficients in compounds whose molecules only differ from one another by one or more atoms of oxygen the relative atomic absorption coefficient of this element can be determined. In my first experiments water-solutions of  $\text{NaClO}_3$  and  $\text{NaCl}$  were employed for this purpose; but in the experiments described below I have preferred to use certain pure organic compounds which, at ordinary temperature, are obtained in the form of liquids. This is done on the ground of absorption for these substances being determined to an appreciably greater extent by the absorption of oxygen than is the case with  $\text{NaClO}_3$  and similar combinations, which, in addition to oxygen, contain heavier and at the same time more strongly absorbing substances. The substances used have been free from water and, moreover, in chemical purity the best obtainable. In the following table are noted down the substances used as well as the values found for  $\kappa_{A/H_2O}$  in the compositions of radiation which have been got by means of the above-mentioned four different aluminium filters (I., II., III., IV.), and also the differences of these values for two compounds which in regard to molecular composition differ from each other only by one atom of oxygen. These differences ( $\kappa_{O/H_2O}$ ) thus indicate the atomic absorption coefficient of oxygen in relation to the molecular absorption coefficient of water.

TABLE II.  
Atomic absorption coefficient of oxygen in relation to the molecular  
absorption coefficient of water.

Chemical combination.	I.		II.		III.		IV.	
	$\kappa_A/H_2O$	$\kappa_O/H_2O$	$\kappa_A/H_2O$	$\kappa_O/H_2O$	$\kappa_A/H_2O$	$\kappa_O/H_2O$	$\kappa_A/H_2O$	$\kappa_O/H_2O$
Methyl formate, $C_2H_4O_2$ .....	2.90	0.57	2.95	0.87	2.98	0.83	3.05	0.81
Paraldehyde, $\frac{1}{3}(C_6H_{12}O_6)$ .....	2.03		2.08		2.16		2.24	
Propionic acid, $C_3H_6O_2$ .....	3.47	0.88	3.58	0.83	3.62	0.74	3.76	0.75
Allyl alcohol, $C_3H_6O$ .....	2.59		2.75		2.88		3.01	
Propionic acid, $C_3H_6O_2$ .....	3.47		3.58		3.62		3.76	
Acetone, $C_3H_6O$ .....	2.59	0.88	2.71	0.87	2.78	0.84	2.88	0.88
Carbonic acid dimethylester, $C_3H_6O_3$ .....	4.35		4.46		4.59		4.61	
Ethyl formate, $C_3H_6O_2$ .....	3.46	0.89	3.56	0.90	3.66	0.94	3.81	0.80
Methylal, $C_3H_8O_2$ .....	3.57		3.68		3.85		4.02	
Isopropyl alcohol, $C_3H_8O_2$ .....	2.65	0.92	2.85	0.83	3.07	0.78	3.16	0.84
Ethyl acetate, $C_4H_8O_2$ .....	4.15		4.28		4.43		4.63	
Methyl ethyl ketone, $C_4H_8O$ .....	3.19	0.96	3.38	0.90	3.61	0.82	3.90	0.73
Benzyl alcohol, $C_6H_5CH_2O$ .....	4.58		4.77		5.02		5.28	
Toluol, $C_6H_5CH_3$ .....	3.66	0.92	3.85	0.92	4.08	0.94	4.42	0.86
Octyl alcohol, $C_8H_{17}O$ .....	5.54		5.92		6.28		6.64	
Octane, $C_8H_{18}$ .....	4.70	0.84	5.02	0.90	5.42	0.86	5.82	0.82
Mean .....	0.895		0.878		0.844		0.811	

The values found for  $\kappa_{\text{O}/\text{H}_2\text{O}}$ , as shown from the table, agree very fairly. On the ground of the additive law and by the aid of the mean values above, we find corresponding values for hydrogen,  $\kappa_{\text{H}/\text{H}_2\text{O}}$ , if the molecular absorption coefficient of water be denoted  $=1$ :

	I.	II.	III.	IV.
$\kappa_{\text{H}/\text{H}_2\text{O}} =$	0.052	0.061	0.078	0.094

In the same manner, by means of the values found for  $\kappa_{\text{H}/\text{H}_2\text{O}}$  and  $\kappa_{\text{O}/\text{H}_2\text{O}}$ , the corresponding coefficients for C may be computed. In the following table we again find the values obtained from the observations for  $\kappa_{\text{A}/\text{H}_2\text{O}}$  indicated in Table II., and also those obtained from observations relatively to methyl alcohol and benzene (Table IV.).

TABLE III.

Atomic absorption coefficients for carbon in relation to the molecular absorption coefficient of water.

Substance.	I. $\kappa_{\text{C}/\text{H}_2\text{O}}$	II. $\kappa_{\text{C}/\text{H}_2\text{O}}$	III. $\kappa_{\text{C}/\text{H}_2\text{O}}$	IV. $\kappa_{\text{C}/\text{H}_2\text{O}}$
Methyl formate, $\text{C}_2\text{H}_4\text{O}_2$ .....	0.450	0.475	0.490	0.525
Paraldehyde, $\text{C}_6\text{H}_{12}\text{O}_3$ .....	0.463	0.469	0.497	0.526
Propionic acid, $\text{C}_3\text{H}_6\text{O}_2$ .....	0.457	0.487	0.488	0.524
Allyl alcohol, $\text{C}_3\text{H}_6\text{O}$ .....	0.460	0.502	0.522	0.544
Acetone, $\text{C}_3\text{H}_6\text{O}$ .....	0.460	0.489	0.489	0.503
Carbonic acid dimethylester, $\text{C}_3\text{H}_6\text{O}_3$ .....	0.450	0.487	0.530	0.536
Ethyl formate, $\text{C}_3\text{H}_6\text{O}_2$ .....	0.452	0.479	0.505	0.540
Methylal, $\text{C}_3\text{H}_8\text{O}_2$ .....	0.453	0.479	0.512	0.547
Isopropyl alcohol, $\text{C}_3\text{H}_8\text{O}$ .....	0.445	0.495	0.534	0.531
Ethyl acetate, $\text{C}_4\text{H}_8\text{O}_2$ .....	0.485	0.509	0.529	0.566
Methyl ethyl ketone, $\text{C}_4\text{H}_8\text{O}$ .....	0.469	0.504	0.518	0.572
Benzyl alcohol, $\text{C}_6\text{H}_5\text{CH}_2\text{O}$ .....	0.467	0.485	0.507	0.547
Toluol, $\text{C}_6\text{H}_5\text{CH}_3$ .....	0.463	0.478	0.492	0.505
Octyl alcohol, $\text{C}_8\text{H}_{18}\text{O}$ .....	0.463	0.493	0.504	0.516
Octane, $\text{C}_8\text{H}_{18}$ .....	0.470	0.490	0.502	0.515
Methyl alcohol, $\text{CH}_4\text{O}$ .....	0.485	0.508	0.494	0.521
Benzene, $\text{C}_6\text{H}_6$ .....	0.488	0.506	0.514	0.543
Mean .....	0.462	0.490	0.508	0.533

There is a very fair agreement between the values found from different compounds, as appears from the table. There does not appear to be any difference between carbon

from alifatic and aromatic compounds. If the mean values are computed from the alifatic substances (14 in number) in the first case and from the aromatic compounds (3 in number) in the second, in which latter case an atom of carbon in toluol and benzyl alcohol is supposed to have the same absorption as in alifatic compounds, then we get :

	I.	II.	III.	IV.
Alifatic compounds ...	0.46	0.49	0.50	0.53
Aromatic       ,, ...	0.47	0.49	0.50	0.53

Thus we get almost identical values from the two kinds of compounds. A difference which I formerly have found in this respect is entirely elucidated by the fact that, as I pointed out at the time, the values for hydrogen and oxygen were not determined with sufficient accuracy.

It has seemed to me to be of particular interest to examine how far the absorption of carbon in a solid form has the same magnitude as that of carbon in chemical compounds in liquid state. Therefore I have made several experiments on graphite plates. Here, however, we have the difficulty that completely pure graphite is hardly obtainable. Interspersed extraneous matters, most frequently consisting of heavier and hence more strongly absorbing elements, may, even in minute quantities, play an appreciable part in absorption. Professor C. Benedicks has kindly placed Acheson graphite plates at my disposal, which on chemical analysis have proved to contain solely 0.2 per cent. of ash substances, chiefly consisting of Fe. On examining this sort of graphite, the following values have been established :—

	I.	II.	III.	IV.
$\kappa_{C/H_2O}$ (Acheson graphite) ...	0.59	0.61	0.62	0.62

The values thus obtained are markedly higher than those found by examining organic compounds. Owing to the included metal particles these values are certainly a little too high, but the stated proportion of ashes does not seem to be so great that the difference can be fully explained by it. It may therefore be possible that carbon in the form of graphite is more strongly absorbing than in the form of organic compounds. Possibly the crystalline structure may have some influence. As, on the other hand, the influence of the included particles cannot with certainty be established,

the importance of the here observed difference can hardly be discussed more in detail. Yet I should wish to add that on examining other kinds of graphite I have found about the same difference. Since the chemical compounds examined must be regarded as particularly pure, and in any case not to contain heavier elements, we may surely assume that the values found for  $\kappa_{C/H_2O}$  are thoroughly reliable.

In the following table are given, by means of the values found for  $\kappa_{H/H_2O}$ ,  $\kappa_{C/H_2O}$  and  $\kappa_{O/H_2O}$ , the calculated values of  $\kappa_{A/H_2O}$  for the organic compounds mentioned above, compared with corresponding observed values.

TABLE IV.  
Comparison between calculated and observed values  
for  $\kappa_{A/H_2O}$  in organic compounds.

