On the Self-Demagnetizing Factor of Bar Magnets.

as those for the bars of circular section. Rectangular rods of the softest Swedish iron of various proportions were procured, and reduced by milling-cutter to the required form, so as in every case to have a sectional area of 1 square centimetre; the ratios of breadth to thickness being respectively 1:1; 2:1; 4:1; 6:1, and 10:1. From each of these rectangular rods pieces were cut of lengths of 10, 8, 6, 5, 4, and 3 centimetres respectively. In all 95 different ones were examined. For each of these a B-H curve was plotted; and the self-demagnetizing-factors were deduced as before.

In figs. 3, 4, 5, 6, 7, and 8 these various curves are plotted; and in fig. 9 the final results are summed up by plotting the several demagnetizing-factors as functions of \( \lambda \) the ratio of the length to the square-root of the area of section.

Table II. gives numerically the values of the self-demagnetizing factors obtained for various ratios of breadth \( b \) to thickness \( t \) of the cross-section, and also for various values of \( \lambda \). The individual bars were carefully gauged for breadth and thickness, and the slight discrepancies (never exceeding 1 per cent. of the intended ratio) were allowed for; but being small they occasioned no difference in the plotting.

**Table II.—Demagnetizing Factors for Bars of different lengths and equal Sectional Area, having Rectangular Sections from 10:1 to 1:1.**

<table>
<thead>
<tr>
<th>( \frac{1}{\sqrt{\lambda}} = 3 )</th>
<th>( \frac{1}{\sqrt{\lambda}} = 4 )</th>
<th>( \frac{1}{\sqrt{\lambda}} = 5 )</th>
<th>( \frac{1}{\sqrt{\lambda}} = 6 )</th>
<th>( \frac{1}{\sqrt{\lambda}} = 8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b/t )</td>
<td>( N )</td>
<td>( b/t )</td>
<td>( N )</td>
<td>( b/t )</td>
</tr>
<tr>
<td>10 03/1</td>
<td>0-823</td>
<td>10/1</td>
<td>0-838</td>
<td>10 05/1</td>
</tr>
<tr>
<td>5 03/1</td>
<td>0-925</td>
<td>5 08/1</td>
<td>0-956</td>
<td>5 09/1</td>
</tr>
<tr>
<td>3 08/1</td>
<td>1-002</td>
<td>3 09/1</td>
<td>1-020</td>
<td>3 28/1</td>
</tr>
<tr>
<td>2 01/1</td>
<td>1 08</td>
<td>2 1/1</td>
<td>0-675</td>
<td>2 2/1</td>
</tr>
<tr>
<td>1 09/1</td>
<td>1-03</td>
<td>1 09/1</td>
<td>0-080</td>
<td>1 28/1</td>
</tr>
<tr>
<td>0 99/1</td>
<td>1-13</td>
<td>0 00/1</td>
<td>0-8</td>
<td>0 99/1</td>
</tr>
</tbody>
</table>

It will be noticed that the Table records values also for bars having the ratio of 1 5:1; but no curves are given for this ratio, as they were practically the same as those for square bars. In plotting the B-H curves for these particular bars, it was possible in two cases only to distinguish the curves from those for the square bars, and in these two cases the difference was extremely small.

For equal values of the ratio of \( l \) to \( \sqrt{A} \), it was found in general that the self-demagnetizing factor, for bars having a sectional ratio of 2 to 1, was about 93 per cent. of that for bars of square section; while for flat bars, having a sectional ratio of 10 to 1, the value of the self-demagnetizing factor went down to about 75 per cent. of that for bars of square section.

**LXIX. The Absorption of Röntgen Rays.**

By C. G. Barkla, M.A., D.Sc., Lecturer in Advanced Electricity, and C. A. SADLER, M.Sc., Olivier Lodge Fellow, University of Liverpool.

The results of experiments that have been made by a number of investigators on the absorption of X-rays are so complicated by a variety of conditions, and frequently appear so inconsistent, that few general conclusions can be drawn from them.

The heterogeneity of the beams used not only masks any peculiarity in the phenomena connected with a particular constituent, but makes exact comparison between the results of different experimenters, and even of the same experimenter, impossible.

In addition to this, as recent investigations have shown, there are peculiarities in the absorption phenomena which are intimately connected with certain phenomena of secondary radiation; and a knowledge of these is necessary in order to classify and explain the former.

Through our investigations on the secondary X-rays emitted by substances subject to X-rays, we have been enabled to use almost perfectly homogeneous beams, and have become acquainted with the character of the secondary radiation emitted by many elements.

It has been found that each of the elements Cr, Fe, Co, Ni, Cu, Zn, As, Se, Ag, when subject to a suitable primary beam of X-rays, emits an almost perfectly homogeneous beam of

* Communicated by the Authors.

The expenses of this research have been partially covered by a Government Grant through the Royal Society.—C. G. B.

Dr. C. G. Barkla and Mr. C. A. Sadler on

X-rays *, the penetrating power of which is characteristic of the element emitting it. As these penetrating powers vary considerably—the radiation from Cr being very soft and that from Ag fairly penetrating—the above metals furnish us with a series of nine homogeneous beams which can conveniently be used for accurate investigations of many X-ray phenomena. The variation in penetrating power is shown by the following values for the coefficient of absorption in aluminum of each radiation, the coefficient λ being defined by the equation \[ I = I_0 e^{-\lambda x} \].

