THE BETA-RAYS FROM RADIUM E

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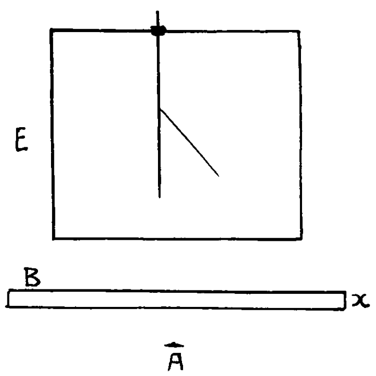
Introduction:

It was originally supposed that the β-rays emitted from some radioactive source, such as Ra.E., were homogeneous, that is, of a definite velocity. When absorption curves were first taken it was natural to try a law of the exponential type, $I = I_0 e^{-\mu x}$ where I_0 is the initial intensity of the radiation, I the intensity of the rays transmitted through an absorbing plate of thickness x, and μ the coefficient of absorption. The intensity is not directly measurable, but the assumption is made that it is proportional to the ionization which is produced in an electroscope. The experimental procedure is as follows:-



The active material is placed at A and the ionization is measured by the rate of fall of the gold-leaf in the electroscope E. The absorbing plate B, of thickness x, is placed in the position as shown, and the ionization measured as before. The ionization, and hence the intensity, is found to decrease as x is increased. To understand the nature of the absorption it is necessary to determine the relation between I and x.

From the equation given above, it follows that -

$$dI = -\mu I_0 e^{-\mu x} \quad dx = -\mu I \, dx$$

or $$\frac{dI}{I} = -\mu \, dx$$

Hence for equal increments of thickness dx the ratio $\frac{dI}{I}$ is constant

A further relation is obtained thus:
$\log I + \mu x = \log I_0$. Hence if log I be plotted against x a straight line curve should result

Also if I_r, I_s, I_t, etc., represent the relative intensities of rays transmitted through thicknesses $x_0, x_0 + x^1$, $x_0 + 2x^1$, etc., then the percent transmitted should be constant. That is $\frac{100 \, I_s}{I_r}$, $\frac{100 \, I_t}{I_s}$, etc., is a series of equal quantities, ~~100~~ each equal to $100 e^{-\mu x'}$

These last two deductions provide very simple tests for exponential absorption, and judging by these a glance at the absorption curves given in Fig. 2 and 3 and at the percentages shown in Table I. makes it evident that the β-rays of Ra.E. do not comply with these requirements.

The explanation has been slowly forthcoming. The loss of intensity in passing through matter is brought about in two ways, i.e. (1) By the particles being slowed down or stopped, the energy going probably into ionization and possibly a small part into the production of X-rays.

(2) By the particles being scattered by collision with the atoms of the absorbing material. It is obvious that the scattering loss will be greater the less the velocity of the particles.

In 1900 Becquerel showed photographically by magnetic deflection that the β-rays from radium are not homogeneous. W. Wilson (Proc. R.S. 1909) used this method to isolate an approximately homogeneous beam of β-rays of velocity v, by magnetic deflection in a circle of radius R, under a field of strength H, the velocity being given by the well known relation $\frac{mv}{e} = H.R.$ His results showed that the absorption was not exponential but that the rays became more and more absorbable as the thickness of absorbing material was increased. He further showed that the absorption increased rapidly as the velocity diminished and in no case could be called exponential.

The best experiments on homogeneous β-rays are those of Crowther (Proc. R.S. 1910). One of his curves showing absorption in aluminium is reproduced in Fig. I. , which indicates that for very thin layers there is practically no absorption (similar to results for α-particles) but the increasingly large scattering effect soon alters the slope of the curve and the relative absorption is seen to increase as the thickness of aluminium is increased.

By putting a thin plate of platinum (.001 cm. thick) over the active material and then absorbing in aluminium, Crowther found that the curve obtained was very nearly exponential, showing that the character of the rays had been altered by passage through a substance of such high scattering power as platinum.

Later experiments of Wilson and von Baeyer showed definitely that β-rays lose velocity in passing through matter