Substances.	I.		II.		III.		IV.	
	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.
Methyl alcohol, $CH_4O$ .....	1·59	1·57	1·62	1·61	1·65	1·66	1·71	1·72
Methyl formate, $C_2H_4O_2$ .....	2·90	2·92	2·95	2·98	2·98	3·02	3·05	3·07
Allyl alcohol, $C_3H_6O$ .....	2·59	2·60	2·75	2·71	2·88	2·84	3·01	2·98
Acetone, $C_3H_6O$ .....	2·59	2·60	2·71	2·71	2·78	2·84	2·88	2·98
Propionic acid, $C_3H_6O_2$ .....	3·47	3·49	3·58	3·59	3·62	3·68	3·76	3·79
Ethyl formate, $C_3H_6O_2$ .....	3·46	3·49	3·56	3·59	3·66	3·68	3·81	3·79
Carbonic acid dimethylester, $C_3H_6O_3$ .....	4·35	4·39	4·46	4·47	4·59	4·52	4·61	4·60
Isopropyl alcohol, $C_3H_8O$ .....	2·65	2·70	2·85	2·84	3·07	2·99	3·16	3·17
Methylal, $C_3H_8O_2$ .....	3·57	3·60	3·68	3·71	3·85	3·84	4·02	3·98
Methyl ethyl ketone, $C_4H_8O$ .....	3·19	3·16	3·38	3·33	3·61	3·50	3·90	3·70
Ethyl acetate, $C_4H_8O_2$ .....	4·15	4·06	4·28	4·20	4·43	4·34	4·63	4·51
Benzene, $C_6H_6$ .....	3·25	3·09	3·40	3·31	3·55	3·52	3·83	3·77
Toluol, $C_6H_5CH_3$ .....	3·66	3·65	3·85	3·92	4·08	4·18	4·42	4·49
Benzyl alcohol, $C_6H_5CH_2O$ .....	4·58	4·55	4·77	4·80	5·02	5·02	5·28	5·30
Paraldehyde, $C_6H_{12}O_3$ .....	6·09	6·09	6·24	6·31	6·46	6·52	6·71	6·77
Octane, $C_8H_{18}$ .....	4·70	4·64	5·02	5·02	5·42	5·47	5·82	5·96
Octyl alcohol, $C_8H_{18}O$ .....	5·54	5·54	5·92	5·90	6·28	6·31	6·64	6·78

For nitrogen I have calculated  $\kappa_{N/H_2O}$  from the determinations of  $\kappa_{A/H_2O}$  for the compounds given in Table V., where besides N only H, O, and C are component parts.

In determining  $\kappa_{a/H_2O}$  for other elements than those now dealt with, chemical solutions of different kinds have been used. By determining  $\kappa_{A/H_2O}$  for  $H_2SO_4$ ,  $Na_2S_2O_3$ ,  $HCl$ ,  $NaCl$ , and  $NaOH$  (Table VII.), and also by the aid of

TABLE V.  
Atomic absorption coefficient for nitrogen in relation to the molecular absorption coefficient of water.

Chemical combination.	I.		II.		III.	IV.
	$\kappa_{A/H_2O}$	$\kappa_{N/H_2O}$	$\kappa_{A/H_2O}$	$\kappa_{N/H_2O}$	$\kappa_{A/H_2O}$	$\kappa_{A/H_2O} \kappa_{N/H_2O}$
Nitric acid, $HNO_3$ .....	3.17	0.43	3.33	0.64	3.38	3.39 0.86
Ammonium nitrate, $H_4N_2O_3$ .....	4.11	0.61	4.14	0.63	4.50	4.71 0.95
Pyridine $C_5H_5N$ .....	3.26	0.69	3.49	0.74	3.63	3.85 0.71
Aniline, $C_6H_5NH_2$ .....	3.78	0.64	4.11	0.74	4.39	4.70 0.84
Ethyl nitrate, $C_2H_5NO_3$ .....	4.40	0.53	4.50	0.58	4.63	4.73 0.76
Nitro-benzene, $C_6H_5NO_2$ .....	5.43	0.61	5.70	0.70	5.92	6.03 0.74
Amyl nitrate, $C_5H_{11}NO_3$ .....	6.17	0.60	6.41	0.66	6.67	6.91 0.77
Mean .....		0.59		0.67		0.76 0.80

values found before of  $\kappa_{O/H_2O}$  and  $\kappa_{H/H_2O}$ , I have calculated  $\kappa_{A/H_2O}$  for the radicles given in the table below.

TABLE VI.

Absorption coefficients of some frequently-used radicles in relation to the molecular absorption coefficient of water.

Radicle.	I.	II.	III.	IV.
OH.....	0.95	0.94	0.92	0.91
NH <sub>4</sub> .....	0.80	0.91	1.07	1.18
NO <sub>3</sub> .....	3.27	3.30	3.29	3.24
SO <sub>4</sub> .....	11.57	10.57	9.46	8.26

From the observed values for  $\kappa_{A/H_2O}$  in the compounds examined have been deduced the above values, when with the respective elements the mentioned radicles have been allied, or when other radicles have been allied, the values in the following table :—

TABLE VII.

Atomic absorption coefficients in relation to the molecular absorption coefficient of water.

Atomic number. Z.	Element.	Substance examined.	I.	II.	III.	IV.
1	H	(Table II.) .....	0.052	0.061	0.078	0.094
3	Li	LiOH .....	0.27	0.29	0.30	0.30
		LiNO <sub>3</sub> .....	0.16	0.24	0.30	0.37
		Mean .....	0.21	0.26	0.30	0.33
4	Be	Be(NO <sub>3</sub> ) <sub>2</sub> .....	0.31	0.32	0.42	0.56
5	B	B <sub>2</sub> O <sub>3</sub> (solution in meth. alcohol) }	0.50	0.49	0.56	0.60
6	C	(Table III.).....	0.46	0.49	0.51	0.53
7	N	(Table V.) .....	0.59	0.67	0.76	0.80
8	O	(Table II.) .....	0.90	0.88	0.84	0.81
9	F	C <sub>6</sub> H <sub>5</sub> F.....	1.43	1.35	1.29	1.14
11	Na	NaOH .....	2.16	2.01	1.87	1.66
12	Mg	MgSO <sub>4</sub> .....	2.73	2.26	2.26	1.77
		Mg(NO <sub>3</sub> ) <sub>2</sub> .....	2.48	2.36	1.86	1.58
		Mean .....	2.60	2.31	2.06	1.67

Atomic number. Z.	Element.	Substance examined.	I.	II.	III.	IV.
13	Al	Metal .....	4.08	3.66	3.23	2.79
14	Si	$C_6H_5Si(CH_3)_3$ .....	5.88	5.05	4.39	3.70
15	P	$H_3PO_4$ .....	6.16	5.47	4.82	4.18
16	S	$H_2SO_4$ .....	7.99	6.81	6.04	5.21
		$Na_2S_2O_3$ .....	7.99	7.30	6.12	4.83
		Mean .....	7.99	7.06	6.08	5.02
17	Cl	HCl .....	10.25	8.94	7.65	6.39
		NaCl.....	10.01	8.94	7.53	7.14
		Mean .....	10.13	8.94	7.59	6.76
19	K	KCl .....	14.7	12.6	11.6	9.2
		$K_2S$ .....	15.1	13.3	11.5	9.7
		Mean .....	14.9	12.9	11.5	9.4
20	Ca	$CaCl_2$ .....	21.3	18.9	15.6	11.2
		$Ca(NO_3)_2$ .....	19.8	18.0	15.4	12.9
		Mean .....	20.5	18.4	15.5	12.0
23	V	$Na_4V_2O_7$ .....	34.8	30.6	27.2	22.5
24	Cr	$K_2CrO_4$ .....	40.1	35.7	30.5	25.3
		$K_2Cr_2O_7$ .....	39.6	36.5	30.1	25.6
		$CrCl_3$ .....	39.7	36.6	31.9	24.8
		Mean .....	39.8	36.3	30.8	25.2
25	Mn	$MnCl_2$ .....	46.2	40.9	35.6	28.9
		$MnSO_4$ .....	48.6	42.0	36.4	28.8
		Mean .....	47.4	41.4	36.0	28.9
26	Fe	Metal .....	55.1	48.7	40.8	33.3
		$FeCl_3$ .....	51.5	44.3	39.7	32.1
		$Fe(NH_4)_2(SO_4)_2$ ...	57.2	48.1	41.4	33.5
		Mean .....	54.6	47.0	40.6	33.0
27	Co	$CoCl_2$ .....	67.6	57.0	51.8	40.6
		$Co(NO_3)_2$ .....	64.0	55.5	47.2	36.9
		Mean .....	65.8	56.2	49.5	38.8
28	Ni	Metal .....	69.7	63.8	54.5	46.8
		$NiCl_2$ .....	70.1	63.0	55.0	43.2
		Mean .....	69.9	63.4	54.7	45.0
29	Cu	Metal .....	81.0	66.9	54.8	47.4
		$CuCl_2$ .....	78.0	69.5	59.1	48.5
		$CuSO_4$ .....	78.4	70.0	61.0	49.4
		$Cu(NO_3)_2$ .....	78.4	64.8	55.5	48.3
		Mean .....	78.9	67.8	57.6	48.4



Atomic number. Z.	Element.	Substance examined.	I.	II.	III.	IV.
30	Zn	ZnCl <sub>2</sub> .....	88.2	75.6	65.4	52.8
		ZnSO <sub>4</sub> .....	88.2	79.6	68.7	56.5
		Mean .....	88.2	77.6	67.0	54.6
33	As	Na <sub>2</sub> HAsO <sub>4</sub> .....	125.6	113.7	98.4	80.1
34	Se	SeO <sub>2</sub> .....	143.0	124.0	109.5	92.2
35	Br	NaBr .....	152.5	137.7	119.9	100.0
37	Rb	RbCl .....	204.3	182.1	153.0	128.4
38	Sr	SrCl <sub>2</sub> .....	207.2	183.8	164.6	140.4
		Sr(NO <sub>3</sub> ) <sub>2</sub> .....	207.8	188.0	168.8	142.6
		Mean .....	207.5	185.9	166.7	141.5
42	Mo	Mo <sub>7</sub> O <sub>34</sub> (NH <sub>4</sub> ) <sub>6</sub> ...	267	239	219	185
45	Rh	RhCl <sub>3</sub> .....	310	293	266	213
46	Pd	Pd(NO <sub>3</sub> ) <sub>2</sub> .....	333	321	288	235
47	Ag	AgNO <sub>3</sub> .....	327	322	313	247
50	Sn	Metal .....	331	364	372	347
53	I	NaI .....	326	352	356	366
56	Ba	BaCl <sub>2</sub> .....	340	357	387	425
82	Pb	Pb(NO <sub>3</sub> ) <sub>2</sub> .....	675	608	544	460

Generally the values of one and the same element which have been obtained from different solutions agree very closely. Only when using the hardest radiation (IV. 10 mm. Al-filter) the difference seems to be somewhat greater on certain occasions. The agreement in this case being less good may in some part be due to decreased intensity of radiation, and, therefore, the adjustment of the comparator is more difficult. The principal cause is surely that a small variation of the wave-length, in the almost homogeneous radiation, must have a proportionally greater influence than when radiation has been less homogeneous. The agreement of the values found in solutions of chemical compounds with those found in the scrutiny of metals in solid form (Fe, Ni, Cu) is particularly good. So there does not appear to be any occasion for doubting the correctness of the idea that absorption is purely an atomic quality, and consequently that it is independent as well of the aggregation form—except perhaps for C, as was said above—in which the substance is taken as of the manner in which it enters into compounds. More especially the strong rule of the additive law is corroborated by the experiments shown

in Table IV., for which the absorption coefficients of the constituent parts are more elaborately determined than in respect to other elements and for which the agreement of observed and calculated coefficients is also the best possible. The deviations from the said law that certain authors think they have found may probably be due either to the error of neglecting the absorption of the lightest elements or else to experimental errors.

