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The Scattering of the α-Particles by Matter.

By H. Geiger, Ph.D.

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In a preliminary note ('Roy. Soc. Proc.,' A, vol. 81, p. 174, 1908) on the above subject, experiments were described which gave direct evidence of the scattering of the α-particles.* In those experiments a strong source of α-radiation was placed at one end of a long exhausted tube, and the α-particles, after passing through a narrow slit, fell upon a zinc sulphide screen sealed to the other end of the tube. When the pressure inside the tube was very low, the narrow line of scintillations which marked the place of incidence of the α-particles on the screen was well defined, but when the rays on their way to the screen passed through gas or through thin metal foils the edges of this line of scintillations became indistinct. The amount of scattering could be estimated for different foils by placing them in the path of the rays and noting the distribution of the scintillations on the screen.

The present investigation was undertaken with a view to obtain a quantitative measurement of the scattering by determining the most probable angle through which an α-particle of definite range is turned by passing through a given thickness of matter. The following are the chief points investigated :—

(1) Determination of the amount of scattering produced in different thicknesses of the same material.

(2) Comparison of the amounts of scattering produced in different materials.

(3) Relation between the velocity of the α-particles and the amount of their scattering.

Experimental Arrangements.

Since the amount by which the α-particles are scattered is comparatively small, accurate measurements could only be obtained in the way outlined above by the use of a very narrow beam of α-particles. In consequence it was necessary to employ a very small and intense source. In the earlier experiments the radiating source consisted of a short glass tube drawn down

* The phenomenon of the scattering of the α-particles was first observed by Rutherford 'Phil. Mag.,' vol. 12, p. 143, 1906), and discussed later by Kucera and Masek, by W. H. Bragg, L. Meitner, and E. Meyer.

conically at one end and closed tightly at the other end by a very thin sheet of mica. The tube was filled with radium emanation and the α-particles expelled from it and its active deposit, could easily pass through the mica window. Although this source fulfilled the conditions of being intense and narrow, it was not suitable for quantitative measurements, as its radiation was not homogeneous, firstly, on account of the different α-ray products present, and, secondly, owing to the absorption by the gas inside the tube. For these reasons the radiating source was modified in a way which will be understood from fig. 1. The conical glass tube A (of less than 2 mm.

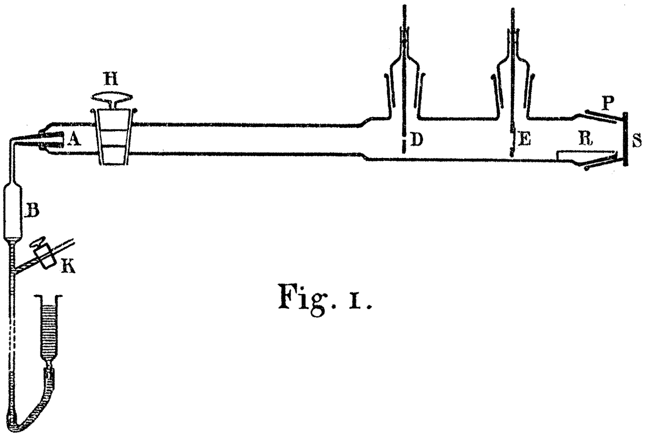


Fig. 1.

diameter at its wider end) was sealed by its narrow end to a glass tube, of very fine bore, leading to the bulb B. A quantity of radium emanation corresponding to about 50 milligrammes $RaBr_2$, which had been partially purified by the methods developed by Prof. Rutherford ('Phil. Mag.,' vol. 16, p. 300, 1908), was introduced into the exhausted bulb B through the stop-cock K. The whole emanation was then compressed into the conical tube by means of mercury. During this process the pressure increased, usually becoming nearly atmospheric. After three hours the active deposit formed from the emanation on the walls of the conical tube had reached nearly its maximum value. At this stage the emanation was expanded again into the bulb B.

On account of the volume of the bulb B being about 200 times that of the conical tube, the pressure on expanding decreased to less than 4 mm., and the amount of α-radiation from the emanation remaining in A was negligible compared with that from the active deposit present on the walls.

Fifteen minutes after the expansion of the emanation, the first product of the active deposit, viz., Radium A, had decayed to an inappreciable value, and the whole α-radiation passing through the window was homogeneous, consisting only of the α-particles expelled from Radium C. This radiation decays to half its value in about one hour, but since the law of decay is accurately known, corrections could easily be applied for measurements taken at different times after expansion.

