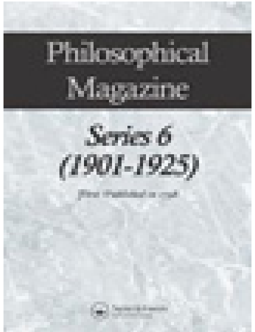

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XIX. Retardation of the α particle from radium in passing through matter

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on the screen and to ask a red-blind to make a match in luminosity with the white. The latter will have to be reduced to almost darkness—a darkness, indeed, that makes the match almost incredible."

It seems incredible that such a person, when comparing red and green with a Flicker photometer, would obtain the same results as if he had normal sight. However, it appears that, according to Dr. Edridge Green *, colour-blindness is of two kinds. A person may be unable to distinguish, say, red-light by colour, but nevertheless a red object may appear as *luminous* to him as to anyone else. On the other hand, the colour-blindness may be due to the fact that the eye is incapable of perceiving red light at all. A colour-blind person of the first variety would presumably make normal photometrical readings. A person of the second class must, surely, obtain abnormal readings with all photometers, Flicker or otherwise.

This is borne out by some of Professor O. N. Rood's experiments on flicker †. He found that those of his students who were colour-blind obtained abnormal results with his Flicker photometer. Indeed, he actually used the Flicker photometer to investigate not only cases of colour-blindness but also the difference in sensibility to light of different colours, of the eyes of persons with normal sight.

In conclusion the writer wishes to express his great indebtedness to Professor Ayrton, and also to Mr. J. M. McEwan, for their assistance and for many valuable suggestions.

XIX. *Retardation of the α Particle from Radium in passing through Matter. By* E. Rutherford, *F.R.S., Professor of Physics, McGill University, Montreal* ‡.

[Plate II.]

In previous papers § I have given an account of some experiments which show that the α particles decrease in velocity in their passage through matter. The source of rays consisted of a fine wire, which had been made active by exposure as the negative electrode in a vessel containing a large quantity of radium emanation.

Fifteen minutes after removal from the emanation, the

* "The Physical Aspects of a Theory of Colour Vision," by F. W. Edridge Green, M.D., British Association, 1902.

† American Journal of Science, 1899, p. 258.

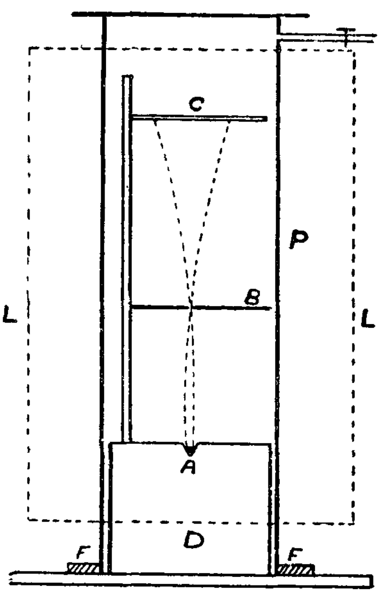
‡ Communicated by the Author.

§ Phil. Mag. July 1905, January and April 1906.

α radiation comes only from the product radium C. I have shown that such an active wire acts as a source of homogeneous radiation; *i. e.*, the α particles which escape from the wire all move at the same speed, and consequently are all deflected to the same extent by a magnetic field.

It is known from the work of Bragg and Kleeman that the α particles from each simple product have a definite range of ionization in air. One of the objects of the present experiments was to determine the velocity of the α particle corresponding to each point of its path in air, in order to determine the law of diminution of velocity of the α particle. This has been accomplished indirectly by observing the velocity of the α particles from radium C after passing through different numbers of layers of aluminium-foil, the stopping power of each layer being separately determined in terms of air by the scintillation or electrical method. The general arrangement of the apparatus is shown in fig. 1.

Fig. 1.



The active wire A was placed in a triangular groove in a solid brass cylinder D which was soldered to a base-plate. A vertical bar was attached to one side of the brass cylinder. By means of a slot in the centre, two movable frames B and C were attached, one of which carried the slit, and the other the small piece of photographic plate. By means of side screws, the distance of the slit and photographic plate from the source could be altered at will. Over this apparatus was placed a brass tube P closed at the upper end. To the lower end was attached a flange FF, which was ground accurately to fit the base-plate. By the use of tap-grease the flange formed an air-tight joint, and the vessel could be at once exhausted by a Fleuss pump without the necessity of waxing down the brass tube to the base-plate. This saving of time as well as of trouble was of great importance in experiments to be described later, in which the magnetic deflexion of the α rays from radium A was determined.