For reasons previously mentioned (p. 170) the values of  $\kappa_{a/H_2O}$  found for the different elements have been recalculated for the purpose of obtaining corresponding coefficients in relation to the atomic absorption coefficient of copper;  $\kappa_{Cu}$  is arbitrarily put equal to 100. For the elements Li-V, besides the values found directly from the observations, the corrected values are also stated, which have been obtained in a way that is stated more in full below (p. 187). The values given in parentheses are not included in the calculated mean values.

TABLE VIII.

Atomic absorption coefficients for the elements below in relation to the atomic absorption coefficient of copper.

Z.	Element.	I.	II.	III.	IV.	Mean.
1	H ..... obs.	0.067	0.090	0.136	0.195	
	corr.	0.00	0.00	0.00	0.00	0.00
3	Li ..... obs.	0.27	0.38	0.52	0.68	
	corr.	0.07	0.11	0.11	0.10	0.10
4	Be ..... obs.	0.39	0.47	0.73	1.16	
	corr.	0.12	0.11	0.19	0.38	0.20
5	B ..... obs.	0.63	0.72	0.97	1.24	
	corr.	0.30	0.27	0.19	0.26	0.25
6	C ..... obs.	0.58	0.72	0.89	1.10	
	corr.	0.31	0.36	0.34	0.32	0.33
7	N ... .. obs.	0.75	0.99	1.32	1.66	
	corr.	0.28	0.36	0.37	0.29	0.32
8	O .... . obs.	1.13	1.30	1.46	1.67	
	corr.	0.86	0.94	0.92	0.89	0.91
9	F ..... obs.	1.81	1.99	2.24	2.36	
	corr.	1.48	1.54	1.56	1.37	1.50
11	Na ..... obs.	2.74	2.96	3.25	3.43	
	corr.	2.27	2.33	2.29	2.06	2.24
12	Mg ..... obs.	3.30	3.41	3.58	3.45	
	corr.	3.03	3.05	3.04	2.67	2.95
13	Al ..... obs.	5.17	5.40	5.61	5.76	
	corr.	4.84	4.95	4.93	4.78	4.87

Z.	Element.	I.	II.	III.	IV.	Mean.
14	Si ..... obs.	7.45	7.45	7.62	7.65	
	corr.	7.18	7.09	7.08	6.77	7.03
15	P ..... obs.	7.81	8.07	8.37	8.64	
	corr.	7.34	7.44	7.42	7.27	7.37
16	S ..... obs.	10.13	10.40	10.55	10.36	
	corr.	9.86	10.04	10.01	9.58	9.87
17	Cl ..... obs.	12.84	13.19	13.17	13.96	
	corr.	12.51	12.74	12.49	12.98	12.68
19	K ..... obs.	18.9	19.0	20.0	19.4	
	corr.	18.4	18.4	19.0	18.0	18.5
20	Ca ..... obs.	26.0	27.1	26.9	24.8	
	corr.	25.7	26.7	26.4	24.0	25.7
23	V ..... obs.	44.1	45.1	47.2	46.5	
	corr.	43.6	44.5	46.2	45.1	44.9
24	Cr .....	50.4	53.6	53.5	52.1	52.4
25	Mn .....	60.1	61.1	62.5	59.7	60.9
26	Fe .....	69.2	69.4	70.5	68.2	69.3
27	Co .....	83.4	82.9	85.9	80.2	83.1
28	Ni .....	88.6	93.5	95.0	93.0	92.5
29	Cu .....	100	100	100	100	100
30	Zn .....	112	114	116	113	114
33	As .....	159	168	171	166	166
34	Se .....	181	183	190	191	186
35	Br .....	193	203	208	206	203
37	Rb .....	259	269	266	265	265
38	Sr .....	(263)	274	289	292	285
42	Mo .....	(338)	353	380	382	371
45	Rh .....	(393)	432	462	440	445
46	Pd .....	(422)	(473)	500	486	493
47	Ag .....	(414)	(475)	544	510	527
50	Sn .....	420	536	646	717	—
53	I .....	413	519	618	756	—
56	Ba .....	431	527	672	878	—
82	Pb .....	855	898	945	950	—

It appears from the table that  $\kappa_{a/Cu}$  for the lightest elements increases with a decreasing wave-length, but starting from Mg this progress lessens more and more when the atomic number increases. As for the elements Sn, I, and Ba, selective absorption plays a considerable part: that is why the values found for these elements are not comparable with the other values. At Pb,  $\kappa_{Pb/Cu}$  increases markedly as the wave-length is diminishing. By means

of very hard rays ( $\lambda = 0.360-0.145$ ) Hull and Rice recently have determined  $\frac{\mu}{\rho}$  for Pb and Cu, in which case the following formulæ have been found to hold :—

$$\frac{\mu}{\rho}_{\text{Pb}} = 0.12 + 430\lambda^3,$$

$$\frac{\mu}{\rho}_{\text{Cu}} = 0.12 + 150\lambda^3.$$

If  $\kappa_{\text{Pb/Cu}}$  is calculated from these formulæ for the mean wave-lengths used by the author (Table I.), we obtain

$\kappa_{\text{Pb/Cu}}$ :—	I.	II.	III.	IV.	Mean.
according to Hull and Rice.	925	925	922	918	922
„ „ Table VIII.	855	898	945	950	912

The mean values found according to the said formulæ and the mean values from my experiments agree very closely; but by comparing the original values, it is seen that whereas in my experiments  $\kappa_{\text{Pb/Cu}}$  increases with a decreasing wave-length, these values according to the Hull and Rice formulæ are fairly constant. After Barkla's opinion, however, the absorption coefficient cannot be exactly expressed by the formula  $\frac{\mu}{\rho} = C + k\lambda^b$ , because neither  $C$  nor  $b$  is perfectly constant within a large wave-length range. In my experiments, it is true, the wave-length range has extended markedly on both sides of the mean wave-lengths stated above; but this can hardly account for the difference between the values found according to the Hull and Rice formulæ and those in my experiments. On the other hand, the deviations can possibly be explained by the circumstance that  $C$  has not, as these physicists have suggested, the same value in all elements, but is greater for Pb than for Cu. In section IV. I shall return to this question.

If by the Hull and Rice formula for aluminium,

$$\frac{\mu}{\rho}_{\text{Al}} = 0.12 + 14.9\lambda^3,$$

$\kappa_{\text{Al/Cu}}$  is calculated, we obtain the values stated in the table below. In Barkla and White's paper values are given of  $\frac{\mu}{\rho}$  for a very wide wave-length range in regard to Al and Cu. By interpolation the necessary values may be

obtained for calculating  $\kappa_{\text{Al/Cu}}$  in the mean wave-lengths used by the author. The calculated values are given below :

$\kappa_{\text{Al/Cu}}$ :—	I.	II.	III.	IV.
according to Hull and Rice . .	4.77	4.88	4.99	5.34
„ „ Barkla and White .	4.89	5.52	6.05	5.85
„ „ Table VIII. . .	5.17	5.40	5.61	5.76

There is, as appears from the table, a fairly good agreement between my values and those of Barkla and White, whereas those of Hull and Rice are more deviating. The reason why, especially for the lighter elements, there are so great differences between the values of the absorption coefficients recorded by different observers may probably first of all be ascribed to the experimental method. As for Al, the observers may have disregarded that a source of errors lies in the fact that the metal plates existing on the market are seldom perfectly pure. The impurities are always Fe and Si, often Cu and also other elements. From a chemical-technical point of view, common aluminium metal, according to Haber, is regarded as satisfactorily pure if it does not contain more than 1 per cent. Fe and Cu and no more than 0.8 per cent. Si. Supposing that in the metal there is 1 per cent. Fe, this would enhance absorption by 6 or 7 per cent., and if we also admit that there are other impurities the error seems not unlikely to amount to as much as 10 per cent. or more. When analysing the metal used by me, it has been found to contain 0.21 per cent. Fe, 0.29 per cent. Si, and only traces of Cu. Hence the metal is comparatively pure. The error caused by the impurities cannot exceed 2 or 3 per cent., and as this is within the limits of experimental errors no correction has been made in this respect. The circumstance pointed out here as to the quality of the common aluminium metal will suffice to show that it is not quite appropriate to be a standard metal for absorption measures. Besides, Barkla has pointed out that Al in regard to absorption with a diminishing wave-length shows a slight, certainly, but very unmistakable increase at  $\lambda=0.37$ , which Barkla thinks must depend on the metal sending out a characteristic so-called J-radiation of that wave-length. Barkla, therefore, prefers copper as a standard metal, and I have made use of it also and found it to be quite appropriate for this purpose. The difference observed by different authors in regard to Al absorption may at least partly be explained by difference in quality of the experimental material. In a still higher

degree may the impurities disadvantageously influence the X-ray absorption of the lightest elements, a case which was already pointed out in respect to carbon.