A small fraction of the α-particles emitted from the source A passed through the narrow circular opening D (of less than 1 mm. diameter), and produced a luminous spot of scintillations on the zinc sulphide screen S. The scattering foils could be brought into the path of the rays, either at E at a distance of 13 cm. from the screen, or at D directly in front of the diaphragm. Foils of higher scattering power could be introduced through the joint P and fixed in position on the slide R at any point near to the screen.

The scintillations were counted by means of a suitable microscope, which could be moved vertically by means of a screw along a millimetre scale fitted with a vernier. The field visible through the microscope had a diameter of 1·1 mm.

Determination of the most probable Angle of Scattering.

Provided that the tube through which the α-particles had to pass was completely exhausted, the spot of scintillations produced by the impact of the α-particles on the screen had a diameter of 1·2 mm., and was clearly visible even with the unaided eye. When a sheet of metal, equivalent in stopping power to a few millimetres of air, was placed in the path of the rays at a point close to the screen, the brightness of the spot of scintillations remained practically undiminished. But when the same sheet was placed at a greater distance from the screen, say at D (fig. 1), the bright spot disappeared completely, the scintillations being distributed over a much greater area than formerly.

A microscopic examination of the screen showed that the density of scintillations was still greatest in the centre, but decreased steadily with increasing distance from the centre. By counting the number of scintillations at different distances from the centre, the most probable angle through which an α-particle is turned by passing through the scattering material could be determined as follows:—

Denoting the distance of the scattering foil to the screen by s, the angle through which the α-particles observed at a distance r from the centre have been turned is approximately r/s. The whole number of α-particles turned through this angle r/s is then represented by $2\pi rndr$, where n is the density of the α-particles striking the screen at the distance r from the centre. If we plot the number of particles $2\pi rndr$ turned through the angle r/s against that angle, we obtain a curve which gives the probability of the occurrence of any scattering angle r/s. This curve is, in many respects, similar to Maxwell's distribution curve of the velocities of the gas molecules. Its maximum corresponds to the most probable angle through which an α-particle is turned by passing through the scattering foil.

In order to determine experimentally the most probable angle of scattering in this way, it is necessary that the distance r at which the scintillations produced by the α-particles are counted should be large compared with the field of the microscope, and large also compared with the area covered by the scintillations when no scattering foil is interposed. These conditions could not be fully realised in the experimental arrangement.

This was mainly due to the fact that on account of the limited intensity of the source the distance of the scattering foil from the screen had to be adjusted so that the greater part of the scintillations should be confined within an area of 3 to 4 mm. diameter. If the distance was increased further, although the amount of scattering would appear greater on the screen, yet the scintillations would be spread out too much for reliable countings to be made. In most of the experiments observations could only be taken up to a distance of about 5 to 7 mm. from the centre. It would be difficult to assign a definite value for the correction which had to be applied, but the magnitude of the probable error could easily be estimated by comparing separate determinations of the most probable angle of scattering for the same foil placed at different distances from the screen.

Several comparative measurements of this kind were made and their agreement showed that the error was negligible. For instance, the distribution of the scintillations over the screen was determined, firstly, when a piece of tinfoil was placed at a distance of 6·4 cm. from the screen; secondly, when the same foil was placed at a distance of 2·72 cm. The two curves showed a maximum at 3·1 and 1·4 mm. from the centre respectively, which correspond to most probable angles of scattering of 2°·8 and 3°.

In describing the procedure of an experiment it will be of advantage to take a special case. In one experiment, for instance, 35 gold foils, which were equivalent in stopping power to 3·68 cm. of air, were placed at a distance of 1·64 cm. from the screen. After introducing the foils the whole apparatus was exhausted by means of a Fleuss pump and finally by charcoal dipping in liquid air. Meanwhile the emanation, which had been kept compressed in the tube A for sufficient time for the active deposit to reach the equilibrium value, was expanded into the bulb B. Usually 15 minutes after expansion the counting of scintillations was entered upon. In this special case, however, measurements could be started at once, since the mica window of the tube A and the gold foils were sufficient to stop all the α-particles emitted from Radium A.