<table>
<thead>
<tr>
<th>Radiator</th>
<th>Coefficient of Absorption in Al (( \rho = \text{density of Al} ) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>136 ( \rho )</td>
</tr>
<tr>
<td>Fe</td>
<td>88.5 ( \rho )</td>
</tr>
<tr>
<td>Co</td>
<td>71.6 ( \rho )</td>
</tr>
<tr>
<td>Ni</td>
<td>59.1 ( \rho )</td>
</tr>
<tr>
<td>Cu</td>
<td>47.1 ( \rho )</td>
</tr>
<tr>
<td>Zn</td>
<td>39.4 ( \rho )</td>
</tr>
<tr>
<td>As</td>
<td>22.5 ( \rho )</td>
</tr>
<tr>
<td>Se</td>
<td>18.9 ( \rho )</td>
</tr>
<tr>
<td>Ag</td>
<td>2.5 ( \rho )</td>
</tr>
</tbody>
</table>

**Phenomena of Transmission.**

Before attempting to make accurate experiments on the absorption of these radiations by various elements, it is necessary to know something of the phenomena accompanying the transmission of X-rays through absorbing substances.

The secondary X-ray phenomena, which have an important bearing on experiments on absorption, may be stated briefly as follows:

When a beam of X-rays is transmitted through any substance, secondary X-rays of the same penetrating power are emitted by that substance in all directions. The distribution of this radiation has, in all the cases investigated, been found to be approximately that expected from a theory of scattering on the ether-wave theory.

In addition to this, many elements—possibly all when subject to a suitable primary radiation—emit a homogeneous X-radiation which is characteristic of the element emitting it, its penetrating power being independent of that of the primary radiation exciting it.

A primary radiation excites this homogeneous radiation only when it—the primary—is of more penetrating type than the homogeneous radiation.

Regarding the distribution of this type of radiation, it has been shown by one of us * that when a polarized beam of Röntgen radiation is incident on Fe, Cu, Sn, Pb, &c., the homogeneous secondary radiation which is emitted is equally intense in directions in and perpendicular to the plane of that polarization—that is, the intensity of secondary radiation in any direction is independent of the position of the plane of polarization of the exciting primary beam.

Again, the homogeneous radiation from these metals has been found equally intense in a direction perpendicular to the direction of propagation of the primary, and one almost opposite to that of primary propagation †.

It is thus evident, and it has since been further verified, that the homogeneous radiation is equally intense in all directions.

Now the energy of this secondary radiation is so great that in many experiments it would produce enormous errors if not taken into consideration. In measuring the intensity of a beam of X-rays transmitted through an absorbing substance and proceeding in the original direction of propagation, it is therefore necessary either to so arrange the apparatus that the effect of the secondary rays may be neglected or to make a correction for it.

It was also important to ascertain if the beam emerging from the absorbing plate and proceeding in the original direction of propagation was identical in properties with the incident beam, or if it was transformed in any manner.

A few simple experiments showed that all the phenomena observed when a homogeneous beam of X-rays was transmitted through a metal plate placed before the detecting electroscope could be explained qualitatively simply by considering the superposition of the secondary radiation

* Mixed with the homogeneous radiation is an exceedingly weak scattered radiation of the same penetrating power as the primary radiation, but the ionization produced by this is usually negligible in comparison with that of the homogeneous radiation—in certain cases not more than 1 per cent. The radiation from Ag was transmitted through Al in order to get rid of most of the scattered radiation.

on the primary radiation, diminished in intensity by transmission.

All the phenomena observed may be divided into two groups:

(1) When a radiation was transmitted through an element whose characteristic secondary radiation was of an equally or more penetrating type, or through an element from which this type of radiation has not been observed, the emergent radiation was identical with the incident radiation.

(2) When a radiation was transmitted through an element whose characteristic radiation was of more absorbable type, the emergent radiation differed from the incident beam in penetrating power.

The following are a few examples of these types of transmission. The first three exhibit no change after transmission, the last three a considerable change.

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Substance through which the radiation was transmitted</th>
<th>Percentage Absorption by transmission</th>
<th>Substance used to test absorbability</th>
<th>Percentage Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Cu</td>
<td>0</td>
<td>Cu (00087 cm.)</td>
<td>25.4</td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td>74</td>
<td></td>
<td>25.8</td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td>0</td>
<td>Zn (00203 cm.)</td>
<td>68.7</td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td>97</td>
<td></td>
<td>68.2</td>
</tr>
<tr>
<td>Ag</td>
<td>Al</td>
<td>16</td>
<td>Al (0208 cm.)</td>
<td>13.8</td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td>92</td>
<td></td>
<td>13.8</td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td>97</td>
<td></td>
<td>14.2</td>
</tr>
<tr>
<td>Ag</td>
<td>Fe</td>
<td>0</td>
<td>Fe (00215 cm.)</td>
<td>30.8</td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td>51</td>
<td></td>
<td>37</td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td></td>
<td></td>
<td>30.1</td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td>0</td>
<td>Al (0208 cm.)</td>
<td>14.5</td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td>51</td>
<td></td>
<td>21.7</td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td>0</td>
<td>Al (0104 cm.)</td>
<td>72</td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td>97</td>
<td></td>
<td>85.6</td>
</tr>
</tbody>
</table>

From these and many other instances it became evident that only in those cases of transmission in which the primary radiation was able to stimulate a homogeneous secondary radiation was there any appreciable difference between the penetrating powers of the incident and emergent beams. It remained, however, to show that this change was simply due to the superposition of the homogeneous secondary radiation on the primary, and that the primary was itself unaltered.