### III. *Distribution of Electrons between the inner and outer region.*

In accordance with what has been shown in previous experiments, the atomic absorption coefficient, at least within a not too wide wave-length range, may be expressed by the formula

$$\kappa_a = C_a + k_a \lambda^b, \quad . . . . . (4)$$

where  $C_a$  is a constant depending on the absorption due to the diffusely reflected radiation, "scattering,"  $k_a$  is a constant exclusively depending on the chemical nature of the substance, and  $b$  has very nearly the value 3.

If we proceed from the theory that absorption is exclusively determined by the number of electrons in the atom and by the manner in which these are attached to the nucleus, it seems highly probable that the electrons arranged in the periphery of the atom, which in the following are designated as *outer electrons* ( $p$ ), must play quite another part than the inner, more closely-attached electrons. When, in the lines below, the expression *inner electrons* ( $c$ ) is used it does not designate those hypothetical electrons being a part of the very nucleus, but only those arranged nearer to the nucleus and the number of which corresponds to the atomic number on deducting the number of the outer electrons. These outer electrons\*, on which the optical and chemical qualities of the atom are generally supposed to depend, and which, therefore, are usually designated as "dispersions" or respectively "valence-electrons," must be considered much more elastically attached to the nucleus than the others. Working with X-ray crystal analysis of different substances, also, Hull† makes the conclusion that certain electrons constituting the atom are more closely attached to the nucleus than others which show a certain degree of freedom.

The theory brought forward by J. J. Thomson on the scattering phenomenon is founded on the assumption that the electrons are quite independent of each other when subjected to the primary radiation. This assumption may be thought to be fulfilled in respect to the electrons of the surface part of the atom, but not in respect to the electrons

\* Comp. Sommerfeld, *Ann. d. Phys.* B. 53, p. 513 (1917).

† Hull, *Phys. Rev.* x. ser. 2, p. 663 (1917).

arranged in the proximity of the nucleus, more especially if they are arranged in some sort of planetary orbits. If the scattering phenomenon is produced solely by the outer electrons, the absorption due to this process according to the said theory must be proportional to the number of such electrons. Of the two terms of the formula for  $\kappa_a$ , the term  $C_a$  seems to be determined by the number of outer electrons.

In the elements, except in the lightest, absorption is chiefly due to the inner electrons and the manner in which they are grouped in relation to the nucleus. On increasing the atomic number, presumably rearrangements of electrons must take place in certain elements, whether according to Bohr one assumes that new electron rings are formed or simply assumes a discontinuous change of concentration by sudden leaps. When such a rearrangement takes place it must make itself perceivable by a sudden increase in absorption. In previous experiments I found that a perceptibly sudden increase in absorption takes place in the elements O, S, Mn, and Cu, which in accordance with the same view might be assumed to be due to rearrangements of the inner electrons of these elements. In the experiments I have given an account of above, a similar sudden increase in absorption has been found again in the same elements except Mn. Owing to an error in the analysis of the first-examined solution of  $\text{CrCl}_3$ , somewhat too low a value was obtained for Cr. The point where rearrangements seem to be occurs at this element. In addition, similar points seem to be at the elements Mg and Ca.

At the elements following from Cu there seems not to be any rearrangement of the inner electrons to Pd; but as the experimental errors may possibly be a little greater here than in the preceding elements, this point may not be quite certain.

To obtain comparable values of the absorption coefficients for the lighter elements, it is necessary to correct the values found in relation to the absorption due to scattering. For Cu, with the mean wave-lengths used by me, the term  $C_a$  in the formula (4) compared with  $k_a\lambda^b$  is certainly very insignificant and may, in maxima, be estimated to 1 per cent. of the whole. If this term is neglected for Cu, we obtain the following formula for calculating  $\kappa_{a/\text{Cu}}$  :—

$$\kappa_{a/\text{Cu}} = \frac{C_a}{k_{\text{Cu}}\lambda^b} + \frac{k_a}{k_{\text{Cu}}}, \quad . \quad . \quad . \quad . \quad . \quad (5)$$

or

$$\bar{\kappa}_{a/\text{Cu}} = \kappa_{a/\text{Cu}} - \frac{C_a}{k_{\text{Cu}}\lambda^b} = \frac{k_a}{k_{\text{Cu}}}. \quad . \quad . \quad . \quad (6)$$

The designation  $\bar{\kappa}_{a/Cu}$  below stands for the relative values of the atomic absorption coefficients, which have been corrected for scattering\*. The correction, however, is of no significance in heavier elements, and in elements of higher atomic number than 23  $\kappa_{a/Cu}$  is therefore assumed to be equal to  $\kappa_{a/Cu}$ .

As pointed out above, according to the theory on scattering of J. J. Thomson, every one of the outer electrons must have an equal influence. If we approve of the common view that the hydrogen atom consists of a nucleus combined only with one electron, we can readily find the value of the scattering effect ( $q$ ) excited by one single electron. Without any noteworthy error we may assume that in the formula (5)

$\frac{k_a}{k_{Cu}}$  may be put equal to zero for H. Thus the absorption

of the hydrogen atom would entirely be determined by the scattering effect produced by the electron combined with the nucleus. In the case of the four different compositions of radiation used in my experiments, the absorption coefficient depending on an outer electron in relation to the atomic coefficient of copper will thence give the following values :—

	I.	II.	III.	IV.
$q =$	0.067	0.090	0.136	0.195

Supposing the number of the outer electrons ( $p$ ) to be known, the correction for scattering, after what has been said above, will simply be  $pq$ .

If Li is regarded as being built up of 3, Be of 4, and B of 5 electrons, then the corrected values ( $\bar{\kappa}_{a/Cu}$ ) for these elements will be obtained by deducting  $3q$ ,  $4q$ ,  $5q$  respectively from the observed values. These values are, as seen from Table VIII., fairly constant, except for  $Be_{IV}$ . An experimental error might be responsible for this difference—a circumstance which is easily accounted for, partly by the difficulty in accurately determining absorption in case of the slightly absorbing lightest elements, partly by the above-mentioned difficulty in keeping radiation unchanged when using the hardest rays.

As for C, the simplest thing would evidently be to regard all of the 6 electrons to be arranged as outer electrons; but if the values found of  $\kappa_{C/Cu}$  are corrected by  $6q$ , we get:

	I.	II.	III.	IV.
$\kappa_{C/Cu} - 6q =$	0.186	0.183	0.080	-0.069,

\* Comp. Glocker, *Phys. Z.* xix. p. 68 (1918).



which shows that all of the electrons presumably are not active as outer electrons. On the other hand, if we assume that 2 of the electrons are more intimately bound up to the nucleus, and consequently that only 4 electrons are electrons of the remotest orbit, then we obtain the values seen in Table VIII., which, indeed, agree very well. Now, in regard to N, all of the electrons seem to be outer electrons, and the values corrected by  $7q$  accordingly agree rather closely. Similarly, we find that O is probably built up of 4 outer electrons; thus the remaining 4 electrons must be regarded as arranged in an inner region. This rearrangement to an inner region may be regarded as causing the above change by a sudden leap in the absorption of the said element. For F ( $Z=9$ ) we are probably right in regarding 5 and for Na ( $Z=11$ ) 7 electrons to be outer electrons. In the elements O-Na the inner region, with 4 electrons as constituent parts, would then remain unchanged. How the four electrons, which so would form the inner region of the elements O-Na, are arranged in relation to each other, is a question to which, of course, my experiments cannot give an answer. Starting from the Rutherford-Bohr atom model, the simplest view seems to be that all of the four electrons are arranged in one ring. It may be well to remember that Vegard\* has shown that from quantum-theory this atom model would lead to the result that the inner ring may be built up of either three or four electrons. With four electrons we arrive, according to Vegard, at a particularly simple formula to calculate the frequency in spectra of X-rays; but the author, however, for certain reasons, thinks it more plausible that the ring is built up of only three electrons.

Another rearrangement, due to the passing of 4 other electrons to the inner region, seems to take place at Mg ( $Z=12$ ). The outer region of Mg-atom would then contain 4 electrons, and after correction by  $4q$  we get almost constant values of  $\kappa_{\text{Mg/Cu}}$ . The found values of  $\kappa_{\text{a/Cu}}$  give no occasion to think of any change at Al and P. The outer region of Al would consist of 5 and that of P of 7 electrons, which, as shown by the table, is in good agreement with the observed values. Concerning Si ( $Z=14$ ), we obtain the following values after correcting by  $6q$  :—

	I.	II.	III.	IV.
$\kappa_{\text{Si/Cu}} - 6q$	7.05	6.91	6.81	6.48

To estimate with greater degree of certainty the number of outer electrons by means of the said correction is

\* Vegard, Phil. Mag. xxxv. p. 302 (1918).

not possible for elements which show greater absorption. Already at Si this method must be regarded as less reliable. The values for Si just mentioned plausibly authorize the assumption that the number of the outer electrons must be less than 6. There is not a long way to the suggestion that the atomic structure of Si is analogous to that of C, which, indeed, in the periodic system stands next above Si in the same vertical row. Consequently, if we suppose 4 outer electrons, the values given in the table will be obtained, which may be regarded as almost constant. In the Si-atom, just as was the case in C, 2 electrons would be more closely attached to the nucleus than the 4 outer electrons. Thus we should be able to account for the value of  $\bar{\kappa}_{\text{Si/Cu}}$  being somewhat higher than it ought to be if this element, like the next preceding and following elements, only contained an inner region with 8 electrons. From the sudden increase of absorption at S ( $Z=16$ ) apparently a new rearrangement takes place at this element, and the above reasons speak in favour of the assumption that here 4 electrons pass from the inner region, which thus should contain 12 electrons. The capacity of absorption indicating that the arrangement of electrons in the inner region of the elements Cl ( $Z=17$ ) and K ( $Z=19$ ) remains unchanged, these atoms would contain 5 and 7 electrons respectively in the outer region. At Ca ( $Z=20$ ) there would occur another rearrangement of the electrons, by which change four other electrons would pass from the outer to the inner region. Thus the inner region of the elements Ca-V would contain 16 electrons and the outer region, as in the preceding group, 4-7 electrons respectively.