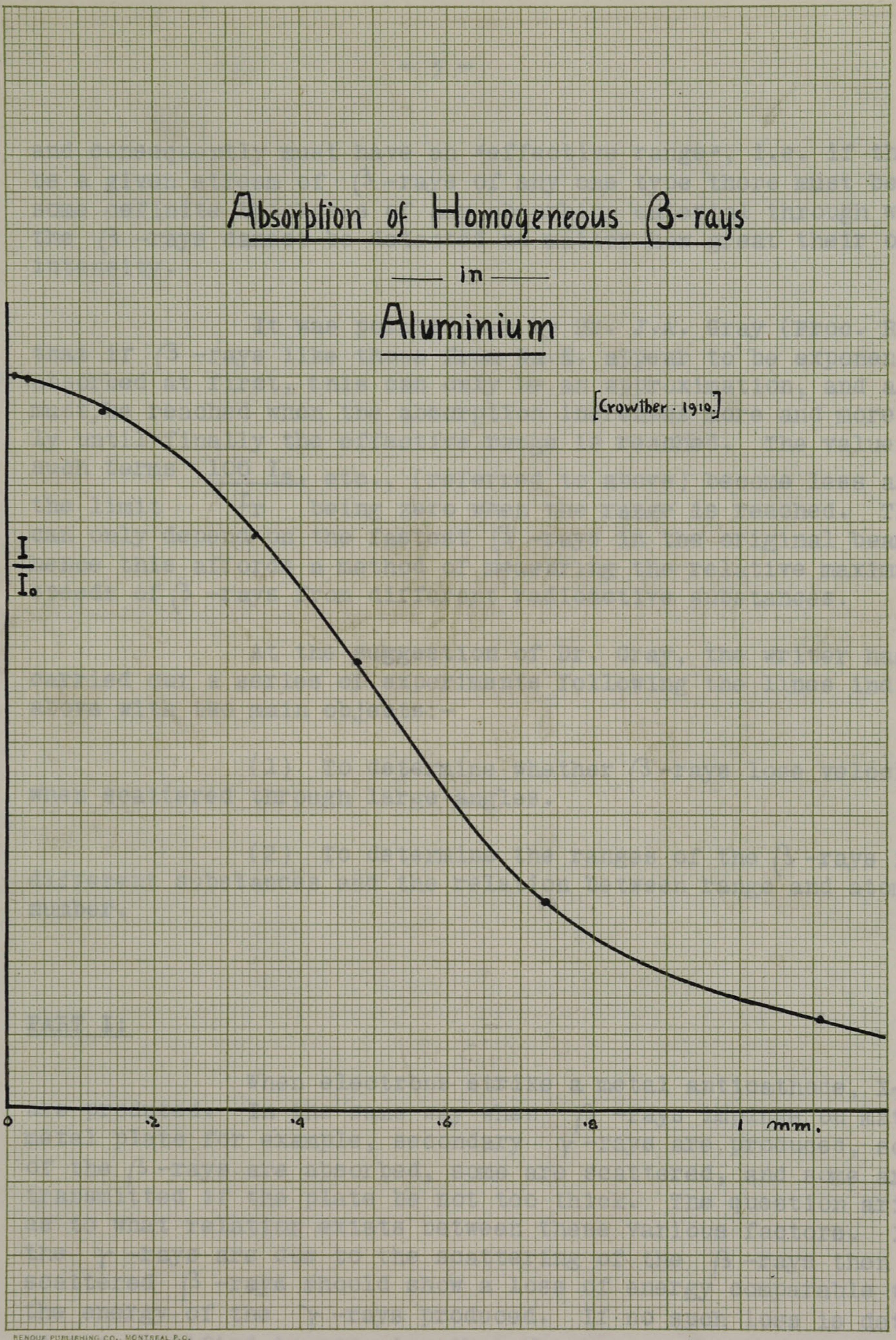

Absorption of Homogeneous β-rays
in
Aluminium
[Crowther · 1910.]
1.0
·8
·6
·4
·2
I / I₀
0
·2
·4
·6
·8
1 mm.
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Fig. 1.

and consequently must have an "effective range", i.e. if there be a given stream of β-rays of any one type there must be some definite thickness of any absorbing material through which the β-rays cannot be detected no matter how great their original intensity.

It was pointed out by Dr. J.A. Gray (Proc. R.S.1912) that if β-rays like those from Ra.E. appear to be exponentially absorbed at first, this can only be an approximation, and a stage must be reached when the absorption increases more and more rapidly until finally the effective range is reached. The values of such terms $\frac{100 I_s}{I_r}$, etc., (referred to above) become less and less, the limit being zero when the range is reached. The range can only depend on the fastest β-rays in the original beam, and hence this affords a method of measuring the relative maximum speeds of β-rays from different radioactive substances.