As an example, Ag radiation, after the scattered rays had been sifted out, was absorbed to the extent of 14.5 per cent. by a sheet of Al·0208 cm. in thickness; but after transmission through Fe—51 per cent. being absorbed—the transmitted radiation was absorbed by 21.7 per cent. by the same sheet of Al. It thus appeared much softer. It was seen, however, that this emergent radiation still consisted of an untransformed Ag radiation with a more easily absorbed radiation superposed. For when the transmitted radiation was again passed through a sheet of Al·0208 cm. thick, the easily absorbed Fe radiation was absorbed completely and the transmitted radiation was again practically pure Ag radiation, being absorbable to the extent of 14.5 per cent. by the same sheet of aluminium.

In order to ascertain if the constitution of the emergent beam in such a case could be quantitatively accounted for, the following simple experiment was made:

A thin sheet of Fe was placed in the path of the homogeneous radiation from Cu, so that the angle of incidence of the central ray was about 20° (Fig. 1).

An electroscope capable of being rotated about a vertical axis through the centre of the Fe sheet B (set in a lead screen) was placed successively in the two positions D₁ and D₂. In position D₁ it received the direct beam after passing through the thin Fe sheet, and a portion of the secondary radiation emerging from the iron sheet, the central ray being inclined at an angle of about 20° to the normal; in position D₂ it received only the secondary radiation which emerged from the sheet at the same angle on the other side of the normal.

The two secondary beams then suffered approximately the same absorption on emerging from the iron plate.

The ratio of the ionizations in the electroscope in positions
the Absorption of Röntgen Rays.

If $A$ is the area of the primary beam, the energy of the secondary radiation emitted by a thin layer of thickness $dx$ in unit time is $kA dx$.

where $k$ is a constant depending on the character of the incident radiation and on the material of the plate. It will be called the transformation coefficient $k$.

But of this the fraction $\frac{\omega}{4\pi} e^{-\lambda_{i}(t-x)}$ enters the electroscope,

where $\omega$ is the average solid angle subtended by the aperture into the measuring electroscope at points in this layer, and $\lambda_{i}$ is the coefficient of absorption of the secondary radiation in the substance of the plate itself, when the effect of obliquity of the secondary rays and the absorption in air and the thin window may be neglected.

![Fig. 2.](image)

The total energy of secondary radiation entering the electroscope per second

$$= \int_{0}^{t} \frac{\omega}{4\pi} kA e^{-\lambda_{i}(t-x)} dx$$

$$= \frac{\omega}{4\pi} kA I_{0} e^{-\lambda_{i} t} \int_{0}^{t} \left( e^{\lambda_{i} x} - e^{-\lambda_{i} x} \right) dx$$

$$= \frac{\omega k}{\lambda_{i}} \frac{AI_{0}}{4\pi} \left( e^{-\lambda_{i} t} - e^{-\lambda_{i} x} \right)$$

Energy of Secondary Radiation entering electroscope

Energy of Primary Radiation entering electroscope

$$\frac{\omega k}{\lambda_{i}} \frac{AI_{0}}{4\pi} \left( e^{-\lambda_{i} t} - e^{-\lambda_{i} x} \right)$$

$$= \frac{\omega k}{\lambda_{i}} \frac{AI_{0}}{4\pi} e^{-\lambda_{i} t}$$

* This coefficient is so called by analogy with the absorption coefficients $\frac{dE}{dx} = -\lambda I$, where $-dE$ is the energy emitted by a thin layer of unit area and thickness $dx$ in unit time.
But the ionizations produced by these beams are not proportional to their energies, as they have different penetrating powers. If \( i_1 \) and \( i_2 \) represent the relative numbers of ions produced by the two beams, if of equal intensity and cross-section, in a thin layer of air,

\[
\frac{\text{Secondary Ionization}}{\text{Primary Ionization}} = \frac{ak}{4\pi(\lambda_2 - \lambda_1)} \frac{i_2}{i_1} [1 - e^{-(\lambda_2 - \lambda_1)k}]
\]

All possible cases can be divided into three classes:

1. When a homogeneous primary radiation passes through a plate of an element whose characteristic radiation is of equal or greater penetrating power, no appreciable secondary radiation of this type is emitted, i.e. \( k = 0 \). The secondary radiation characteristic of the absorbing element is then present in the transmitted radiation, and this exhibits no special powers of penetration.

This type of transmission occurs when the radiation from Cr passes through C, Mg, Al, Fe, Ni, Cu, &c., or when Cu radiation passes through Cu, Zn, Ag, &c.