As a rule the number of scintillations at points farthest away from the centre was determined first, in order to take advantage of the high initial intensity of the α-ray radiation. The counting experiments were continued for about 70 minutes. After that time the activity of the source became too small to allow reliable measurements to be made. The emanation was then again compressed to permit another set of readings to be taken after three hours' interval. The numerical results obtained for 35 gold foils are given in the table below.

Table I.

1.	2.	3.	4.	5.
Distance r from centre in mm.	Time of observation in minutes after expansion.	Number n of scintillations per minute.		$2\pi rn$.
		Observed.	Corrected for decay.	
4·6	7	3·3	3·4	98
3·6	16	8·5	9·4	212
2·6	24	16·1	19·4	316
1·6	38	22·1	33·0	330
0·8	49	27·2	49·3	247
(centre)	58	25·2	55·0	55

Whole number of scintillations counted in this experiment = 803.

Column 1 shows the distance from the centre at which scintillations were counted. The number of scintillations observed per minute are entered in Column 3, and those corrected for decay in Column 4. The calculated values of $2\pi rn$ (Column 5) are plotted in fig. 2 against the distance from the

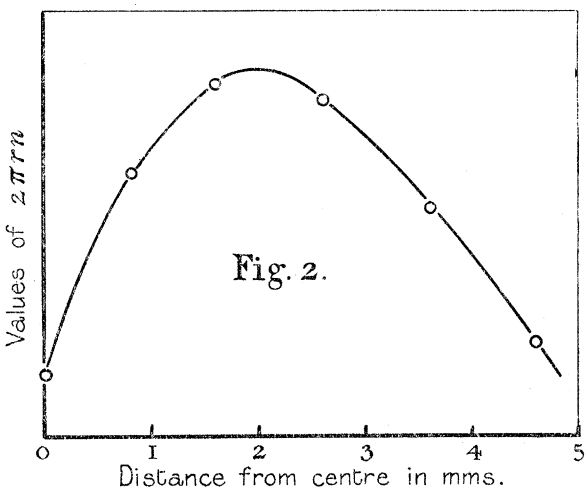


Fig. 2.

centre. The maximum of the curve, which occurs at 2 mm. from the centre, corresponds to the most probable deflection. Since the distance from scattering foil to screen was 1·64 cm., the most probable angle through which the α-particles were turned in passing through the 35 gold foils was nearly 7°.

The average angle through which an α-particle is turned will be somewhat greater than the most probable angle. In the following, reference is always made to the most probable angle, the determination of which can be obtained with greater accuracy than that of the average angle, which involves a determination of the area of the curve. Since, however, the distribution curves found for different metals and varying thicknesses were similar in shape, it appears probable that the ratio between the average and most probable angle is the same in all cases.

The Scattering produced by different Thicknesses of the same Material.

As in the experiment described above, the most probable angle through which the α-particles were turned was measured for different thicknesses of gold. Gold appeared to be the most suitable substance for such comparative measurements, since it can be obtained in very thin and uniform foils, and in addition its scattering power is higher than that of any other material available. Two different types of gold foil were used: the thinner foil corresponded to 0·038 cm. of air, the thicker foil to 0·108 cm.