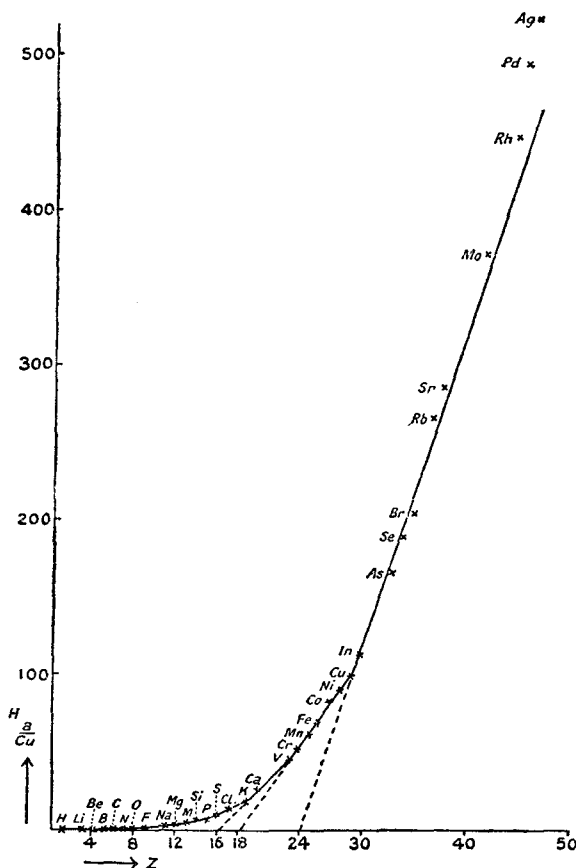
With increasing atomic weight the term  $\frac{C_a}{k_{\text{Cu}} \lambda^2}$  becomes, in comparison with the term  $\frac{k_a}{k_{\text{Cu}}}$  (5), of still less importance and, certainly in the latter of the just-mentioned elements, lies within the limits of experimental errors. If, however, the relation between  $\bar{\kappa}_{a/\text{Cu}}$  and  $Z$  is pictured graphically (fig. 2), it is seen that  $\kappa_{a/\text{Cu}}$  within each group appears to be very nearly a linear function of the atomic number. Thus the relation between the two quantities may be expressed :

$$\bar{\kappa}_{a/\text{Cu}} = K(Z - c), \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where  $c$  stands for the number of inner electrons of the elements constituting the group, and  $K$  is a constant characteristic of the group. If the straight line designating

$\kappa_a/\text{Cu}$  for a certain group is drawn so as to cut the X-axis, the section thus cut off corresponding to the value  $Z=c$  will give the number of electrons of the inner region in the group mentioned. By means of a graphical construction we accordingly find that the elements Cr ( $Z=24$ )—Ni ( $Z=28$ ) form a group having an inner region containing 18 electrons,

Fig. 2.



and that the elements Cu ( $Z=29$ )—Rh ( $Z=45$ ) form another group whose inner region is characterized by 24 electrons. It must be mentioned that for the last elements in the latter of the just-mentioned groups there may be some uncertainty for the above-given reasons, the more so as the values

exhibited in the figure fall a little above the straight line that represents the group. In the group Cr—Ni the number of outer electrons is 6–10 respectively ; but presumably there are in these elements two or more electrons more closely attached to the nucleus, as we found it likely to be the case for C and Si.

At Cu the outer electrons would be 5, which will then successively be augmented by one electron at each element of the following group. Now it does not seem very likely that in so great a number of outer electrons as would be present in the outer region for the latter elements in this group all the electrons would occupy an equivalent position. Possibly here, too, some kind of ring formation may take place by means of which certain among the outer electrons may concentrate towards the inner region and so more closely adhere to the nucleus. Thus the circumstance pointed out, that  $\kappa_{a/Cu}$  in the latter elements of this group is somewhat greater than what ought to have been the case if the formula (7) were quite correct, might be explained.

We may well anticipate that the just mentioned rearrangements may be perceivable in the X-ray spectra of the elements. As Sommerfeld\* has made probable, the N-ring ought to commence by Mg and the M-ring by Ca. This is in good agreement with my results. That there are no new lines in the spectra of S and Cr—as up to the present had been detected—may be explained easily, if we assume that by rearrangements of the electrons no new ring has been formed, but only the number of electrons in the already existing inner rings has been increased. The sudden increase in absorption by  $Z=29$  (or perhaps  $Z=30$ ) seems to stand in some relation to the at-this-point-beginning L-series, which, after our present knowledge, just begins at  $Z=30$ . This question is, however, not so simple, as it is not evidently proved that elements with lower atomic number than 30 do not show L-lines. Perhaps these lines have escaped detection owing to their considerably great wave-length.

In Table IX. there is an arrangement indicating, in accordance with what is said above, the most probable distribution of electrons between the inner and outer region in the first 23 elements. The first figure given for the respective elements indicates the number of electrons in the inner region and the second figure gives the number of electrons in the outer region. The elements are arranged in accordance with the periodic system.

\* Sommerfeld, *Phys. Z.* xix. p. 298 (1918).

TABLE IX.—Distribution of Electrons between the outer and inner regions.

	O.	I.	II.	III.	IV.	V.	VI.	VII.
H, 0, 1	He, 0, 2	Li, 0, 3	Be, 0, 4	B, 0, 5	C, 0, 2+4	N, 0, 7	O, 4, 4	F, 4, 5
	Ne, 4, 6	Na, 4, 7	Mg, 8, 4	Al, 8, 5	Si, 8, 2+4	P, 8, 7	S, 12, 4	Cl, 12, 5
	Ar, 12, 6	K, 12, 7	Ca, 16, 4	Sc, 16, 5	Ti, 16, 2+4	V, 16, 7		

As appears from the table, elements with similar chemical qualities will in this distribution of electrons have the same number of outer electrons—only the elements He and Li form exceptions to this rule,—and the periodicity exhibited by the Mendelejeff scheme comes out plainly. The hypothesis of Kossel \* regarding the arrangement of electrons in the atom also may be applied here. Instead of 8 electrons, 2 or 6 should, however, be the number of electrons which form a stabile outer ring. I will further discuss this question in a following paper. I only want to mention that the cause of the two periods of 8 elements at the beginning of the scheme seems to be that in the first four rearrangements taking place when the number of electrons is successively augmented, 4 electrons each time pass from the outer to the inner region.

To draw conclusions from the experiments related here regarding the arrangement of electrons within either of the two regions can hardly be possible. That the electrons of the inner region should be distributed to different rings (K-, L-, M-, etc. rings) is in no way in contradiction to the suppositions made here. Neither seems it unlikely that a similar formation of rings can take place also among the outer electrons. It is evident that the values given for the number of electrons of the different elements in the inner regions do not claim to be absolute, as they apparently only give the difference between the respective atomic number and the number of outer electrons.

Bragg and Peirce have, for the relation of the atomic number, established the following formula :

$$\kappa = K \cdot Z^4 \cdot \lambda^{5.2}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where K is a constant. Owen † shows that this formula gives better results if the values are corrected for scattering.

\* Kossel, "Über Molekülbildung als Frage des Atomhaus," *Ann. d. Phys.* xlix. p. 229 (1916).

† Owen, *Proc. Roy. Soc.* xciv. no. A 664, p. 552 (1918).

Thus we obtain :

$$\kappa_{a/\text{Cu}} = \left( \frac{Z_a}{Z_{\text{Cu}}} \right)^4 \cdot \cdot \cdot \cdot \cdot \quad (9)$$

Moore \* confirms this equation, but instead of the atomic number he puts the atomic weight ( $M$ ) ; consequently,

$$\bar{\kappa}_{a/\text{Cu}} = \left( \frac{M_a}{M_{\text{Cu}}} \right)^4 \cdot \cdot \cdot \cdot \cdot \quad (10)$$

Yet Moore admits that the determinations hitherto performed are not sufficiently exact to allow of asserting whether atomic weight or atomic number should properly appear in the formula.

Glocker † recently has derived the following formulæ for the mass absorption coefficient :

$$\frac{\bar{\mu}}{\rho} = 0.0004 Z^{3.14} \lambda^{2.8} \text{ for } \lambda > \lambda_A, \quad \cdot \cdot \cdot \quad (11)$$

$$\frac{\bar{\mu}}{\rho} = 0.0195 Z^{2.58} \lambda^{2.8} \text{ for } \lambda \leq \lambda_A, \quad \cdot \cdot \cdot \quad (12)$$

where  $\lambda_A$  indicates the wave-length of the absorption-zone limit for K-radiation. Now, as in all examined elements with  $Z < 47 \lambda_m < \lambda_A$ , it follows that  $\kappa_{a/\text{Cu}}$  for these elements might be calculated after the formula

$$\bar{\kappa}_{a/\text{Cu}} = \left( \frac{Z_a}{Z_{\text{Cu}}} \right)^{2.58} \frac{M}{M_{\text{Cu}}} \cdot \cdot \cdot \cdot \cdot \quad (13)$$

In Table XI. are arranged the values of  $\kappa_{a/\text{Cu}}$  which have been obtained from observations, mean amounts from Table VIII., with values of the same constant that have been calculated by the aid of the formulæ (7), (9), (10), and (13). In the formula (7) the values of  $K$  seen in the following table have been used.

TABLE X.—Values of  $K$  in Formula (7).

Group.	$Z$ .	Electrons of the inner regions.	$K$ .
I. ....	1-7	0	0.05
II. ....	8-11	4	0.26
III. ....	12-15	8	0.98
IV. ....	16-19	12	2.55
V. ....	20-23	16	6.42
VI. ....	24-28	18	9.00
VII. ....	29-46?	24	19.8

\* Moore, Phys. Soc. of London, xxvii. p. 432 (1918).

† Glocker, *Phys. Z.* xix. p. 71 (1918).

TABLE XI.

Comparison between observed and calculated values of  $\bar{\kappa}_a/\text{Cu}$ .