The whole apparatus was fixed on a wooden frame and placed between the poles of a large electromagnet so that the source of rays and the slit were parallel to the direction of the magnetic field. In these experiments, the magnetic field was practically uniform over the whole path of the rays. The extent of this magnetic field is shown by the dotted lines LL in the figure. The electromagnet was excited by a constant current of 12 amperes, and was kept from overheating by an electric fan. The duration of exposure of the plate in the magnetic field was usually two hours, the direction of the field being reversed every ten minutes.

In most of the experiments, the region between the active source and the photographic plate was divided into two equal parts by means of vertical mica plates. One half of the active wire was either bare or covered with some known absorbing screen, while the other half of the wire was covered with the number of layers of aluminium-foil under examination. In this way two sets of bands were obtained on the photographic plate, the distance between the centres of the bands of each set representing twice the deflexion in the magnetic field of the pencil of rays from the normal. The distance between the deflected bands is inversely proportional to the velocity of the α particles after emerging from the absorbing screen.

Measurement of the Photographic Plates.

In a previous paper, I pointed out a peculiarity exhibited by the photographic trace of a pencil of α rays from the active wire when a narrow slit was used. The trace of the pencil of rays consisted of two dark lines with sharply defined outside edges, and with a whitish line running symmetrically down the centre of the trace. This effect was shown to be a necessary consequence of the fact that the

α particles were projected uniformly in all directions from the thin film of active matter distributed over the wire. This sharpness of the edge of the photographic trace with or without the magnetic field materially assisted in making an accurate measurement of the distance between the centres of the deflected bands obtained by reversal of the magnetic field.

In connexion with the experiments described in this and later papers, I have, in all, made more than a hundred photographs showing the effect of a magnetic and an electric field in deflecting a pencil of α rays under various conditions. Since each of these photographic traces, obtained on the plates, had to be accurately measured up, it may be of interest to others engaged in similar observations to describe in some detail the method finally adopted.

A microscopic method was first used, but this proved very trying to the eyes, and could only be used with advantage when the photographic traces were strongly marked. I finally had recourse to the following procedure. The small piece of photographic plate was mounted on a clear glass plate of the same size as a lantern-slide. This was placed as a slide in an ordinary arc-lantern and a magnified image of the photograph thrown on a screen. In most of the experiments, the magnification used was between 20 and 40, and was determined by means of an accurately subdivided millimetre-scale on glass placed in the position of the photographic plate. The image to be measured was thrown on a cardboard screen fastened into a large drawing-board. The observer with a sharp pencil then marked the edges of the photographic traces at intervals along the whole length. The screen was then removed and lines drawn through the points of observation, and the distances between the parallel lines measured by means of a scale and vernier.

With a clear photograph, the measurements obtained by two separate observers in the course of a few minutes did not differ more than a half per cent., while the mean of a number of observations was in very close agreement.

The great advantage of the lantern over the microscopic method lies in two factors. In the first place, the observer sees clearly the whole outline of the photographic traces before him, and is not likely to make a false estimate of the edge of the line on account of local imperfections of the plate. In the second place, even very weak photographic traces show up clearly on the screen, and can be measured with much greater rapidity and certainty and with less labour than by the use of the microscope.

Retardation of the α Particles in passing through Aluminium.

The experiments given in a preliminary paper have been repeated with greater accuracy, and by using more active wires and with the photographic plate at a smaller distance from the source, I have been able to determine the velocity of the α particle closer to the end of its range of ionization in air.

The method adopted was to determine the deflexion of a pencil of α rays after passing through successive layers of aluminium-foil. Each layer of foil was found by a separate experiment to be equivalent in stopping power to about 0·50 cm. of air.