2. When a homogeneous primary radiation passes through a plate of an element whose characteristic radiation is of more absorbable type and more absorbable in the plate itself than is the primary radiation, then the secondary radiation is excited, \( k \) is finite and \( \lambda_2 - \lambda_1 \) is positive.

In this case, as the thickness of the absorbing plate is increased, the beam received by the spectroelectrode gradually approaches a final constitution in which the ratio of the energies of secondary and primary radiations is

\[
\frac{\omega}{4\pi} \frac{k}{(\lambda_2 - \lambda_1)}.
\]

Such conditions are obtained when a radiation much more penetrating than the radiation characteristic of an element passes through that element, as when radiation such as is emitted by Ag is transmitted through Fe, Ni, Cu, Zn, &c.

3. When a homogeneous radiation passes through an element whose characteristic radiation is of more absorbable type, but more penetrating to the element emitting it, \( k \) is again finite and \( \lambda_2 - \lambda_1 \) is negative.

In this case, as the thickness of the absorbing plate is increased, the ratio of the energy of secondary radiation to that of the primary radiation increases indefinitely; that is, the primary radiation becomes ultimately transformed into radiation characteristic of the absorbing substance.

The absorption of Röntgen rays.

Such a transformation occurs when a radiation like that characteristic of Se passes through Zn, Cu, Ni, Fe, &c., or the radiation characteristic of Cu is transmitted through Fe.

Absorption Experiments.

In the experiments which were made to determine the true absorption of homogeneous beams, the radiator \( R \), used to produce the beam, was placed at a distance of about 7 centimetres from a rectangular aperture \( A_1 \) (3 cm. x 2 cm.) in a lead screen. A second lead screen with a similar rectangular aperture \( A_2 \) was placed at a distance of 7 centimetres from the other, and behind the second aperture was placed the thin paper and aluminium face of the spectroelectrode used to measure the intensity of the beams.

The absorbing plates were placed across the aperture \( A_1 \).

As the radiation from \( R \) necessarily produced a diverging beam, only a portion of the energy passing through \( A_1 \) passed through the aperture \( A_2 \); consequently the secondary radiation from the plate produced greater proportional effects than that calculated for a parallel beam. The ratio of the ionizations due to the secondary and primary beams had to be multiplied by a factor which expresses the ratio of the energy passing through aperture \( A_1 \) to that passing through aperture \( A_2 \) when no absorbing plate intervened. This was found to be about 4:9.

Thus

\[
\begin{align*}
\text{Secondary Ionization} &= 4:9 \times \frac{\omega}{4\pi} \lambda_2 - \lambda_1 \frac{i_2}{i_1} [1 - e^{-(\lambda_2 - \lambda_1)k}] \\
\text{Primary Ionization} &= 4:9 \times \frac{\omega}{4\pi} \lambda_1 \frac{i_2}{i_1} \lambda_2 - \lambda_1 \frac{1 - e^{-(\lambda_2 - \lambda_1)k}}{\lambda_2 - \lambda_1} \text{approximately.}
\end{align*}
\]

Now, \( \frac{k}{\lambda_1 i_1} \) may be got by direct experiment, for \( \frac{k}{\lambda_1 i_1} \) is merely the fraction of the energy of primary radiation absorbed which is transformed into or which appears as secondary radiation—as measured by the ionizations produced in a thin film of air.

\( \lambda_2 \) has been determined by one of us by direct experiment; \( \lambda_2 \) was determined by using the absorbing substance as a radiator also, and so observing the absorption of the radiation characteristic of the substance by the same substance—this, of course, required no correction for secondary absorption.

Radiation; \( \lambda \) was determined approximately without the application of the correction term.

Thus as an example—

When As radiation was transmitted through Cu,

\[
\left( \frac{\lambda_2}{\lambda_1} \right) = 368 \times \frac{128.9}{60.7}
\]

\( \lambda_1 \) or As\( \lambda \) Cu = 169 \( \times \) \( \rho \) Cu.

\( \lambda_2 \) or Cu\( \lambda \) Cu = 53 \( \times \) \( \rho \) Cu.

\[
(\lambda_2 - \lambda_1) = -116 \times \rho \text{Cu} = -1038.
\]

Secondary Ionization

Primary Ionization

= 4.9 \times 0.01 \times 368 \times \frac{128.9}{60.7} \times \frac{1}{1 - e^{1038/1000}}

= 0.06 approximately.

The ionization in the electroscope due to the primary beam when the absorbing plate of Cu was in position was thus found to be about 0.6 per cent. less than the observed ionization. Similar corrections were made in the other cases of transmission in which a secondary radiation characteristic of the absorbing substance was set up. The maximum correction affected the absorption coefficient by about 4 per cent.

A correction was also necessary in a few cases for the presence in the radiation from Cr of the weak heterogeneous scattered radiation. Though in most experiments the effect of this was inappreciable, when the absorbing plates used absorbed over 90 per cent. of radiation, the much more penetrating scattered rays having been only slightly absorbed appeared in much higher proportion than normally, and introduced an error.