Element.	number. Z.	Atomic weight. M.	$\bar{\kappa}_a/\text{Cu}$ after Table VIII.	$K(Z-e)$ .	$100 \left( \frac{Z_a}{Z_{\text{Cu}}} \right)^4$ .	$100 \left( \frac{M_a}{M_{\text{Cu}}} \right)^4$ .	$100 \left( \frac{Z_a}{Z_{\text{Cu}}} \right)^{2.58} \frac{M_a}{M_{\text{Cu}}}$ .
H .....	1	1.0	—	—	—	—	—
Li .....	3	6.94	0.10	0.15	0.00	0.01	0.03
Be .....	4	9.1	0.20	0.20	0.04	0.04	0.09
B .....	5	11.0	0.25	0.25	0.09	0.09	0.19
C .....	6	12.0	0.33	0.30	0.18	0.13	0.32
N .....	7	14.0	0.32	0.35	0.34	0.24	0.56
O .....	8	16.0	0.41	1.04	0.58	0.40	0.91
F .....	9	19.0	1.50	1.30	0.93	0.80	1.46
Na .....	11	23.0	2.24	1.82	2.07	1.71	2.96
Mg .....	12	24.3	2.95	3.92	2.98	2.13	3.92
Al .....	13	27.1	4.87	4.90	4.04	3.30	5.37
Si .....	14	28.3	7.03	5.88	5.44	3.92	6.80
P .....	15	31.0	7.37	6.86	7.17	5.64	8.90
S .....	16	32.1	9.87	10.20	9.27	6.49	10.99
Cl .....	17	35.5	12.68	12.75	11.81	9.70	14.10

K .....	19	39.1	18.5	17.85	18.4	14.3	20.7
Ca .....	20	40.1	25.7	25.6	22.6	15.8	24.2
V .....	23	51.0	44.9	44.0	39.6	41.3	44.1
Cr .....	24	52.0	52.4	54.0	46.9	44.7	50.1
Mn .....	25	54.9	60.9	63.0	55.2	55.5	58.8
Fe .....	26	55.8	69.3	72.0	64.6	59.2	66.0
Co .....	27	59.0	83.1	81.0	75.1	74.1	77.1
Ni .....	28	58.7	92.5	90.0	87.0	72.5	84.3
Cu .....	29	63.6	100.0	99.0	100.0	100.0	100.0
Zn .....	30	65.4	114	119	114	112	112
As .....	33	75.0	166	178	168	193	165
Se .....	34	79.2	186	198	189	240	188
Br .....	35	79.9	203	218	212	249	201
Rb .....	37	85.4	265	257	265	325	252
Sr .....	38	87.6	285	277	295	360	277
Mo .....	42	96.0	371	356	441	519	392
Rh .....	45	102.9	445	416	580	685	503
Pd .....	46	106.7	493	—	633	793	550
Ag .....	47	107.9	527	—	690	828	590



From the table it appears that the values calculated by means of the formula (9) undoubtedly agree much better with the observed values than those obtained by means of the formula (10). The formula (9), as Owen using the values in my first paper also shows, approximately gives the relation between the relative atomic absorption coefficient and the atomic number of a great number of elements rather satisfactorily, but we cannot pretend that it has proved to be the proper expression of the real facts over the whole range of the section examined. For the elements Li-F they will thus turn out to be too low, for Ca-Ni all of the calculated values are lower than the observed, and for Sr-Ag all the calculated values are too high. On the whole, the Glocker's formula (13) describes the relation of  $\bar{\kappa}_{a/Cu}$  and  $Z$  in a better way than that just mentioned; but here, too, marked deviations occur, for instance at N, P, Cl, K, and for Ca-Ni as well as for Mo-Ag the same view will be true as for the formula (9), though the deviations here are considerably less.

Thus, although the atomic absorption coefficient in a great number of elements may be pronounced to be proportional to a power of the atomic number, such a formula, however, cannot render the real relation. From the above experiments it is clear that in certain elements there are some very marked discontinuities in the values of  $\bar{\kappa}_{a/Cu}$ , which in the lighter elements are still more marked by the change by sudden leaps of the absorption effected by scattering (fig. 4). As shown by Table XI. and fig. 2, the different elements may be arranged into groups within which  $\bar{\kappa}_{a/Cu}$  according to formula (7) is expressed as a linear function of the atomic number. Great deviations do not occur except at Mg and Si. In respect to the latter element, the probable cause of the deviation has already been discussed. As to the former element, the deviation presumably depends on the fact that in the examined salts absorption for about 80 per cent. is determined by the negative radicle, and that therefore the errors in determining the absorption of these radicles will proportionally too much influence the calculation of  $\kappa_{Mg/Cu}$ .

#### IV. Outer Electrons and Scattered Radiation.

It was shown previously that the part of the relative absorption coefficient which was thought to be due to the outer electrons is in a high degree dependent on the

wave-length. Now, as the mean wave-lengths employed in my experiments have only comprised a relatively limited wave-length range ( $\lambda=0.38-0.30$ ), the said experiments do not afford sufficiently safe starting-points for judging the connexion between absorption due to the outer electrons and the wave-length. Barkla and White have in their above-mentioned work given the results of a set of observations regarding  $\frac{\mu}{\rho}$  for Cu, Al, and  $H_2O$ , comprising a very large wave-length range. In the table below we find again both the values taken from the said work for  $\frac{\mu}{\rho}$  of Cu and  $H_2O$  and the values of  $\kappa_{Cu/H_2O}$  and  $q$  calculated by that means. The last-mentioned values have been obtained by aid of the value of  $\bar{\kappa}_{a/Cu}$  for Cu and O,

TABLE XII.

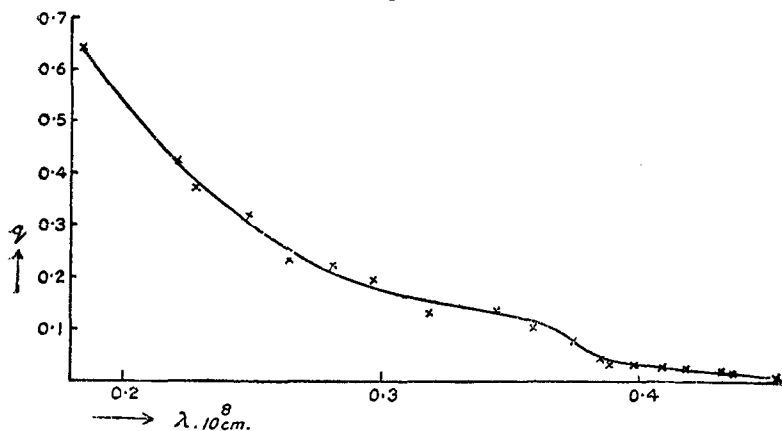
$\kappa_{Cu/H_2O}$  and  $q$  calculated from the table of Barkla and White.

$\lambda$ .	$\frac{\mu}{\rho}$ Cu.	$\frac{\mu}{\rho}$ $H_2O$	$\kappa_{Cu/H_2O}$	$q$ .	$q \frac{\mu}{\rho}$ Cu.	Mean.
0.504	18.10	0.539	118.7	-0.011		
0.499	17.7	0.524	119.4	-0.012		
0.477	15.4	0.479	113.6	-0.005		
0.468	14.55	0.473	108.7	+0.002		
0.460	13.75	0.436	111.5	-0.002		
0.454	13.10	0.411	112.7	-0.004		
0.437	11.6	0.400	102.5	+0.011		
0.433	11.2	0.388	102.0	0.012		
0.419	9.98	0.371	95.1	0.024		
0.409	9.28	0.349	94.0	0.024		
0.400	8.55	0.329	92.1	0.030		
0.390	7.82	0.302	91.5	0.031		
0.387	7.61	0.312	86.2	0.042		
0.376	6.90	0.335	72.8	0.078	0.538	0.678
0.359	5.87	0.311	66.7	0.100	0.587	
0.346	5.17	0.314	58.2	0.137	0.709	
0.320	4.54	0.270	59.4	0.131	0.594	
0.299	3.71	0.271	48.4	0.196	0.727	
0.283	3.20	0.253	44.7	0.226	0.723	
0.266	2.77	0.226	43.3	0.238	0.660	
0.250	2.33	0.229	35.9	0.320	0.722	
0.229	1.86	0.203	32.4	0.376	0.699	
0.222	1.71	0.204	29.6	0.423	0.723	
0.187	1.20	0.196	21.6	0.645	0.774	

assuming that there are 5 outer electrons in Cu and 6 in  $\text{H}_2\text{O}$ , consequently after the formula

$$\frac{100 + 5q}{0.91 + 6q} = \kappa_{\text{Cu}/\text{H}_2\text{O}} \cdot \cdot \cdot \cdot \cdot \quad (14)$$

Fig. 3.



It appears from the table that  $q$  practically is 0 for radiation of greater wave-length than  $\lambda = 0.42$ , which roughly indicates the limit of the absorption-zone in the J-radiation for carbon found by Barkla. With diminishing wave-length  $q$  increases, as shown in fig. 3, where the values of  $q$  found in Table XII. are graphically indicated, very rapidly to a wave-length of about 0.37, whereupon  $q$  continually increases with a still more diminishing wave-length. In regard to the fact that characteristic radiation of the wave-length indicated for J-radiation according to what has been mentioned by Siegbahn† has not been possible to state directly, there is good evidence for believing that this same increase of scattering within the range of  $\lambda = 0.42 - 0.37$  is the cause of the increase of absorption that has been the occasion of supposing an especial J-radiation.

It is seen from the table that  $q \frac{\mu}{\rho}_{\text{Cu}}$ , beginning at a wave-length of  $\lambda = 0.37$ , is nearly constant with a diminishing wave-length. Starting from the medium value (0.678) of the values found for  $q \frac{\mu}{\rho}_{\text{Cu}}$ , one readily finds the value of  $q$  when  $\frac{\mu}{\rho}_{\text{Cu}}$  for the wave-length in question

\* Siegbahn, *Die Naturwissenschaften*, Heft xxxiii. (1917).

is known. In the table below are arranged the values of  $q$  found in this way, from the table of Barkla and White, corresponding to values of  $\kappa_{\text{Al/H}_2\text{O}}$  (Obs.) calculated from the table referred to, and (Calc.) calculated by aid of my values of  $\bar{\kappa}_{\text{Al/Cu}}$  and  $\bar{\kappa}_{\text{O/Cu}}$  previously found thus, after the formula

$$\kappa_{\text{Al/H}_2\text{O}} = \frac{4.87 + 5q}{0.91 + 6q} \quad . \quad . \quad . \quad . \quad (15)$$

TABLE XIII.