At the suggestion of Dr. Gray, the writer has carried out a series of experiments following the lines indicated above with two main objects:-

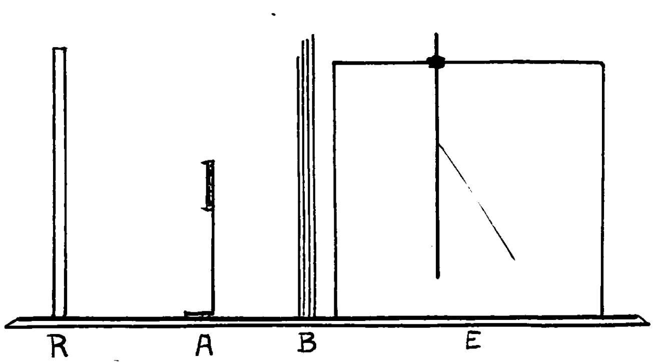
(1) To determine whether β-rays lose velocity when scattered through large angles.

(2) To determine the ranges of the β-rays in different substances and the relation between range and atomic number.

PART I:

When electrons strike a metal anticathode, X-rays are produced. In the same way when β-rays impinge on matter, a metal plate for example, secondary γ-rays are produced, some of the β-rays are absorbed, some are scattered, and some are transmitted if the plate be not too thick. The question arises as to what relation exists between these various factors. If the γ-rays are due to the scattering of the β-rays then the scattered β-rays should show a loss of energy comparable to the energy of the γ-rays produced. If no such loss is detectable we are justified in assuming that γ-rays are not produced when β-rays are scattered, but when they are stopped by some particular type of collision.

The experimental procedure was as follows:- The preparation of Ra.E. was enclosed in a small lead case (A) with one open face and was mounted centrally in front of, but turned away from the foil face of the electroscope. The latter was a 14 cm. cube. Between it and the active material was placed the absorbing material(B), and in front of the active material stood the radiator.(R) Thus only rays scattered through approximately 160° to 180° could enter the electroscope.



The intensity of the direct radiation was obtained by replacing the radiator by the active material with its open face towards the electroscope.

Corrections had to be made in both cases for γ-rays. This is possible to a high degree of accuracy if the mass-absorption coefficient for γ-rays be known. These coefficients have been determined for various substances, including carbon and aluminium, by Dr. Gray, who has shown that whereas the mass-absorption coefficient of β-rays in carbon is approximately 16, that of γ-rays in carbon is 0.100. In the case of the scattered radiation a further correction was necessary to eliminate the effect of air-scattering. This presented no greater difficulty than the careful repetition of every reading with the radiator completely removed.

Table I shows the results obtained for (1) Absorption of primary β-rays; (2) Absorption of β-rays scattered from a lead radiator, 3 m.m. thick; (3) Absorption of β-rays scattered from a silver radiator, 0.3 m.m. thick. The absorber in each case was paper, each sheet of which weighed 0.00848 gms. per sq. cm.

In Fig. 2 are given the curves corresponding to (1) and (2) above mentioned.

Absorption of β-Rays from Ra.E.

