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LVII. Scattering of α particles by gases

Professor E. Rutherford F.R.S. ^a &
J.M. Nuttall M.Sc. ^a

^a University of Manchester
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LVII. *Scattering of α Particles by Gases.* By Professor
E. RUTHERFORD, *F.R.S.*, and J. M. NUTTALL, *M.Sc.**

THE scattering of α particles by matter has been examined in detail by the scintillation method by Geiger† and by Geiger and Marsden‡. In the experiments of Geiger, the most probable angle through which an α particle was scattered was determined by the scintillation method for different thicknesses of a number of elements. It was found that the most probable angle of scattering for thicknesses of different elements, equivalent in stopping power of the α particle to one centimetre of air, was proportional to the atomic weight of the scattering element. A systematic investigation was later made by Geiger and Marsden of the "large angle scattering" by thin films of matter. The results were shown to be in complete accordance with the theory of "single" scattering advanced by Rutherford§. This theory supposes that the atom consists of a charged nucleus surrounded by a compensating distribution of electrons. The large angle scattering is due to the passage of the α particle through the intense electric field of the nucleus. It was deduced by Rutherford, and Geiger and Marsden, that the charge on the nucleus for atoms between carbon and gold was approximately proportional to the atomic weight, and was equal to $\frac{1}{2}Ae$, where A is the atomic weight in terms of that of hydrogen and e is the electronic charge. On this theory it is to be anticipated that hydrogen has a nucleus of one charge, helium of two, and carbon of about six.

As this deduction is of great importance in connexion with the constitution of the simpler atoms, experiments were undertaken to determine the scattering of α particles by the simple gases. The method employed by Geiger and Marsden for solids is not altogether suitable for gases; in addition, the large angle scattering to be expected for the light elements is exceedingly small, and would be difficult to measure with accuracy.

In some preliminary experiments, the α particles were made to pass between two parallel plates, placed a small distance apart, and the number of issuing particles were observed (1) in a vacuum and (2) when the space between the plates was filled with gas at a known pressure. The number of α particles was counted photographically, using a string electrometer. On account, however, of the probability

* Communicated by the Authors.

† H. Geiger, *Proc. Roy. Soc.* lxxxi. p. 174 (1908).

‡ H. Geiger and E. Marsden, *Phil. Mag.* xxv. p. 604 (1913).

§ E. Rutherford, *Phil. Mag.* xxi. p. 669 (1911).

variations, a very large number would have to be counted in order to obtain a reliable result. This would involve much time and labour, and it was consequently felt desirable to use a more indirect but rapid method.

The experimental arrangement finally adopted is shown in fig. 1. A narrow pencil of α particles was obtained by placing

a thin platinum wire W (see fig. 1), coated with radium C, between two thick glass plates A and B, 14.5 cm. long and 2 cm. in width, and kept about 0.3 mm. apart by mica stops. After traversing the space between the glass plates, the beam passed through a mica window M, of stopping power equivalent to 1.9 cm. of air, and then into an ionization chamber D, consisting essentially of three parallel equidistant brass plates 5 cm. long and 3 cm. wide, 7 mm. apart. The outer plates were earthed and the central one insulated and connected to the gold-leaf system of an electroscopical system E. The latter was kept exhausted in order to diminish the ionization due to β and γ rays. The upper part of the apparatus, consisting of a cylindrical glass tube (with ground-glass ends) containing the plates A and B and the source of α rays W, could be completely exhausted and filled with any gas or vapour to any desired pressure, measured in the usual way by a mercury gauge. It was necessary to employ a strong source of α particles, and this was obtained by exposing about one centimetre length of thin platinum wire 0.2 mm. diameter to radium emanation for three hours as cathode in an electric field. A short time after removal from the emanation, radium C is the only α -ray product remaining on the wire, and since its curve of decay is accurately known, the amount of radium C present at any subsequent time can be readily calculated. Care was taken to remove any traces

of emanation from the wire by washing it in absolute alcohol and heating it slightly.

The method of procedure in an experiment was as follows. An active wire was placed in position between the glass plates AB and the upper part of the apparatus was exhausted. The source W emitted a pencil of homogeneous α particles which passed through the mica window M, and the ionization they produced in chamber D was measured in the electroscope E. The whole issuing beam of α rays was completely absorbed in the chamber D, and the ionization due to β and γ rays was never more than 2 per cent. of the whole effect. If a gas is now introduced into the upper chamber, *i. e.* between the plates A and B, and the ionization current again measured, any decrease, when correction is made for decay of source, will be due either to partial absorption of α particles by the gas in the upper chamber or to the scattering of α particles against the faces of the plates resulting in a diminution in the number entering the ionization chamber. The decrease of ionization due to loss of range by absorption was measured in a separate experiment. For this purpose the plates AB forming the long narrow slit were removed, and the ionization current measured for various pressures of gas in the upper cylinder, the source W

Fig. 2.

being placed in exactly the same position as before. In this way a curve can be obtained showing the relation between the pressure of the gas in the upper cylinder and the ionization produced by the source in the chamber D. A typical curve is shown in the curve A of fig. 2*.