By absorbing the radiation from Cr by various thicknesses of Al and comparing the absorption coefficients calculated from these absorptions, the error introduced in the case of the higher absorptions was obtained. A curve was plotted giving the error corresponding to any particular absorption. This correction was then applied to the calculated values of the absorptions by C, Ag, and Sn—substances which absorb similarly to Al. In no other case could the error, due to the same cause, have been more than 1 or 2 per cent., \( \lambda \), and that in one or two cases only. The values finally obtained for the coefficients are given in the following table. As the

* As\( \lambda \) Cu means the coefficient of absorption of the radiation from As by Cu.

The absorptions by Pt and Au of the radiation from Cr are excepted. These were too high to be relied upon. The value given in the table for Pt was obtained not by experiment, but by calculation from the observed ratio between the absorption coefficients.

The Absorption of Röntgen Rays.

value of \( \lambda \) varies as the density of the absorbing element, the values of the more fundamental quantity \( \frac{\lambda}{\rho} \) are tabulated, \( \rho \) being the density of the absorbing element. The quantity \( \lambda \) \( \rho \) may be called the mass coefficient of absorption.

**Table I.**

<table>
<thead>
<tr>
<th>Radiator</th>
<th>C</th>
<th>Mg</th>
<th>Al</th>
<th>Fe</th>
<th>Ni</th>
<th>Cu</th>
<th>Zn</th>
<th>Ag</th>
<th>Sn</th>
<th>Pt</th>
<th>Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>15.3</td>
<td>129.5</td>
<td>136</td>
<td>103.8</td>
<td>129</td>
<td>143</td>
<td>170.5</td>
<td>580.5</td>
<td>713.7</td>
<td>[507-6]</td>
<td>[507-9]</td>
</tr>
<tr>
<td>Fe</td>
<td>19.1</td>
<td>86.5</td>
<td>85.2</td>
<td>69.2</td>
<td>58.8</td>
<td>95.1</td>
<td>112.5</td>
<td>341</td>
<td>472</td>
<td>340</td>
<td>307</td>
</tr>
<tr>
<td>Co</td>
<td>7.25</td>
<td>71.6</td>
<td>76.2</td>
<td>67.2</td>
<td>75.3</td>
<td>91.5</td>
<td>314</td>
<td>352</td>
<td>321</td>
<td>251</td>
<td>305</td>
</tr>
<tr>
<td>Ni</td>
<td>6.58</td>
<td>51.1</td>
<td>59.1</td>
<td>53.4</td>
<td>56.9</td>
<td>61.8</td>
<td>74.4</td>
<td>292</td>
<td>328</td>
<td>235</td>
<td>223</td>
</tr>
<tr>
<td>Cu</td>
<td>5.22</td>
<td>41.4</td>
<td>47.7</td>
<td>263</td>
<td>62.7</td>
<td>53.0</td>
<td>60.9</td>
<td>214</td>
<td>272</td>
<td>194</td>
<td>210</td>
</tr>
<tr>
<td>Zn</td>
<td>4.36</td>
<td>34.7</td>
<td>39.4</td>
<td>221</td>
<td>265</td>
<td>55.5</td>
<td>50.1</td>
<td>175</td>
<td>225</td>
<td>125</td>
<td>178.2</td>
</tr>
<tr>
<td>As</td>
<td>9.49</td>
<td>19.3</td>
<td>22.5</td>
<td>134</td>
<td>166</td>
<td>176</td>
<td>203.5</td>
<td>105.3</td>
<td>131.5</td>
<td>105.7</td>
<td>100.1</td>
</tr>
<tr>
<td>Se</td>
<td>2.04</td>
<td>15.7</td>
<td>18.9</td>
<td>119.3</td>
<td>141.3</td>
<td>149.8</td>
<td>174.6</td>
<td>37.5</td>
<td>112</td>
<td>90.9</td>
<td>100.0</td>
</tr>
<tr>
<td>Ag</td>
<td>4.1</td>
<td>22</td>
<td>25</td>
<td>174</td>
<td>22.7</td>
<td>24.3</td>
<td>27.1</td>
<td>13.3</td>
<td>16.5</td>
<td>65.6</td>
<td>61.4</td>
</tr>
</tbody>
</table>

![Fig. 3 (p. 750)](image)

Fig. 3 (p. 750) exhibits the relation between the mass coefficients of absorption in a number of elements and the mass coefficient of absorption in Al—the former being plotted as ordinates and the latter as abscissae.

**Discussion of Results.**

In studying these results it is necessary to know something of the secondary rays emitted by the various absorbing substances.

C, Mg, and Al are elements from which a characteristic secondary radiation has not yet been observed. They certainly do not emit such a radiation in appreciable intensity when subject to ordinary beams of X-rays, unless the be in the form of exceedingly soft radiation, much softer than that of chromium, and such as would be absorbed in a thin layer of air. There is, however, the possibility, if not the probability, of the emission of such a radiation from all elements.
Subject to a primary more penetrating than any radiation here used. The results obtained are not consistent with the view that the elements are more penetrating or just more penetrating than the elements of Ag, Pt, and Au. It would be found that a radiation which is not consistent with the view that the elements are more penetrating or just more penetrating than the elements of Ag, Pt, and Au.

Table II.

<table>
<thead>
<tr>
<th>Element</th>
<th>Absorption Coefficient</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Pt</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Pt</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

On examining the results obtained from the preliminary experiments, it appears that the radiation from Ag, Pt, and Au is more penetrating than that from As. Moreover, it is seen that the absorption coefficients of the primary radiation are approximately equal to the absorption coefficients of the secondary radiation.