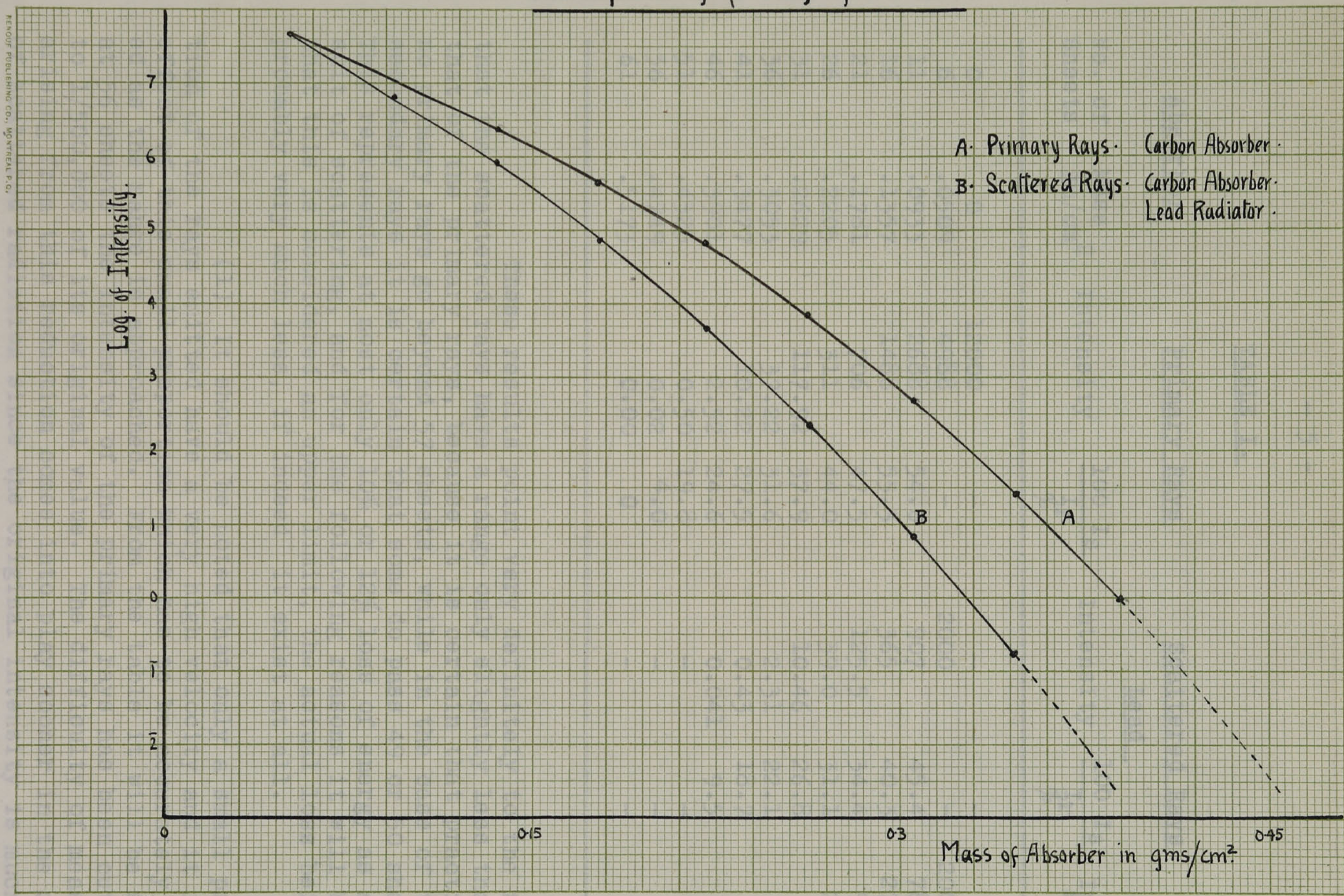


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Fig. 2.

TABLE I.

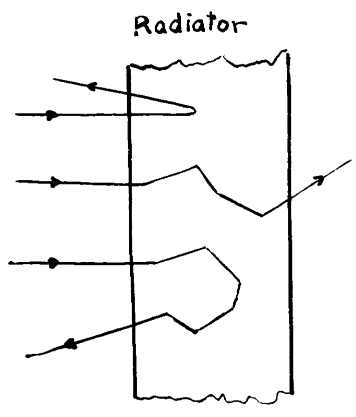
Absorber		Primary Rays		Scattered Rays			
				Lead		Silver	
No. of Sheets	Mass gm/cm^2	Intensity	$\frac{100\ I_s}{I_r}$ %	Intensity	$\frac{100\ I_s}{I_r}$ %	Intensity	$\frac{100 I_s}{I_r}$ %
0	0	12000	-	-	-	-	-
6	.0509	4988	-	2000	-	2000	-
11	.0933	2688	54.0	907	45.4	780	39.0
16	.1357	1488	55.3	365	40.3	278	35.6
21	.1781	706	47.5	125.5	34.4	91.5	32.9
26	.2205	311	44.0	39.0	31.1	27.1	29.7
31	.2629	117.92	37.9	10.46	26.8	6.88	25.4
36	.3053	37.22	31.6	2.31	22.1	1.63	23.7
41	.3477	10.22	27.5	0.43	18.7	0.33	20.4
46	.3901	2.52	24.6	0.041	9.5	0.028	8.3
51	.4325	0.50	19.8	-	-	-	-
56	.4749	0.02	4.0	-	-	-	-
61	.5173	0.00	0	-	-	-	-

These results point very definitely to the fact that the scattered rays have a range only slightly less than that of the primary rays, because it is certain that practically no primary rays go beyond 57 sheets, while in the case of the secondary rays it is certain that some do pass 49 or 50 sheets. This represents at most only 10% or 12% loss of energy as a result of scattering, and for the following reasons it will be shown that this is considered an upper limit, the actual loss being probably very much less, if indeed it exist at all.

(1) It should be noted that only a small proportion of the rays emitted have a very high velocity and it is the effect of this small proportion which has to be accurately measured as the range is approached. From the table it will be seen that at 56 sheets the intensity of the primary rays has been cut down to 1/500,000 of its original value. The difficulty of measurement arising from this reduction comes into play sooner in the case of scattered radiation since the original intensity is much less, and the proportion of high velocity rays is lower since they are less likely to be deflected than the slower ones. Intensities of this order are much smaller than the natural leak and consequently a slight fluctuation of leak will give a very large error in the intensity.

For these reasons it seems almost certain that with a very intense source of radiation and a more precise method of measurement a measurable quantity of scattered radiation would be detected through a mass of absorber more closely approaching the range of the primary rays.