Some of the probability curves are plotted in fig. 3 after reducing them

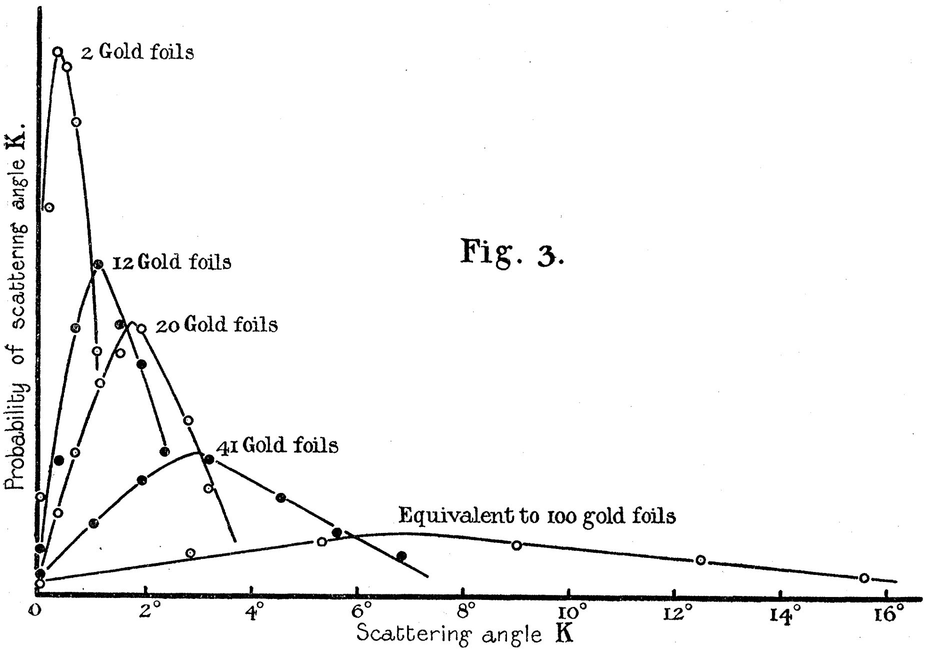


Fig. 3.

to such a scale that their areas were equal. This reduction was necessary, as the total intensity of the radiation was not the same in different experiments.

In the following Table, Column 3 gives the distances from the screen at which the foils were placed, and Column 4 gives the corresponding distance from the centre of the maximum in the distribution curve. From these figures the most probable angle of scattering is calculated and given in Column 5. The curve which connects the probable angle of scattering with the thickness of gold through which the α-particles had to pass is shown in fig. 4. The values obtained for the thin type of gold foils are denoted by circles, those for the thick type by dots. The thick gold foils were not so uniform as the thin ones, this probably being the reason that the points obtained for thick gold foils fall slightly higher than the corresponding ones for the thin foils.

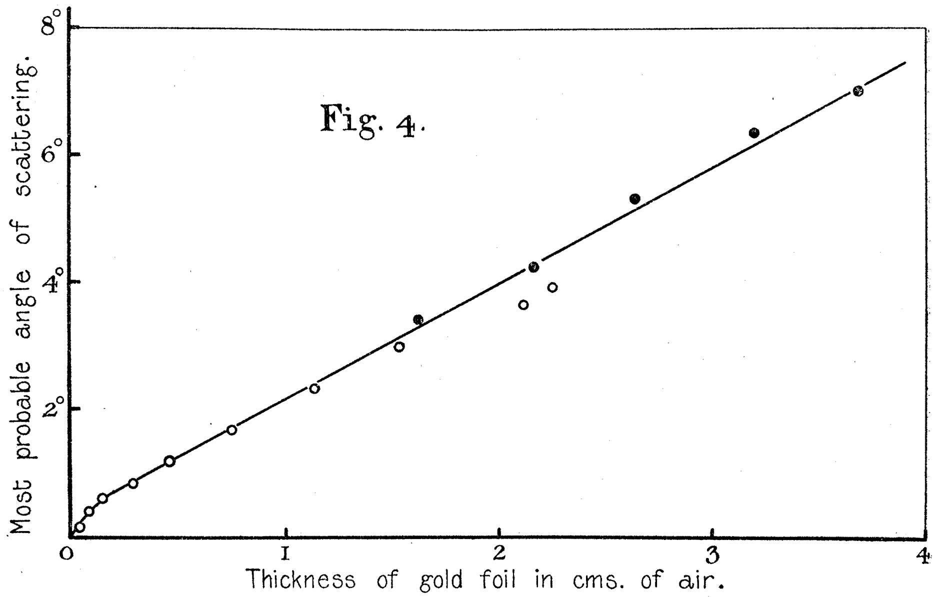
Table II.

1.	2.	3.	4.	5.
Number of gold foils.	Stopping power expressed in cm. of air.	Distance of foil from screen.	Most probable deflection.	Most probable scattering angle.
	cm.	cm.	cm.	° ′
1 thin gold foil	0·04	32·0	0·09	0 10
2 thin gold foils	0·08	30·5	0·20	0 23
4 " "	0·15	30·5	0·32	0 36
8 " "	0·29	14·1	0·20	0 49
12 " "	0·46	13·8	0·28	1 10
20 " "	0·76	13·8	0·41	1 40
30 " "	1·14	6·2	0·25	2 20
41 " "	1·53	4·72	0·25	3 0
56 " "	2·12	4·11	0·26	3 40
60 " "	2·25	5·67	0·39	3 55
15 thick gold foils	1·62	2·72	0·16	3 25
20 " "	2·16	1·87	0·14	4 15
25 " "	2·64	2·72	0·26	5 30
25 " "	2·64	1·65	0·15	5 10
30 " "	3·20	1·64	0·18	6 20
35 " "	3·68	1·64	0·20	7 0