B and C. The equation $a = a' \times a''$ gives the ratio of the coefficient of absorption in each absorbing substance used in these experiments. The relationship is, however, more clearly shown by the curves in Fig. 3.

Fig. 2.

Dr. G. B. Dalziel and Mr. C. A. Shaler on the Absorption of X-Rays.

Dr. G. B. Dalziel and Mr. C. A. Shaler on the Absorption of X-Rays.

Fe, Ni, Cu, and Zn are among the elements from which a homogeneous characteristic radiation is obtained in considerable intensity, when the primary beam is of ordinary penetrating power. Ag emits a homogeneous radiation when the primary beam is of ordinary penetrating power, but this is not the case when the primary beam is of ordinary penetrating power.

Dr. G. B. Dalziel and Mr. C. A. Shaler on the Absorption of X-Rays.

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It is also seen that in the cases of absorption which result in the emission of the secondary radiation characteristic of the absorbing substance there is considerable deviation from this relationship, the absorption being invariably greater by a considerable amount than would be produced if the simple proportionality still held. There is thus a special absorption and a very large one invariably connected with the emission of the secondary radiation which is characteristic of the absorbing element.

The point is so important that one curve will be treated in detail as typical of all substances. Beginning with a very soft homogeneous primary radiation, the absorption in a substance B (say) is considerable. As the radiation is made more penetrating the absorption in aluminium and in B diminish proportionately, as shown by the portion of the curve PQ (fig. 4). This proportionality continues until the primary radiation is just as penetrating as the secondary radiation characteristic of the substance B. When the incident radiation is made more penetrating than the secondary radiation characteristic of the absorbing substance B, the absorption first ceases to diminish as rapidly as the absorption in Al, then it increases along RS. At the same time the secondary radiation characteristic of B begins to be emitted, and rapidly increases. As the primary radiation becomes still more penetrating, the absorption in B begins to diminish as along ST, and the intensity of the secondary radiation diminishes at the same rate as the ionization produced by the primary radiation in air, which is probably at approximately the same rate as the absorption in air and consequently in Al, over the range of penetrating powers experimented upon.

The portion of the ordinates above PO may be regarded as representing the absorption in the substance B which is connected with the emission of the secondary radiation characteristic of B. We may thus divide the absorption coefficient into two parts, one bearing an approximately constant ratio to the corresponding quantity for any absorbing substance, and the other the part connected with the emission of the characteristic secondary radiation.

A few features require special mention. The greatest deviations from the law of proportionality occur in those cases in which the energy scattered is a considerable fraction of the total energy. It has been calculated that in the light elements the portion of due to scattering is of the order \( \cdot 2 \). It is seen here, however, that if we subtract \( \cdot 16 \) from \( \Lambda C \), \( \Lambda M \), and \( \Lambda A \), there is strict proportionality within the limits of experimental error, between the coefficients of absorption in C, Mg, and Al.

Again, the apparent departure in the cases of \( \Lambda C \) and \( \Lambda A \) is much diminished by a similar consideration. There appears, however, to be a slight residual change in the ratios in the cases of \( \Lambda C \) and \( \Lambda S \) absorptions, and possibly very slight in the cases of absorption by Pt and Au, but the energy of the radiation scattered in these two cases has not been determined.

We may therefore conclude that the proportionality spoken of is a very accurate one through a big range of penetrating powers, if we subtract the energy scattered from that absorbed before determining the absorption coefficient.

Without yet entering into the discussion of any theory, let

us consider how much of the energy absorbed has been accounted for. One of us in a previous paper has shown that when X-rays within the range of penetrating powers experimented upon are transmitted through a substance of atomic weight less than sulphur, the energy of the radiation scattered is independent of the penetrating power of the radiation, and depends merely on the quantity of matter traversed.

It was shown that if \( I \) be the intensity of a beam passing through air under atmospheric conditions,

\[
\frac{dI}{dx} \text{ due to scattering} = -0.0024 I, \text{ approximately},
\]

so \( \frac{1}{\rho} \frac{dI}{dx} \) due to scattering = \(-\frac{2}{\rho} I\)

for all light elements.

If by analogy with the absorption coefficient we call the portion of \( \frac{1}{\rho} \frac{dI}{dx} \) due to scattering the scattering coefficient \( s \), we get \( \frac{s}{\rho} \) for elements of atomic weight less than sulphur to be 2.

This law does not hold, however, for elements of higher atomic weight. The value of \( \frac{s}{\rho} \) is much more difficult to determine in these owing to the usual admixture of the characteristic secondary radiation. Only in the case of Ag has the scattered radiation been measured after complete elimination of the other type of radiation. In this case it was found to be about 5.5 times that found from light elements. This would give for \( \frac{s}{\rho} \) about 1.3.

In copper, however, an estimate of the quantity of scattered radiation mixed with the homogeneous secondary rays was made and found to be about twice as great as for the light elements, when a penetrating primary radiation was used.