(2) Scattering is not a surface phenomenon. Some of the β-particles will have penetrated a considerable distance into the radiating material before being deflected back, some will undergo several deflections inside the radiator before emerging backwards. Hence there will be an average distance inside the radiator which the scattered particles traverse and while doing so they will lose velocity just as has been shown to be the case whenever β-rays pass through matter. It is evident, then, that the real range of the scattered rays is the range actually found plus the equivalent of the average path in the radiator. It is not impossible, though it cannot yet be stated definitely, that this completely explains the apparent difference in range between the primary and scattered rays, and if so, it may be said that to a first approximattion there is no loss of energy due to scattering.



(3) This conclusion is confirmed by the following theoretical considerations:-

In the Phil. Mag. Vol. 27, 1914, p. 499, C.G. Darwin gives the calculations regarding the collisions of α-particles with light atoms. In the Phil. Mag. Vol. 21, 1911, p. 684, Sir E. Rutherford states that collisions with light atoms by α and by β-particles obey the same general laws; the main difference being that the probability of a large deflection is much greater in the case of the β-particle due to its mass and its momentum being so much less than the mass and momentum of the α-particle.

It seems reasonable, then, to employ Darwin's method of approach, extending his reasoning to the problem of energy loss.

Consider the deflection of a β-particle of mass M and velocity V due to collision with the nucleus of an atom of mass m at rest. Let ϕ be the deflection of the

β-particle and v its resultant velocity; and let the atom be set in motion in a direction θ with a velocity u.

The equations of motion are -

$$MV = Mv \cos\phi + m u \cos\theta$$
$$0 = Mv \sin\phi - mu \sin\theta$$
$$MV^2 = Mv^2 + m u^2$$

and hence $$v = \frac{V}{M + m}(M \cos\phi \pm \sqrt{m^2 - M^2 \sin^2\phi})$$

The energy of the β-particle before collision was $\frac{1}{2}MV^2$. Its energy after collision is

$$\tfrac{1}{2}Mv^2 = \tfrac{1}{2}M\left\{ \frac{V}{M + m}(M \cos\phi \pm \sqrt{m^2 - M^2 \sin^2\phi})\right\}^2$$

Hence the loss in energy is given by

$$\tfrac{1}{2}MV^2\left\{1 - \frac{1}{(M + m)^2}(M \cos\phi \pm \sqrt{m^2 - M^2 \sin^2\phi})^2\right\}$$

In the particular case of scattering through an angle of 180°, this loss of energy becomes $\frac{1}{2}MV^2\left\{1 - \left(\frac{-M \pm m}{M + m}\right)^2\right\}$

The lower sign gives zero, while the upper sign gives

$$\tfrac{1}{2}Mv^2\left\{1 - \frac{(m - M)^2}{(m + M)}\right\}$$

In the case of β-particles scattered by hydrogen $M = \frac{1}{1800}$, m = 1.008, and it is evident that the loss in energy is of a very small order being 1 in 460 or 0.216%. If this theory could be applied to heavy atoms such as lead (207) and silver (108), then the loss in energy is seen to be almost non-existent, actually for lead 0.00105%.

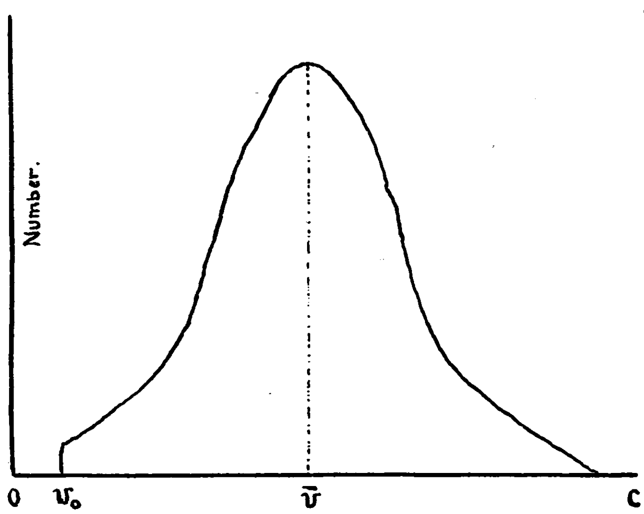
This analysis is based on the assumption that the collision is of the nature of the passage of a comet around a large star, that is to say, considerations of energy-loss due to radiation, and of alteration of mass with velocity are neglected. These points would require special treatment. It is true that, unlike the case of the α-particle, a large deflection of a β-particle may sometimes be the result of many collisions whereby the electron has been buffeted about in an erratic manner for possibly a considerable time before it finally emerged in the direction from which it entered. But on the above theory it would require 10,000 collisions with lead atoms to produce a 10% loss in energy.