Comparison between observed and calculated values of  $\kappa_{\text{Al/H}_2\text{O}}$ .

$\lambda$ .	$\frac{\mu}{\rho} \text{ Cu}$ .	$\frac{\mu}{\rho} \text{ Al}$ .	$\frac{\mu}{\rho} \text{ H}_2\text{O}$ .	$q = \frac{0.678}{\frac{\mu}{\rho} \text{ Cu}}$ .	$\kappa_{\text{Al/H}_2\text{O}}$ .		$\frac{4.87 + 6q}{0.91 + 6q}$ .
					Obs.	Calc.	
0.376	6.90	0.802 *	0.335	0.098	3.60	3.58	3.64
0.368	6.38	0.707	0.327	0.106	3.25	3.51	3.55
0.345	5.00	0.713	0.305 *	0.136	3.52	3.21	3.29
0.320	4.54	0.622 *	0.270	0.149	3.47	3.12	3.20
0.303	3.77	0.519	0.265 *	0.180	2.95	2.90	2.99
0.283	3.20	0.450 *	0.253	0.212	2.69	2.72	2.82
0.266	2.77	0.391	0.226	0.245	2.60	2.56	2.66
0.257	2.58	0.382	0.224	0.263	2.57	2.49	2.59
0.229	1.94	0.300	0.203	0.349	2.22	2.20	2.32
0.212	1.54	0.263	0.199	0.440	1.99	1.99	2.12
0.192	1.29	0.228	0.196 *	0.526	1.75	1.84	1.97
0.175	1.03	0.210	0.194 *	0.658	1.63	1.68	1.82
0.166	0.95	0.192	0.194 *	0.714	1.49	1.63	1.76

\* Inter- or extra-polated values.

There is a very good agreement between the observed and calculated values of  $\kappa_{\text{Al/H}_2\text{O}}$ , as the table shows. If we compare the values of  $q$  that have been calculated in the above way for the medium wave-length used in my experiments with the values resulting from the experiments, we obtain :

	I.	II.	III.	IV.
$q = \frac{0.678}{\frac{\mu}{\rho} \text{ Cu}}$	0.095	0.115	0.139	0.182
$q_{\text{obs.}}$	0.067	0.090	0.136	0.195

The values observed for  $q$  corresponding to the radiations

I. and II. being somewhat lower than those calculated may be due to the fact that, with a thinner filter, besides waves of shorter wave-lengths there have occurred rays of an appreciable intensity of greater wave-length than  $\lambda=0.37$ . As the found values of  $\kappa_{a/Cu}$  for the lighter elements have been calculated by aid of the observed values of  $q$  for the radiation referred to, no error can have originated in the fact that the wave-length range has partly extended beyond the limit just mentioned. From what is said it appears, however, that the formula  $\kappa=C+A\lambda^b$  is not applicable on different sides of the limit unless  $C$  gets the value corresponding to respective wave-length, and more especially this holds regarding the lighter elements, in which  $C$  plays a proportionally great part.

In case we assume that in Al 6, instead of 5, electrons are arranged as outer electrons, and accordingly  $\kappa_{Al/H_2O}$  is calculated by the formula  $\frac{4.87+6q}{0.91+6q}$ , the values stated in the last column of Table XIII. will be obtained. The agreement of the thus calculated and the observed values is for the greater wave-lengths about as good as in the case where the calculation is made after the formula (14); but, on the other hand, the agreement for the shorter wave-lengths is less good and shows a clear divergence.

If we believe that the number of electrons is the same as the atomic number, then with decreasing wave-length the limiting value for  $\kappa_{Al/H_2O}$  must be  $\frac{13}{10}$ . But Barkla and

White have shown that  $\frac{\mu}{\rho}$  for Al, in case of shorter waves, tends towards being less than for  $H_2O$ , and, in case of sufficiently short waves  $\kappa_{Al/H_2O}$  must be apt to be less than 1. If, according to the formula (15), we merely suppose 5 outer electrons in Al and 6 in  $H_2O$ , then  $\kappa_{Al/H_2O}$  will get the value of 1 when  $q$  has reached the value of 3.96; and as this value still increases with decreasing wave-length,  $\kappa_{Al/H_2O}$  will be  $<1$ . Thus we have reasons for believing that the number of outer electrons must be less in Al than in  $H_2O$ , and the observations (Table XIII.) show that the relation of these electron numbers may very closely be regarded as 5:6.

From the known values of  $q$  the mass scattering coefficient  $\left(\frac{s}{\rho}\right)$  may be calculated. According to what was

said above, it is admitted that

$$\kappa_{a/\text{Cu}} = \frac{\frac{\mu}{\rho} a M_a}{\frac{\mu}{\rho_{\text{Cu}}} M_{\text{Cu}}} = \frac{K_a + p_a q}{100 + p_{\text{Cu}} q},$$

or

$$\frac{\mu}{\rho} a = \frac{M_{\text{Cu}} \cdot K_a}{M_a (100 + p_{\text{Cu}} q)} \frac{\mu}{\rho_{\text{Cu}}} + \frac{M_{\text{Cu}} p_a q}{M_a (100 + p_{\text{Cu}} q)} \frac{\mu}{\rho_{\text{Cu}}}; \quad (16)$$

and as  $\frac{\mu}{\rho} = A\lambda^b + \frac{s}{\rho}$ , then will

$$\frac{s}{\rho} = \frac{M_{\text{Cu}} p_a q}{M_a (100 + p_{\text{Cu}} q)} \cdot \frac{\mu}{\rho_{\text{Cu}}}, \quad . \quad . \quad . \quad (17)$$

or as  $q \frac{\mu}{\rho_{\text{Cu}}} = 0.678$  and  $p_{\text{Cu}} q$  is supposed to be negligible,

$$\frac{s}{\rho} = \frac{M_{\text{Cu}}}{M_a} \cdot p_a \cdot 0.00678. \quad . \quad . \quad . \quad (18)$$

In the following table we again find the mass scattering coefficients for the elements 1-20, calculated by the formula (18).

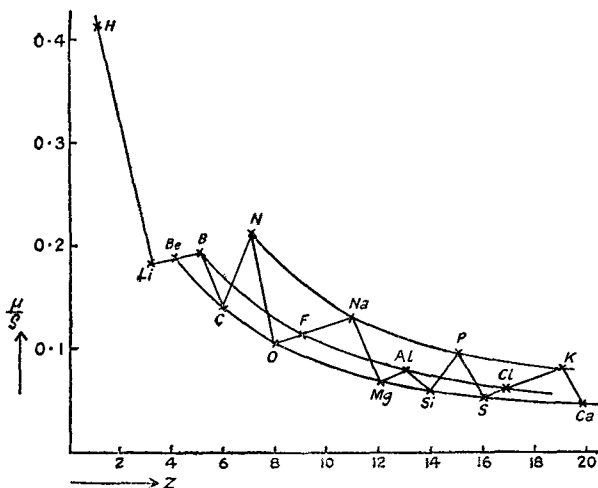
TABLE XIV.

Mass scattering coefficients for the elements 1-20.

Atomic number.	Element.	Number of outer electrons.	$\frac{s}{\rho}$ , calculated according to	
			formula (18).	formula (19).
Z.		p.		
1	H	1	0.432	0.205
3	Li	3	0.187	0.205
4	Be	4	0.190	0.205
5	B	5	0.196	0.205
6	C	4	0.144	0.137
7	N	7	0.216	0.205
8	O	4	0.108	0.103
9	F	5	0.114	0.114
11	Na	7	0.132	0.130
12	Mg	4	0.071	0.068
13	Al	5	0.080	0.079
14	Si	4	0.061	0.059
15	P	7	0.097	0.096
16	S	4	0.052	0.051
17	Cl	5	0.061	0.060
19	K	7	0.077	0.076
20	Ca	4	0.043	0.041

In fig. 4 the connexion between  $\frac{\mu}{\rho}$ , calculated by the formula (18), and  $Z$  is given graphically. As we find from the figure, the values, except for H and Li, are distributed to three hyperbolas corresponding to  $p=7$ ,  $p=5$ ,  $p=4$  respectively.

Fig. 4.



But in regard to H, the Table XIV. shows that the mass scattering coefficient also may be expressed by the formula

$$\frac{s}{\rho} = \frac{0.205p}{Z}. \quad . . . . . (19)$$

For elements, in case of which  $p=Z$ , that is identical with the known value given by Barkla for the light elements. In case of H, the formula (19) is not applicable and by means of it we get a value that is merely about half the real. This, however, is in good agreement with experience; for after what is shown by the experiments of Barkla and

Crowther,  $\frac{s}{\rho}$  is twice as great for H as for other lighter elements. The exceptional position seemingly occupied by H is in appearance only, and may be fully explained if one takes as granted that not all electrons which constitute the atom, but merely the outer ones, give off scattered rays. On the other hand, as has been clearly made out, not only by above-mentioned experiments on C, N, and O, but also

by the Barkla and White determinations of  $\frac{\mu}{\rho}$  for Al and H<sub>2</sub>O, the assumption that  $\frac{s}{\rho}$  for all light elements has the same value cannot be considered to be in harmony with reality; and still less, I think, can this be the case for the heavier elements, as was assumed by Hull and Rice. So it follows that all evidence of the assumption that the number of electrons in the lightest elements should be the same as the atomic number, which is based on the estimate of mass scattering coefficients, cannot be thought conclusive except perhaps for the elements H, Li, Be, B, and N.