On comparison of the scattering coefficients with the total absorption coefficients it will be seen that only when the rays are fairly penetrating and when absorption takes place in light atoms does the scattering account for a large fraction of the loss of energy of the primary beam. Thus in the case of the transmission of Ag radiation through C, nearly half of the total loss of energy is due to scattering. Below are given


the Absorption of Röntgen Rays.

approximate values for the fraction energy scattered for the most penetrating and the most absorbable beams used in these experiments.

<table>
<thead>
<tr>
<th>Absorbing Substance</th>
<th>( \lambda ) ( \rho )</th>
<th>( \frac{s}{\rho} )</th>
<th>( \frac{\lambda}{\rho} )</th>
<th>Total energy absorbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.409</td>
<td>2</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>Al</td>
<td>2.5</td>
<td>2</td>
<td>-</td>
<td>0.08</td>
</tr>
<tr>
<td>Cu</td>
<td>24.3</td>
<td>4</td>
<td>-</td>
<td>0.016</td>
</tr>
<tr>
<td>Ag</td>
<td>13.3</td>
<td>1.5</td>
<td>-</td>
<td>0.11</td>
</tr>
</tbody>
</table>

II. Very soft radiation (from Cr):

<table>
<thead>
<tr>
<th>Absorbing Substance</th>
<th>( \lambda ) ( \rho )</th>
<th>( \frac{s}{\rho} )</th>
<th>( \frac{\lambda}{\rho} )</th>
<th>Total energy absorbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>15.3</td>
<td>2</td>
<td>-</td>
<td>0.013</td>
</tr>
<tr>
<td>Al</td>
<td>135</td>
<td>2</td>
<td>-</td>
<td>0.007</td>
</tr>
<tr>
<td>Cu</td>
<td>143</td>
<td>4</td>
<td>-</td>
<td>0.003</td>
</tr>
<tr>
<td>Ag</td>
<td>580.5</td>
<td>1.5</td>
<td>-</td>
<td>0.002</td>
</tr>
</tbody>
</table>

It has been shown in a previous paper that the energy of the secondary radiation characteristic of an absorbing element is in many cases probably very great. In a certain case the ionization produced by these rays from Cu was about 300 times that produced by the scattered rays from an equal mass of light elements. If we assume as an approximation that the absorptions of two different beams in air are proportional to the ionizations produced in air, we are led to the conclusion that in this case the energy of the homogeneous radiation was 45 times the energy of scattered radiation and about \( \frac{1}{3} \) of the total absorption, or more than \( \frac{1}{3} \) of the special absorption connected with the emission of these homogeneous rays.

It was also shown in the paper referred to that the secondary radiation excited in one of these substances (Cu) was proportional to the ionization produced by the primary beam in a thin film of air—or proportional to what may be called the coefficient of ionization in that substance—when the primary was beyond a certain penetrating power.

We may thus express this:

\[ \frac{\lambda_{Cu}}{\lambda_{air}} \propto \frac{x_{Cu}}{x_{air}} \]

but, on the assumption stated,

\[ \frac{x_{air}}{x_{Cu}} \propto \frac{\lambda_{air}}{\lambda_{Cu}} \]

from the results of the experiments on absorption;

\[ \lambda_{\text{air}} \propto \lambda_{\text{Al}} \]

This leads us to the conclusion that the energy of secondary radiation produced by a primary radiation in passing through a thin sheet of copper is proportional to the absorption of the primary radiation in a thin sheet of aluminum, provided this primary radiation is beyond a certain penetrating power.

Though the assumption made has not been strictly justified, it probably gives us an approximation to the truth.

One of us has made more detailed investigation of the energy of this type of radiation based on the same assumption.*

Energy is also emitted by the absorbing-substance in the form of corpuscular radiation.

Thus in at least three forms is energy re-emitted.

Besides these, a portion of the energy absorbed must be spent in the process of ionization, and probably some is transformed directly into heat.

The results of these experiments are of such wide application and affect so many phenomena connected with X-rays, that it is impossible to enter into a detailed discussion of their bearing on the results of investigations on X-rays. The simplification that results is frequently enormous. It is, however, desirable to say something of the absorption of a heterogeneous beam of X-rays such as is commonly experimented upon.

When such a heterogeneous beam is transmitted through any element X, there is of course (1) a selection of the rays of the more absorbable type, (2) a special selection of those rays of greater general penetrating power than the secondary radiation characteristic of X—i.e. those able to stimulate the secondary radiation in X, and (3) an emission of secondary rays which are of more absorbable type than the radiations which produced them, but which may be much more penetrating to the element X and to elements whose characteristic radiations are more penetrating than that characteristic of X.

All of these factors contribute to the change in the character of the beam resulting from transmission.

By a proper choice of radiations and absorbing substances it becomes a simple matter to arrange experiments in which there appears (1) no change in transmission, (2) change to more penetrating type, (3) change to more absorbable type,


without even considering the secondary rays which are superposed on the primary.

A few words are also necessary regarding the rays emitted by an X-ray tube. As the substance of the anticathode of an X-ray tube is subject to a very intense X-radiation, it is the source of an intense secondary radiation. The primary radiation proceeding towards the surface of incidence of the cathode rays, unless very "soft," excites the secondary radiation, which is usually more penetrating to the anticathode and produces greater ionization in the air outside. The primary radiation penetrating further into the anticathode also excites an intense secondary radiation which proceeds in all directions. Half of this is therefore directed towards the surface, and as it usually suffers much less absorption than the primary radiation producing it, it emerges with little loss of intensity and is superposed on the primary beam.