The curve (fig. 4) extends over a wide range, the last point of the curve corresponding to a thickness of gold nearly 100 times as great as that of the first. With the exception of the initial portion, where the scattering increases somewhat more rapidly, the curve appears to a first approximation to be a straight line. Later experiments showed that a similar law holds for other metals.

The results obtained above for different thicknesses of matter need a few words of discussion. Let us assume that an α-particle in passing through each atom is deflected from its path through a small constant angle w. Since the angle of deflection may have any orientation, the resulting deflection of such an α-particle after passing through n atoms may have any value between zero and $n \times w$. Now, if a great number of α-particles were allowed to pass through n atoms and the resulting angle measured for each of them, there would be one value which is more likely to occur than any other.

In his 'Theory of Sound' (Second Edition, p. 39, 1894), Lord Rayleigh treats a related problem, namely the composition of unit vectors whose directions are accidental. Applying the deductions given there to our case, it would follow that the most probable deflection varies as the square root of the number of atoms traversed. In other words, the most probable angle of



scattering ought to increase at a rate proportional to the square root of the thickness of matter traversed.

A close examination of the curve (fig. 4) shows that for small thicknesses of gold (up to an equivalent thickness of about 5 mm. of air) the scattering increases approximately at that rate, but for greater thicknesses the increase becomes practically proportional to the thickness itself. This quick increase can be explained as due to an increase of the scattering angle w, on account of the decrease of velocity of the α-particle in passing through successive atoms. As will be shown later, the angle w is, to a first approximation, inversely proportional to the third power of the velocity,

The most probable angle through which an α-particle will be turned by passing through a layer of gold equivalent to 1 cm. of air is $2^\circ\cdot1$. This angle, which gives us a direct conception of the scattering power, may be denoted as the scattering coefficient. It is to be expected that this coefficient will vary with different materials, and will also depend on the velocity of the α-particles. Experiments in this direction will be described in the two following sections of this paper.

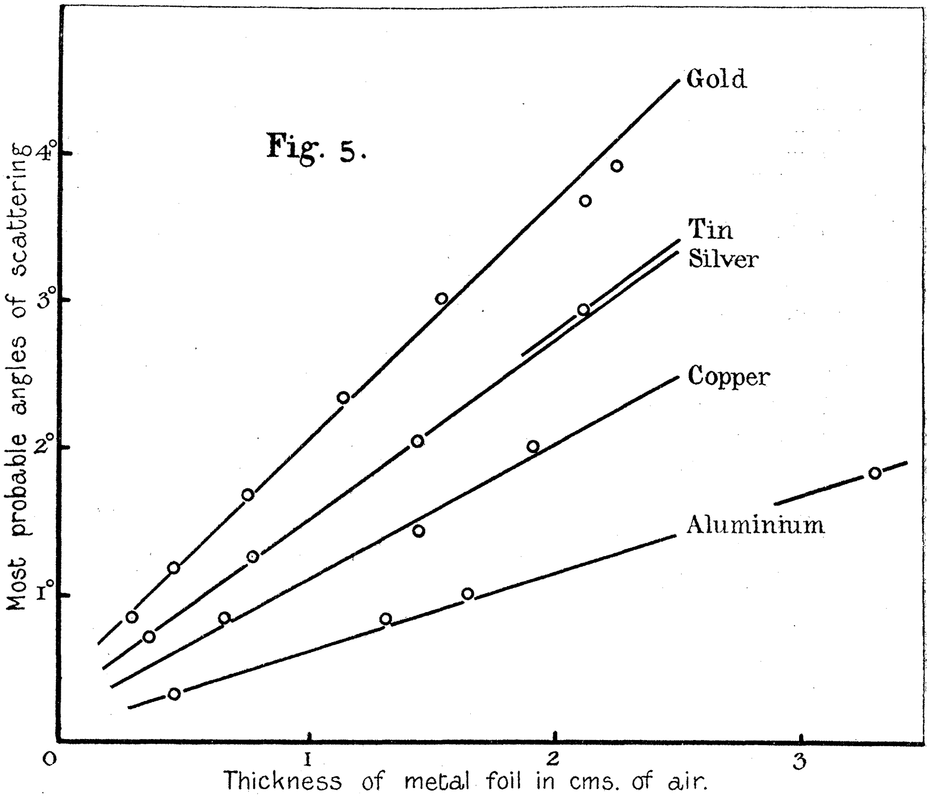
By an extrapolation from our curve (fig. 4), we are enabled to form an estimate of the most probable angle through which an α-particle is turned by the encounter with a single atom. Taking the diameter of an atom as 2×10^{-8} cm., the number of atoms through which it will pass in penetrating one gold foil of $8\cdot6 \times 10^{-6}$ cm. actual thickness will be about 160. If we assume that the square root law holds accurately for small thicknesses, we find by extrapolation that the most probable angle through which the α-particle is turned in passing through 1 atom of gold is of the order of 1/200 of a degree. This angle may be denoted as the atomic scattering coefficient of gold.