It is therefore concluded that the loss in energy is certainly much less than 10% and is possibly zero.

This is a point of considerable theoretical importance, proving as it does that the phenomenon of the scattering of β-rays will not furnish an explanation of the production or excitation of γ- or X-rays.

PART 2:

The complex β-rays emitted from a source like Ra.E. can be represented by a Velocity Distribution Curve of the type of the Maxwellian Probability curves. There will be a minimum velocity v_0 near the origin below which β-rays do not ionize and hence are not detectable as β-rays. The curve will begin at this point, rise to its maximum over $\bar{v}$, where $\bar{v}$ is the most probable velocity, and then fall to a point just short of c where c is the velocity of light. The presence of an absorbing plate in the path of the rays causes a two-fold change - (1) in the shape of the curve, $\bar{v}$ approaching v_0 as the velocity of the transmitted rays is decreased, (2) in the area under the curve, as some of the rays are stopped or absorbed, and others are scattered through angles greater than 90°.



It is of interest to note that the exponential law of absorption requires that the rate of decrease of area under the curve is constant, due to the combined effects of absorption and scattering through angles greater than 90°, and it may be remarked again that this is proved not to be the case, the area actually decreasing more rapidly as the thickness of absorber is increased.

As the area diminishes and $\bar{v}$ approaches v_0 there will come a time when even the fastest particles have been slowed down so much that they cannot escape complete absorption, hence a range must exist, and that thickness of absorber may be termed the "effective range" which makes the whole curve shrink finally to v_0. The "actual range" which is not directly obtainable experimentally will be referred to later.

The determination of the range in different substances was made by the following method:-

A 10 cm. cube electroscope, the base of which consisted of one sheet of aluminium foil (.004615 gms/cm^2) and one sheet of paper (.00848 gms/cm^2), was mounted on the pole pieces of an electromagnet. The active material was placed 6 cm. below the electroscope. The magnetic field was sufficiently strong to deflect between 40% and 50% of the primary β-rays unabsorbed, and when their velocity was reduced by about 40 sheets of paper, or its equivalent, complete deflection of the β-rays took place. For small amounts of absorber the intensity with the field off exceeds the intensity with the field on. As the thickness of absorber is increased this excess is diminished until when the range is reached the intensities are the same whether the field be off or on.

The difficulties encountered in these experiments, as in all those carried out during the course of the investigation, arose in two ways - (1) The variability of the natural leak and its continued high value, and the extreme sensitivity of the electroscope to air currents in spite of the precaution of placing draught-screens around three sides of the apparatus and protecting its base by several layers of absorber: (2) The comparative weakness of the active material which was used for the majority of the experiments, making accurate measurements very difficult when the reduction of intensity was of the order of 1 in 500,000, as has already been explained.

As a result of these, the exact location of the range was not possible to the degree of precision hoped for, but the extreme limits were found by repeated observations and the values shown in Table II as "Average Range" are accurate probably to 0.01 gm. per sq. cm. A correction was necessary, due to the permenent base of the electroscope, and the values obtained after this has been made are given under the heading "Corrected Range".

TABLE II

Effective Range of β-Rays from Ra.E.

Absorbing Material	Atomic Number	Average Range (gms/cm^2)	Corrected Range (gms/cm^2)
Carbon	6	.462	.474
Aluminium	13	.448	.460
Copper	29	.421	.432
Tin	50	.385	.395
Lead	82	.345	.354
Foil (40% Sn (60% Pb	(69)	.362	.371

The values here shown can only be considered as the result of preliminary experiments which the writer hopes to continue at some future date.

In Fig. 3 are shown the absorption curves terminating in the ranges for carbon, aluminium and copper.

In Fig. 4 the range has been plotted against the Atomic number, and a smooth curve is found to result. It would be necessary, however, to examine the range in many more substances before the relation between effective range and Atomic number could be definitely established. By analogy to Crowther's and McClelland's curve of mass-absorption coefficients against Atomic number, and Bragg's curve of molecular diameters against Atomic number, it seems a plausible forecast that a broken curve of that nature might be found, the breaks occurring at the Atomic numbers of the inert gases.

The range of α-particles in different substances has been found by Bragg and Kleeman (Phil. Mag. 1905) to vary very nearly as the square root of the Atomic weight. At first sight it appears strange that the range of the β-particle should follow an entirely opposite law and decrease with increase of Atomic weight.