* Compare H. L. Bronson, Phil. Mag. xi. p. 806 (1906).

In the same figure, curve B gives the result of a typical experiment showing the effect of both scattering and absorption together. From the two curves A and B, a curve can be obtained which gives the effect of scattering alone. To obtain this, the ratios of the ordinates of the curves A and B at each pressure must be plotted. It is obvious that this ratio gives the fraction of α particles scattered by the gas at each particular pressure, and is independent of any change of ionization due to loss of range. Curve C obtained in this way indicates the amount of unscattered radiation passing between the plates at various pressures. It is seen that, over a certain range of the α particle at least, the amount of unscattered radiation passing between the plates varies nearly exponentially with the pressure of gas, *i. e.* if N_0 is the number of α particles at zero pressure and N_p the number at pressure p cm., then $N_p/N_0 = e^{-\lambda p}$, where λ may be called the "scattering coefficient" for the particular gas under the given conditions. It should be noted that this formula does not hold accurately when the pressure of the gas becomes so large that the velocity of the α particle is much reduced. For pressures of the gas, whereby the loss of range of the α particle is equivalent to more than 2 cm. of air at atmospheric pressure, the scattering will increase more rapidly. Indications of this were obtained in some of the experiments. Table I. gives the results of a typical experiment, air being used as the scattering gas.

TABLE I.

Pressure of Gas p .	Scattering and absorption.	Absorption alone.	Intensity N due to scattering alone.	$\log N_0/N_p$
				p .
0 cm.	100	100	100	
.92	84.2	98.2	86.8	.66
1.9	72.6	96.5	75.2	.65
3.55	58.0	93.0	62.5	.58
5.10	45.9	88.6	51.9	.56
7.15	33.5	82.5	40.6	.55
9.00	24.6	76.5	32.0	.55

The numbers in the last column show that the radiation is scattered approximately according to an exponential law over a considerable range of pressure.

Variation of scattering with the distance between the plates.

A few experiments were made to determine approximately the variation of scattering with the distance between the plates. The latter distance was varied from $\cdot 173$ mm. to $\cdot 89$ mm.; the corresponding least angles of scattering to deflect the α particles against the faces of the plates varying from $0^{\circ}069$ to $0^{\circ}356$.

The collected results are shown in Table II. The relative scattering coefficients are compared by observing from the curves the pressure of gas required to scatter 50 per cent. of the initial number of α particles.

TABLE II.

Distance d apart of plates.	Relative scattering coefficient λ .	$\lambda \cdot d^{5/4}$.
$\cdot 172$ mm.	$\cdot 562$	$\cdot 618$
$\cdot 325$	$\cdot 256$	$\cdot 627$
$\cdot 586$	$\cdot 126$	$\cdot 643$
$\cdot 890$	$\cdot 0712$	$\cdot 615$

Within the limits employed, the scattering appears to vary rather more rapidly than the inverse of the linear distance d between the plates and to be nearly proportional to $d^{-5/4}$.

It will be shown later that the scattering coefficient increases rapidly with decrease of velocity of the α particle. A correction has consequently to be applied to reduce the amount of scattering to a standard velocity. This correction has been made in the results of Table II.

Variation of scattering with atomic weight.

The gases whose scattering coefficients were compared were as follows:—air, hydrogen, helium, methane, carbon dioxide, and sulphuretted hydrogen. A few experiments were made on the scattering produced by the heavy vapours, methyl iodide and ethyl bromide, but they are not included in this paper. In all cases two sets of experiments were performed: (1) experiments on the scattering and absorption combined, and (2) experiments on the absorption alone. The latter were in agreement with the stopping powers of the gases as calculated by Bragg's* square-root law.

The distance between the plates was kept constant during

* W. H. Bragg, Phil. Mag. x. p. 318 (1905).

the course of these experiments, and the scattering of each gas was compared with air as a standard. The scattering curve for air, which was repeated before and after each experiment, was found to be unchanged throughout the investigation. The logarithmic curves for the different gases are shown in fig. 3. The pressures of gas are plotted as

Fig. 3.

abscissæ, and the logarithms of the intensity of the unscattered radiation passing between the plates as ordinates.