It is also of interest to refer here to experiments made by E. Marsden and myself (see 'Roy. Soc. Proc.,' A, vol. 82, p. 495, 1909) on the diffuse reflection of the α-particles. It was found that some of the α-particles falling upon a metal plate appear to be reflected, *i.e.* they are scattered to such an extent that they emerge again on the side of incidence. It was shown that from gold 1 in about 8000 of the incident α-particles suffers reflection, and that this reflection takes place within a relatively thin surface layer equivalent to about 5 mm. of air. According to the curve (fig. 4), the probable angle through which the α-particles are turned in passing through this equivalent thickness of gold is only about 1°, and a simple calculation, assuming the ordinary probability law, shows that the probability of an α-particle being scattered through an angle exceeding 90° is extremely small, and of a different order from that which the reflection experiment suggests.

It does not appear profitable at present to discuss the assumption which might be made to account for this difference.

Comparison of the Amount of Scattering produced in different Metals.

It appeared of interest to extend the measurements to other metals in order to make a comparison of their relative scattering powers. Since thin and uniform sheets could only be obtained for gold, tin, silver, copper, and aluminium, the experiments were confined to these metals. With the exception of tin, which was only available in one thickness, equivalent to 2·12 cm. of air, measurements were carried out for several thicknesses of each metal. The most probable angles of scattering obtained for different metals from the maxima in the distribution curves are plotted in fig. 5 against the respective stopping powers. The points belonging to the same metal lie approximately on straight lines, which all seem to cut the negative X axis at nearly the same distance from the origin. Thus the law which gives the most probable angle of scattering for varying thicknesses of matter appears to be similar for different metals.



The most probable angle through which an α-particle is turned in passing through a layer equivalent to 1 cm. of air has been defined above as the scattering coefficient for the material considered. These coefficients, taken from the curves (fig. 5), are entered in Column 3 of the following table. Their ratios to the square root of the atomic weight are approximately constant (see Column 4).

Remembering that the coefficients refer to *equivalent* thicknesses of the scattering metals, this result may be stated somewhat more clearly from the following consideration. The experiments of Bragg and Kleeman ('Phil. Mag.,' vol. 10, p. 318, 1905) have shown that the stopping power of an atom of atomic weight A is proportional to $\sqrt{A}$. Consequently the numbers of

Table III.

1.	2.	3.	4.	5.	6.
Scattering material.	Atomic weight, A.	Scattering coefficient,* K.	$K/\sqrt{A}$.	Relative atomic scattering coefficient,† K_0.	$\frac{K_0}{A} \times 10^2$.
		°			
Gold	197	2·1	0·150	1·00	0·51
Tin.................	119	1·5	0·138	0·56	0·47
Silver..............	108	1·5	0·144	0·53	0·49
Copper	64	1·1	0·138	0·30	0·47
Aluminium	27	0·6	0·115	0·106	0·39

* The scattering coefficient is measured by the most probable angle through which an α-particle is turned in passing through a thickness of the metal equivalent to 1 cm. of air.