This leads to the distinction already referred to between effective and actual range. It will be seen from Table II that the effective range decreases very slightly for large increases in the Atomic number of the absorbers. On the other hand

Absorption of Primary β-Rays

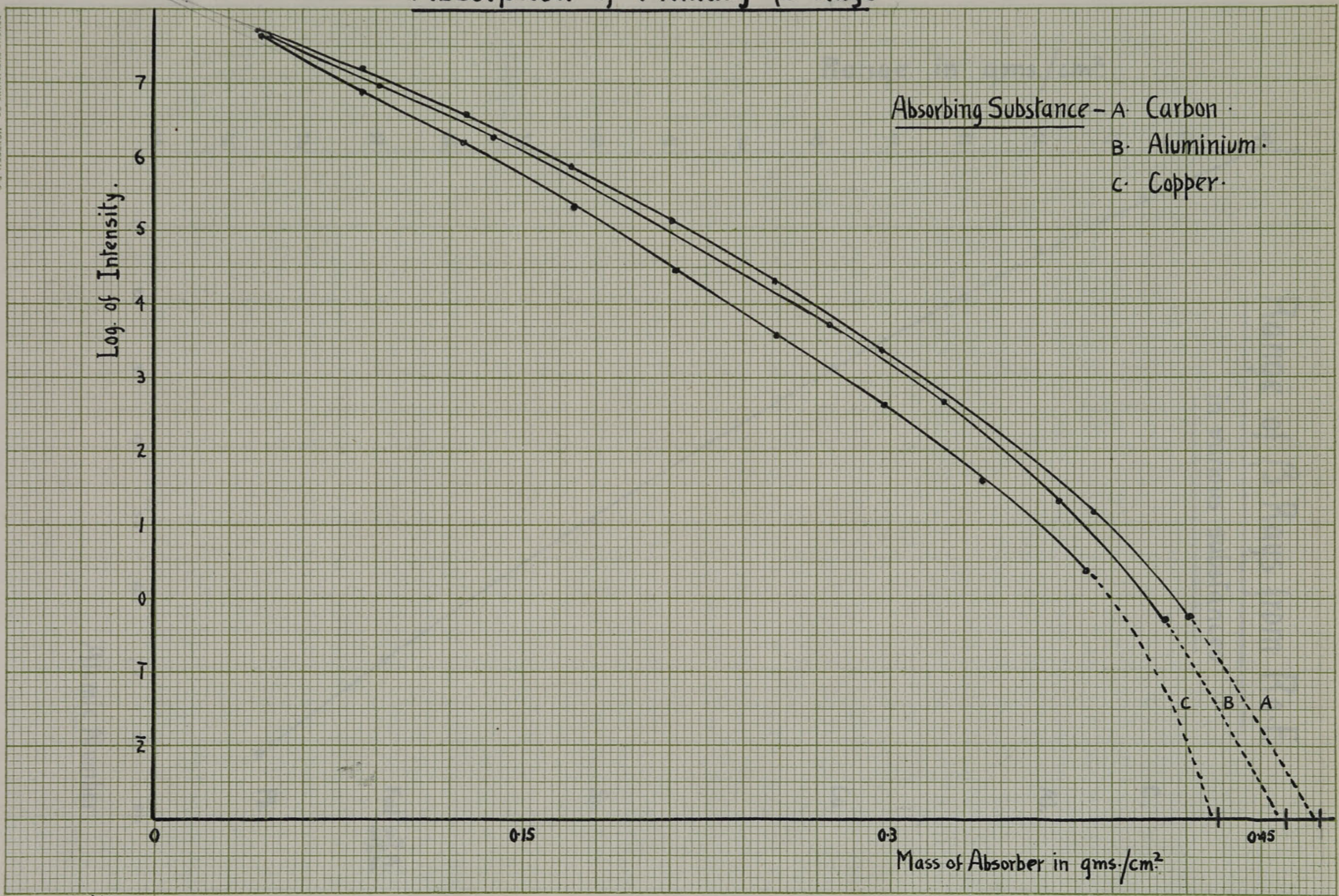


Fig. 3.