A few details of the method of preparation and purification of the gases are given.

Hydrogen. This was prepared electrolytically and dried carefully. It contained about 1 per cent. of impurity, chiefly oxygen. A correction was made for this in the curve of fig. 3, which is the mean of several experiments.

Helium. The helium was purified by passing over charcoal immersed in liquid air. This removed all traces of air and other impurities, except possibly the last traces of hydrogen.

Methane. This was prepared by acting on aluminium carbide with water and passing through cuprous sulphate to remove the acetylene. The resulting impure methane was condensed by liquid air, and pure methane obtained by fractional distillation.

Carbon dioxide was obtained from a cylinder of compressed gas, which on analysis was found to be of 99.7 per cent. purity.

Sulphuretted hydrogen was prepared by action of sulphuric acid on calcium sulphide. It was analysed and found to be of 99.8 per cent. purity.

From the results obtained in these experiments, the relative atomic coefficients of scattering were deduced for hydrogen, helium, carbon, air, oxygen, and sulphur. In the case of complex molecules, it was assumed that the scattering coefficient of the molecule was the sum of the values for each of its individual components. For example, the coefficient for carbon was deduced from the value of methane (CH_4) by subtracting from the observed value the scattering coefficient due to four atoms of hydrogen. In a similar way, the value for oxygen was deduced from CO_2 and sulphur from H_2S . A correction was required in each case to allow for the variation of scattering with velocity of the α particle. The reduction in velocity of the α particle in passing through a sufficient pressure of gas to scatter half the α particles was deduced from the loss of range of the α particle in the gas, using the relation between velocity and range found by Geiger. In making this correction it was assumed, as will

TABLE III.

Gas.	Corrected pressure to scatter half of incident radiation.	Relative scattering coefficient.	Atomic weight.	Remarks.
Air	5.32 cm.	1.00	14.4	Diatomic.
Carbon (from CH_4) ..	13.32 „	.40	12.0	Monatomic.
Carbon dioxide	3.64 „			
Oxygen	5.00 „	1.064	15.99	Diatomic.
Sulphur	3.36 „	1.61	32.0	Monatomic.
Hydrogen*	46.3 „	.0353	1.0	Diatomic.
Helium*	26.2 „	.064	3.99	Monatomic.

* In the cases of hydrogen and helium the pressures given are those required to cut down the incident radiation to 80 per cent. of its initial value, and they are compared with the pressure of air required to scatter to the same extent, viz. 1.68 cm. of mercury.

be seen later, that the scattering coefficient varied inversely as the fourth power of the velocity. In practice, the value of the pressure was corrected so as to give the scattering observed, assuming that the velocity was equal throughout to the initial value for the α particle.

Variation of scattering with velocity.

Geiger found that the most probable angle of scattering of α particles by solid matter increased rapidly with decrease of velocity of the α particle. This also holds for light gases. The initial velocity of the α particle was diminished by placing a sheet of aluminium foil of known stopping power under the active wire. The results are shown in fig. 4,

Fig. 4.

where the logarithm of the corrected ionization in the testing vessel is plotted as ordinates and pressures as abscissæ. In curve A, the initial velocity was the maximum velocity of α particles from radium C, whilst in curve B the initial velocity was 0.893 of the maximum velocity. The scattering coefficients observed in the two cases were in the ratio 1:1.66. The scattering thus varied approximately as the

inverse fourth power of the velocity. This is the law of scattering with velocity found by Geiger and Marsden in their experiments on "single" scattering.

Consideration of the Results.