Glocker has pointed out that  $\frac{s}{\rho}$  in case of Al must be less than 0.2, because already at the wave-length  $\lambda=0.16$  the uncorrected mass absorption coefficient  $\left(\frac{\mu}{\rho}\right)$  is 0.18, and  $\frac{s}{\rho}$ , as we know, can only be a part of the whole absorption coefficient. Now, for the lightest elements (Li, Be, B, N) the value 0.2 must undoubtedly be nearly correct; thus  $\frac{s}{\rho}$  cannot have the same value for all the lighter elements. As I have shown before (Table XIII.), the value 0.080 may well agree with the determinations of  $\frac{\mu}{\rho}$  by Barkla and White for Al.

As was previously pointed out (p. 183),  $\kappa_{\text{Pb/Cu}}$  rapidly increases with decreasing wave-length. This would, according to what has been said above, mean that absorption dependent on scattering is much greater in case of Pb than of Cu, *i. e.* that in an atom of Pb there would be present a considerably greater number of outer electrons than in an atom of Cu. Yet whether the simple law that defines the scattering power in case of the lighter elements be in force in case of the heaviest must for the present be left undecided. Presumably the electrons in case of the heavier elements are not active individually but in groups, as is the opinion of Barkla and White. By direct determinations of  $\frac{s}{\rho}$ , Barkla and Dunlop\* have shown

that  $\frac{\left(\frac{s}{\rho}\right)_{\text{Pb}}}{\left(\frac{s}{\rho}\right)_{\text{Al}}}$  is about 2 or 4 times greater than  $\frac{\left(\frac{s}{\rho}\right)_{\text{Cu}}}{\left(\frac{s}{\rho}\right)_{\text{Al}}}$ .

\* Barkla and Dunlop, Phil. Mag. xxxi. p. 222 (1916).



V. *Absorption and Scattering of  $\gamma$ -rays.*

Formula (18) is valid merely on condition that the term  $p_{\text{Cu}}q$  is so small relatively to 100 that it is negligible. Already, at a wave-length of  $\lambda=0.166$ , on the assumption that in Cu there are 5 outer electrons, absorption produced by scattering amounts to 3.4 per cent. of the whole absorption; and in case of a still shorter wave-length this part is very rapidly augmented. According to what was pointed out by Barkla and Glocker, absorption for the heavier elements will therefore in  $\gamma$ -radiation in a great measure, and for the lighter elements necessarily mostly, depend on scattering. When calculating  $\frac{s}{\rho}$  of  $\gamma$ -radiation, the term  $p_{\text{Cu}}q$  is therefore not negligible, and in this case formula (17) must be used.

Without too great a mistake we may assume that the ratio  $q \frac{\mu}{\rho}_{\text{Cu}} = 0.678$  is correct also for shorter wave-lengths than those given in Table XII.; then, in consequence, the value of  $q$  can be found when  $\frac{\mu}{\rho}_{\text{Cu}}$  is known. In Table XV. we again find the last-mentioned values for  $\gamma$ -rays emitted from some radioactive elements in accordance with determinations performed by Soddy and Russell. Indeed,  $\lambda_m$  may not be thought the same for the different substances, but the values of  $\frac{\mu}{\rho}$  showing that the difference cannot be very great, mean values for  $\frac{\mu}{\rho}_{\text{Cu}}$  may be used for approximate calculation. By aid of this mean value, 0.0407, we find  $q$  to be 16.7, which, put in formula (17), for Al gives the value 0.043. By direct observations, Ishino\* has for the same metal found the value 0.045, which very nearly agrees with the value calculated here.

When inserting the just-named value of  $q$ , also  $\kappa_{a/\text{Cu}}$  for Fe, S and Al may be calculated if the values found for  $\bar{\kappa}_{a/\text{Cu}}$  are assumed to be valid for  $\gamma$ -rays. Using the values given in Table VIII., and assuming that  $p$ -values for Al, S, Cu according to the above are 5, 4, 5 respectively, and for Fe 5, we in the same way as in the case of formula (14) obtain the values given in the table below. The assumption that there are 5 outer electrons in Fe is quite arbitrary, but

\* Ishino, Phil. Mag. xxxiii. p. 129 (1917).

in accordance with the circumstance that, as was previously stated (p. 191), the number may probably be less than 8.

TABLE XV.

$\kappa_{a/Cu}$  in  $\gamma$ -rays, according to Soddy and Russell.

Element.	Thorium D.		Radium C.		Mesothorium 2.		Uranium X.		Mean.	
	$\frac{\mu}{\rho}$	$\kappa_{a/Cu}$	$\frac{\mu}{\rho}$	$\kappa_{a/Cu}$	$\frac{\mu}{\rho}$	$\kappa_{a/Cu}$	$\frac{\mu}{\rho}$	$\kappa_{a/Cu}$	Obs.	Calc.
Cu .....	0.0334	100	0.0398	100	0.0423	100	0.0472	100	100	
Fe .....	0.0328	86.2	0.0399	87.9	0.0415	86.1	0.0472	87.8	87.1	83.7
S .....	0.0369	55.8	0.0438	55.6	0.0465	55.5	0.0516	55.2	55.5	41.7
Al.....	0.0324	41.3	0.0406	43.5	0.0421	42.4	0.0469	42.3	42.3	48.1
Paraffin-wax.	0.0361		0.0464		0.0580		0.0502			

Merely approximate calculations being here at issue, the agreement of the medium amounts of the observed and calculated values of  $\kappa_{a/Cu}$  seems to be as good as can reasonably be demanded, more especially when considering that determinations of  $\frac{\mu}{\rho}$  for  $\gamma$ -rays are in a high degree dependent on the experimental arrangements\*.

In the case of the lighter elements absorption of  $\gamma$ -rays will chiefly depend on the number of outer electrons, and this being the same or nearly the same the values of  $\frac{\mu}{\rho}$  for these elements must tend towards being the same. As for S, however, the observed absorption coefficients seem to be somewhat greater than what would have been expected on account of the above-assumed number of outer electrons; but this question, I think, ought to remain undecided till a wider range of observations on absorption of  $\gamma$ -rays is at hand.

The apparent anomaly that has been observed in respect to absorption in paraffin-wax, and that consists in  $\frac{\mu}{\rho}$  for this substance being equally great or even on some occasions greater than for the heavy metals, may be explained in the same way as was done for absorption of X-rays of very short wave-length in case of Al and  $H_2O$ . In paraffin-wax there are, as we know, a great number of hydrogen atoms—a fact that makes the number of outer electrons greater, counted by mass unit, than in metals.

\* Comp. Kohlrausch, *Jahrb. d. Rad. u. Elektronik*, xv. p. 93 (1918).

Taking as granted that scattering merely depends on outer electrons, we thus can easily account for the observations performed. It may therefore be superfluous to assume that the electrons should behave otherwise for different wave-lengths. On the contrary, we have every reason for believing, a fact advocated by Glocker, the simple law that was found valid for X-rays also to be in force for  $\gamma$ -rays.

*Summary.*

(1) By aid of the compensation method described by the author for the purpose of determining the relative absorption coefficients of X-radiation, a number of different elements have been examined.

(2) In the chemical compounds examined the additive law has been found thoroughly valid. Perhaps with the exception of carbon, the state of aggregation appears to have had no influence on the quantity of absorption. In examining chemical compounds of which the same element but in different valences is a constituent part, I have not been able to ascertain any difference as to the quantity of absorption of the element at issue.

(3) The relation between the atomic absorption coefficients for most elements, starting from H and inclusive of Ag and for Pb, and the same coefficient for Cu, have been determined at the medium wave-lengths  $\lambda = 0.38, 0.36, 0.34$ , and  $0.30 \cdot 10^{-8}$  cm.

(4) On assuming that absorption for H is exclusively due to scattering produced by the electron combined with the atomic nucleus, scattering for other elements has been found likely to be solely due to the electrons constituting the outer layer of the respective atoms, *i. e.* to the "outer electrons," and by aid of the relative atomic absorption coefficient for H, the number of the outer electrons has been estimated for the lighter elements.

(5) The atomic absorption coefficient increases for different elements by groups nearly proportionally to the atomic number. If we accept that the atomic number gives the number of electrons combined with the atomic nucleus, we may by the increase of absorption with increasing atomic number determine the distribution of electrons between the outer and inner region.

(6) From the determinations of  $\frac{\mu}{\rho}$  for Cu and  $H_2O$  of Barkla and White a formula of the mass scattering coefficient for different elements has been calculated.

(7) The values calculated for the relative absorption coefficients for  $\gamma$ -rays agree fairly with the observed absorption coefficients. The value of mass scattering coefficient of Al for  $\gamma$ -radiation, calculated by means of the said formula, agrees very nearly with the value directly observed by Ishino.

(8) The number of the outer electrons in the lighter elements seem to be the same for the element placed in the same vertical row of the periodic system; and the distribution of electrons thus appears to be in close connexion with the periodicity of the chemical qualities of the elements as expressed by this system.

Nobel Institute for Physical Chemistry,  
Stockholm, June 1918.

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XVIII. *Calculation of Scattered Radiation from a Plate exposed to a beam of X-rays.* By OSKAR KLEIN, *Lic. phil.*\*

IN a paper treating of the absorption and scattering of  $\gamma$ -rays, Ishino† has undertaken a few theoretical calculations of scattered radiation issuing from the layer of a substance. Such calculations combined with measurements of the radiation scattered within known solid angles would lead to a determination of the scattering coefficient.

Some time ago T. E. Aurén, in connexion with his researches on the absorption of X-rays, performed some experiments in this direction. He measured the absorption coefficient in different positions of the plate exposed to the primary radiation. If the scattered radiation had been of any considerable amount, he would have found different values for the apparent absorption coefficient in the different positions. Now the differences were very small. Therefore it was of interest to Aurén to know how far this was in agreement with the theory. For this purpose I have undertaken the calculation below. As mathematical formulæ are obtained which may be used in numerical calculation, the results may perhaps have a certain interest for those who treat these questions experimentally. In this connexion it must be mentioned that Ishino in his paper just cited has made an error in reckoning, which has caused his final value to take the

\* Communicated by the Author.

Since this paper was finished and sent to the *Phil. Mag.* a quite similar calculation has been published by Glocher, *Phys. Zeitschr.* xix. p. 251 (1918).

† Ishino, *Phil. Mag.* vol. xxxiii. p. 129 (1917).