† Atomic scattering coefficient denotes the most probable angle through which an α-particle is turned in passing through 1 atom of the metal.

atoms which are contained in equivalent thicknesses of different metals are inversely proportional to $\sqrt{A}$. Approximate values for the relative atomic scattering coefficients are therefore obtained by multiplying the figures in Column 3 by the square root of the atomic weight of the metal to which they refer. These coefficients are entered in Column 5, the coefficient for gold being taken as unity. It follows that they will be approximately proportional to the atomic weight itself.

We may therefore conclude that the most probable angle through which an α-particle is turned when passing through an atom is proportional to its atomic weight.

Variation of the Scattering Coefficient with the Velocity of the α-Particles.

All the previous experiments were made with homogeneous α-rays of one definite velocity. In the following set of experiments the velocity of the α-particle was varied as much as possible, while in each experiment the same thin gold foil served to scatter the α-particles.

The velocity of the α-particles was diminished by interposing in their path sheets of mica or aluminium of known stopping power. These sheets were placed directly in front of the mica window of the radiating source. The distribution curves of the scintillations on the screen were then determined in the same way as before.

In the following table, Column 2 gives the range which the α-particles still possessed after passing through the absorbing screen, and Column 3 their corresponding velocities expressed in terms of the initial velocity of the α-particles from Radium C. The observed probable angles of scattering which are seen in Column 4 give the relative scattering coefficients for different speeds of the α-particle. The curve (fig. 6) shows the rapid increase of the scattering coefficient with the decreasing velocity of the α-particle.

Table IV.

1.	2.	3.	4.	5.
Sheets interposed in addition to mica window.	Range.	Velocity, V.	Relative scattering coefficient, K.	K × V³.
	cm.		°	
(Mica window alone)	5·60	0·92	0·15	0·12
Sheet of aluminium	4·00	0·82	0·18	0·10
" mica..................	3·40	0·78	0·18	0·08
" aluminium	2·21	0·67	0·35	0·11
" mica..................	2·21	0·67	0·38	0·11
" "	1·20	0·55	0·75	0·12
" aluminium	0·89	0·48	1·27	0·14

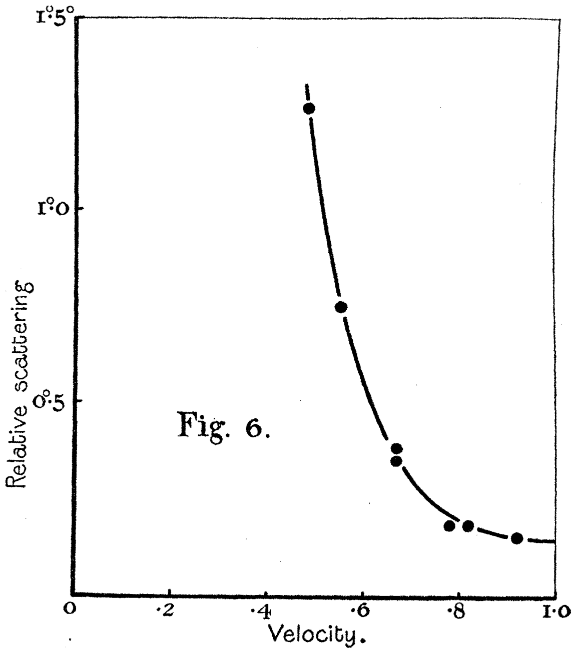


Fig. 6.

Although the accuracy of the coefficients obtained for low velocity suffered from the difficulties in counting scintillations under such conditions, it may be of interest to state that the coefficient appears to be inversely proportional to the third power of the velocity. This is demonstrated by the ratios tabulated in Column 5.

This rapid increase of the scattering coefficient with decreasing velocity suggests that scattering plays an important part in the apparent stoppage of the α-particles at the end of their range.

Results.

In all the foregoing experiments the scattering was measured by the most probable angle through which an α-particle was turned in passing through the scattering foil under investigation.

(1) The most probable angle of scattering increases for small thicknesses approximately proportional to the square root of the thickness of matter traversed by the α-particle. For greater thicknesses the scattering angle increases more rapidly.

(2) The probable angle through which an α-particle is turned in passing through an atom is proportional to its atomic weight. The actual value of this angle in the case of gold is about 1/200 of a degree.

(3) The most probable angle of scattering increases rapidly with decreasing velocity of the α-particle, being, to a first approximation, inversely proportional to the third power of the velocity.

In conclusion, I desire to express my thanks to Prof. Rutherford for his kind interest in this research.