In drawing deductions from these experiments, it is of importance to decide whether the scattering coefficient observed is to be ascribed to "single" or "compound" scattering. If the reduction in the number of α particles in passing between the glass plates is due mainly to "single" scattering, we should expect the scattering to vary directly as the pressure of the gas and inversely as the fourth power of the velocity—results observed experimentally. On the other hand, if the reduction in number is due mainly to "compound" scattering, we should expect that the scattering should be proportional to the square root of the pressure, and to vary as the inverse square of the velocity. It is thus clear from the experiments that the scattering coefficient observed is a consequence mainly of "single" scattering. This conclusion is still further strengthened by the rapid variation of the scattering with atomic weight between carbon and sulphur. No doubt "compound" scattering produces some effect, but the main part of the scattering is to be ascribed to the scattering of individual atoms resulting from the passage of the α particle through the intense field close to the electrons and the nucleus. If we consider the atom to be composed of a nucleus with a charge ne and a compensating distribution of n electrons, the scattering due to the n electrons is proportional to n , and the scattering due to the nucleus is proportional to n^2 . Mr. C. Darwin kindly examined this question mathematically for us, and concluded that if the electrons and the nucleus were a sufficient distance apart so as not to interfere seriously with the electric fields close to them, the scattering for simple atoms should be proportional to $n + n^2$ or $n(n+1)$, where ne is the charge on the atomic nucleus. For deflexions through a small angle, such as are involved in the experimental arrangement employed in this paper, we should expect the scattering in the heavy atoms to be proportional to $n + kn^2$, where k is less than unity. This is borne out by the fact that under the experimental conditions the scattering due to heavy atoms like bromine and iodine was found to be less than the theoretical values when k is taken as unity. Assuming the simple formula found by Darwin as applicable to light atoms, the scattering coefficient λ is proportional to $n(n+1)$ or $\lambda = cn(n+1)$, where c is a constant.

It should be noted that Geiger and Marsden found that the "single" scattering per atom was proportional to the square of the atomic weight. This undoubtedly holds in the case of heavy elements for large angles of scattering, where the α particle passes close to the nucleus. It is a different matter, however, when the scattering angle is only about $1/10$ of a degree, as in the present experiment. It is to be anticipated that under such conditions this simple law would be widely departed from, especially in the case of heavy atoms for which the number of electrons is large.

The following table gives the observed and calculated scattering coefficient for an *atom* of each of the elements examined. The value of n , the number of electronic charges assumed for the nucleus, is given in the second column. For a comparison of the calculated with the experimental values, carbon is assumed in both to have a scattering coefficient of 40 on the arbitrary scale. The scattering coefficient for nitrogen is deduced on the assumption that air is composed of 80 per cent. of N with 20 per cent. of O.

Gas.	Assumed value of n .	Relative scattering per atom.	
		Calculated values.	Experimental values.
H atom ...	1	·0190	·0176
He „ ...	2	·057	·064
C „ ...	6	<u>·40</u>	<u>·40</u>
N „ ...	7	·53	·48
O „ ...	8	·69	·53
S „ ...	16	2·58	1·61

Considering the difficulty of determining with accuracy the scattering by the light gases, the agreement between the simple theory and experiment is as close as could be expected for hydrogen, helium, and carbon. The probable explanation of the divergence between theory and experiment for the heavier atoms, like sulphur, has already been outlined. From the experiments of Geiger and Marsden (*loc. cit.*) on the large angle scattering of α particles by carbon, it is clear that the carbon atom behaves as if the nucleus carries a charge of about six units. Assuming this value of n for carbon, the results indicate that the hydrogen nucleus has a charge of *one* fundamental unit and the helium nucleus of *two* units. This value for helium is to be anticipated from

the observed fact that the α particle in its flight carries two unit positive charges.

The observations on the scattering of α particles by matter in general afford strong experimental evidence for the theory that the atom consists of a positively charged nucleus of minute dimensions surrounded by a compensating distribution of negative electrons. The charge on the nucleus for heavy atoms is approximately $\frac{1}{2}Ae$, where A is the atomic weight and e the electronic charge. The experiments in this paper on the scattering of simple gases indicate that the hydrogen atom has the simplest possible structure of a nucleus with one unit charge, and helium comes next with a nucleus of two unit charges. This simple structure for hydrogen and helium atoms has been assumed by Bohr* in a recent interesting paper on the constitution of atoms, and has been shown by him to yield very promising results.

We desire to express our thanks to Dr. Pring for his assistance in preparing and purifying the gases employed.

University of Manchester,
July 1913.

LVIII. *On the Transmission of X Rays through Metals.* By H. B. KEENE, Assistant Lecturer in Physics at the University of Birmingham†.

MANY investigators have studied the transmission of X rays through metal sheets and the distribution of the "incident" and "emergent" radiation. The method of measurement adopted has been an electrical one, the photographic method having fallen into disuse. Its revival in the experiments of Messrs. Friedrich, Knipping, and Laue on the transmission of X rays through crystals and the remarkable results obtained, suggested that interesting results might follow with materials other than crystals if the ionization chamber was replaced by the photographic plate. It seemed probable that the ionization method might have overlooked certain effects which the photographic plate would record. A photographic investigation of the "incident" and "emergent" radiation from metal sheets led to some striking results which are described in the present paper.

* Phil. Mag. July 1913.

† Communicated by Prof. J. H. Poynting, F.R.S.