Even if the primary rays were all produced in the surface-layer of molecules, the secondary radiation would produce ionizations comparable with those produced by the true primary rays: as the primary rays cannot be produced absolutely at the surface, the proportion of secondary rays must increase rapidly with an increase at the depth at which they are produced. Thus the "soft" radiations experimented upon by Mr. Kaye (Phil. Trans. A. vol. 209, pp. 123–151) are what might have been expected from our previous experiments on secondary rays, and many of the properties which he records are the properties of the secondary rays previously published by us. A comparison of some of the absorption coefficients reveals their unmistakable identity.

In the majority of experiments on X-rays, however, the radiation has already passed through a comparatively thick sheet of glass and has been robbed of a large proportion of the secondary rays.

These considerations also afford an explanation of the fact that the beam of X-rays proceeding from a "soft" tube is much more completely polarized than one from the same tube when harder. In the former case there are less secondary X-rays, as well as less X-rays produced by secondary corpuscular rays.

They also show why the more penetrating portion of a heterogeneous beam from an X-ray tube is the more polarized. The penetrating portion contains the true primary radiation in larger proportion.

[Note.—All our experiments on the behaviour of nickel have confirmed our previous conclusion—that in all phenomena
connected purely with X-rays with which we are experimentally acquainted, nickel behaves as a normal element of atomic weight 61.3. This is true of (1) the absorption by nickel unconnected with the production of X-rays, (2) the absorption connected with the emission of secondary X-rays, (3) the character of the secondary rays emitted, (4) the intensity of the secondary X-rays emitted.

Theory.

If an attempt be made to account for these results on Prof. Bragg's neutral pair theory, we are at once led into difficulties. The pairs constituting the homogeneous secondary radiation characteristic of a particular element must have been either in the primary radiation or in the atoms of the element subjected to that radiation. If we make the former assumption we have to account for pairs varying enormously in velocity being scattered in all directions with one velocity—a velocity characteristic of the atom. If, on the other hand, we assume that the pairs were originally in the atom, we must account for their ejection with one velocity by assuming some disruption to occur in the atom. The former of the two assumptions is inconceivable, and it is against the latter—the disruption theory—that much of Prof. Bragg's argument has been directed. If, however, we change the point of view and assume disruption, we must account for—All the pairs transmitted through an element are undiminished in velocity; those moving with a velocity greater than a critical velocity being stopped in greater proportion than those moving more slowly; those moving more quickly being stopped in smaller proportion; and the equality of the velocity required to produce instability with that acquired by another pair due to the instability set up in the atom. Assumptions might possibly be made to satisfy any individual result, but in the combination we find the difficulties insuperable.

The results of these experiments are, however, in their general nature what would be expected on the ether-pulse theory, as shown in previous papers.*

A more detailed discussion of this theory will be given when several points have been further tested.

It is possible that all the substances experimented upon also emit a very easily absorbed secondary radiation, and that the absorptions which have been observed in the case of very "soft" radiations have been accompanied by the emission of such radiations.

In all experiments on absorption, both the normal absorption of "soft" rays and the special absorption connected with the emission of secondary rays, and on secondary rays, both as regards intensity and character, nickel behaves as a normal element of atomic weight about 61.3.

George Holt Physics Laboratory,
Liverpool.

LXX. On the Distribution of Thorium in the Earth's Surface Materials. By J. Joly, F.R.S.*

Recent observations have shown that the emanation of thorium exists in the atmosphere to an extent which is difficult to account for unless a very considerable quantity of the element thorium is distributed in the surface rocks and soils. Thus Bumstead (Am. Journ. Sc. July 1904) and Dadourian (Am. Journ. Sc. Jan. 1905) in New Haven, Conn., Bland (Phil. Mag. March 1907) at Rome, and Wilson (Phil. Mag. Feb. 1909) at Manchester, have found that of the total active deposit gathered upon a negatively charged wire exposed for many hours to the air, a considerable part—may be even a major part—exhibits the properties of the active deposit derived from the emanation of thorium. Bland estimates that at Rome from 50 to 70 per cent. of the whole activity is due to thorium; and Wilson infers from his observations at Manchester that there must be about seven times as much thorium as uranium in the surface soils. On the other hand, Gockel (Le Radium, Jan. 1909) finds that at Zermatt the emanation of thorium is almost entirely absent.

It is a question of much importance to geological science to decide how far these observations refer to purely local conditions, or whether they indicate a general prevalence of thorium in rocks.

Method of Measurement.

The material under investigation is brought into solution by the aid of reagents (e.g. hydrochloric acid and the carbonates of soda and potassium) which are themselves shown to be free from thorium by the method to be now described. The solution is boiled in a flask (see figure, p. 761) to which the steam is returned by an attached condenser. A preliminary boiling, lasting from 20 to 30 minutes, is required to completely expel any accumulated emanation of radium. A small quantity of powdered talc must always be put into the solution in order to secure uniformity of ebullition.

* Communicated by the Author.