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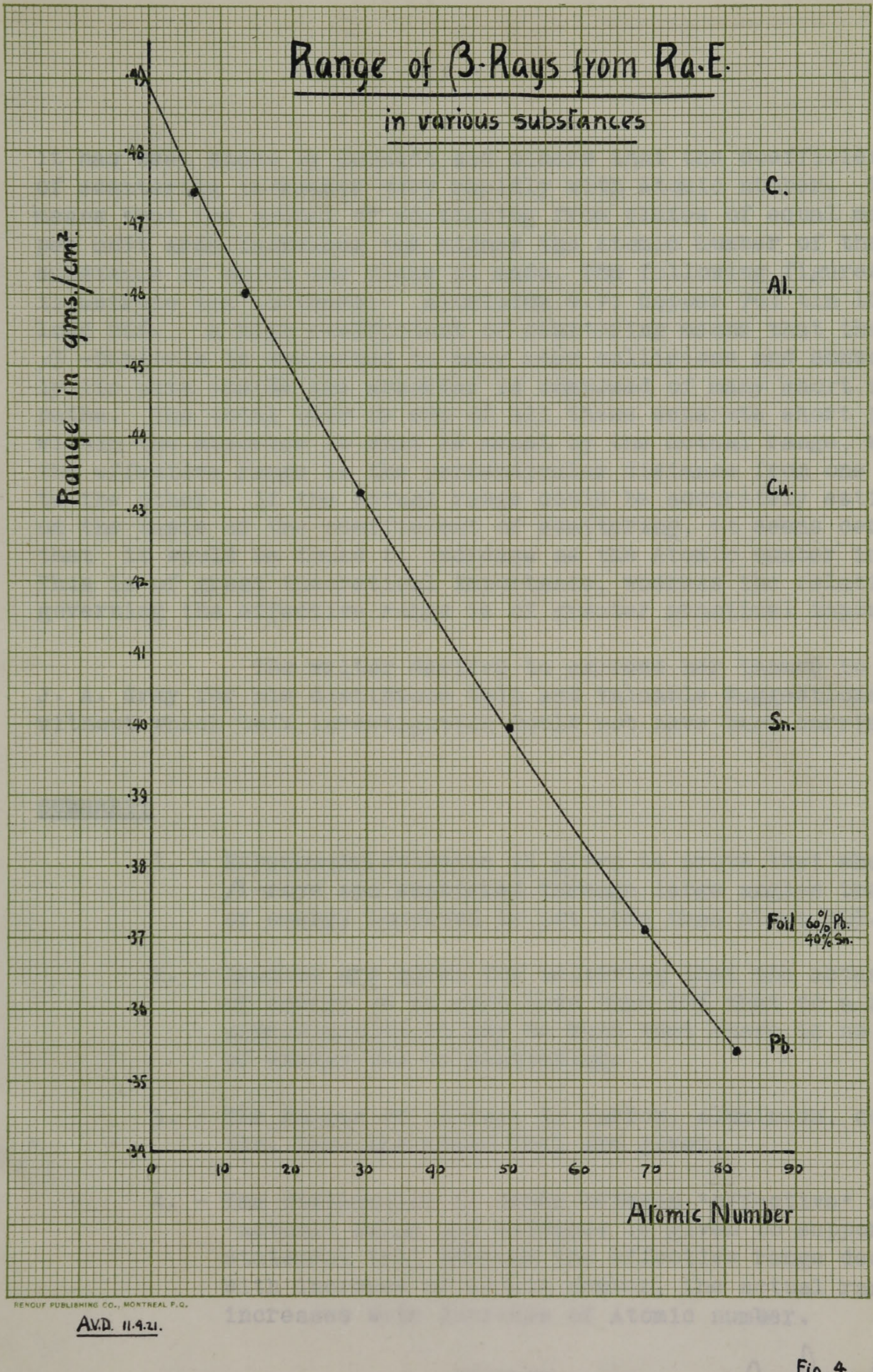

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Fig. 4.

it has been shown by Schmidt and others that the coefficient of scattering increases very rapidly with Atomic number. This means that the amount of scattering from plates of equal mass per unit area increases the higher the Atomic number of the substance of which the plate is made. The following figures illustrate the increase:- Aluminium 9.7; Copper 70; tin 100; lead 266. A high coefficient of scattering means that the β-particle is subjected to many more collisions and consequently its path inside the absorber is composed of many short zig-zag paths. The total path or sum of all these separate short paths within the absorber is what is meant by the actual range, whereas the effective range is the perpendicular distance from one face to the other. If the actual range could be accurately estimated on the basis of the coefficient of scattering, it seems certain that it would be found to increase as the Atomic number increases. This is of great theoretical importance, whereas the relation governing the effective range is of greater practical importance.

The writer desires to express her thanks to Dr. J. A. Gray for his continuous help and valuable suggestions, without which this investigation would not have been carried out.

<u>SUMMARY:</u>

1. - Experimental evidence is given to prove that when β-rays are scattered through large angles the loss of energy observed is not more than about 10%.

2. - Reasons are given for believing that the actual loss of energy is so much less than 10% that to a first approximation it may be said that there is no loss of energy due to scattering.

3. - The ranges of β-rays in carbon, aluminium, copper, tin, lead and mixed foil are given.

4. - The distinction is drawn between "effective" and "actual" range and evidence is given to support the statement that whereas the effective range decreases with increase of Atomic number, the actual range increases with increase of Atomic number.

A. V. Douglas.

15/4/21.