In these experiments, the slit was 2 cms. from the wire and the photographic plate 2 cms. from the slit. This gave a conveniently large deflexion of the pencil of α rays in a magnetic field of strength about 8000 C.G.S. units. One side of the active wire was bare, and the other covered successively with 2, 4, 6, 8, 10, and 12 layers of aluminium-foil. Although a very strong photographic effect was obtained with the bare wire, the effect through the 12 layers of foil was very weak, but was sufficiently well defined for accurate measurement. The slit was then removed to a distance of 0·5 cm. from the source and the plate to within 1·5 cms. of the slit. The intensity of the photographic impression was consequently increased four times, and the part of the active wire covered with the 12 layers gave a well-marked effect on the plate. The amount of deflexion of the pencil of rays was, however, reduced to ·375 of that observed at the first distance. The other side of the wire was successively covered with 12 and 14 layers of foil, and the deflexions compared with that due to the original 12 layers, used as a standard of comparison.

A weak though measurable impression was obtained through 14 layers. Two layers of Dutch metal, equivalent in stopping power to ·64 of a layer of foil, were then added. A slight darkening of the plate was noted, but was too weak and ill-defined for measurement.

The results obtained are collected in the following table, where the velocity of the α particles is expressed in terms of V_0, the velocity of the α particles from the unscreened wire. It will be shown in a later paper that the value of e/m for the α particle is unchanged by its passage through matter, so that the deflexion of the pencil of rays in a magnetic field is inversely proportional to the velocity of the rays.

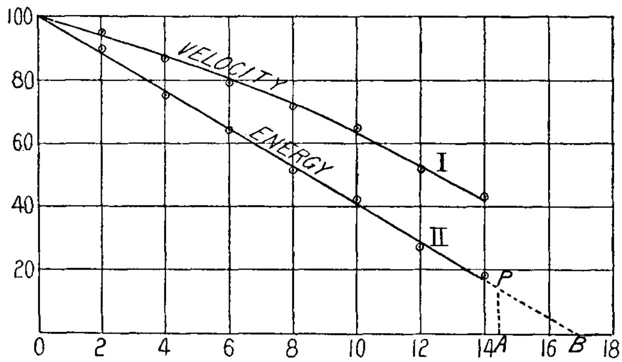
Number of Layers of Aluminium-foil over the Wire.	Velocity.
0	1·00 V_0
2	·95 „
4	·87 „
6	·80 „
8	·72 „
10	·65 „
12	·52 „
14	·43 „
14·6	not measurable.

The lowest velocity observed was ·43 V_0, due to the rays which had passed through 14 layers of foil.

One of the main difficulties in these experiments arose from the slight variations of thickness of the individual layers of foil. The sheet of foil to be used was doubled on itself so as to obtain the requisite number of layers, slightly pressed together, and an area of suitable size cut out. Care has to be taken in making sure of the number of foils in the layers, for it is not an easy matter to count them with certainty when once the foils have been pressed together. This may appear to be a small point; but I have found by experience how easy it is to make a mistake.

The thickness of foil used in the experiment was found by the scintillation method to be equal in stopping power to almost 0·50 cm. of air. 14 layers thus corresponded to a

Fig. 2.



LAYERS OF ALUMINIUM FOIL.

thickness of about 7·0 cms. of air. Since the range in air of the *α* particles from radium C is 7·06 cms., this thickness of foil was nearly sufficient to absorb completely the *α* rays.

The results given above are shown graphically in fig. 2, Curve I. The velocity of the rays from the bare wire is taken as 100. The abscissæ represent the number of layers of foil over the active wire. Curve II. shows the energy curve, the energy of the α particle escaping from the bare wire being taken as 100. This was obtained by taking the squares of the observed velocities. It will be seen that the points lie nearly on a straight line, which cuts the axis of abscissæ at a distance corresponding to 16·9 layers of foil. Each layer of foil absorbs absorbs about 6·0 per cent. of the maximum energy of the α particle.

The photographic effect of the rays after passing through 14 layers of foil was not more than 5 per cent. of that produced by the bare wire in the same interval. The actual energy of the α particle at this stage is ·18 of the initial energy, so that it is seen that the photographic intensity of the α particles near the end of their course falls off more rapidly than their kinetic energy.

Taking as the most probable value that the α rays are completely absorbed in 14·4 layers of foil, which would correspond to 7·06 cms. of air at atmospheric pressure and temperature, we see that each layer of foil on an average corresponds to slightly less than 0·50 cm. of air.

Now the continuation of the energy curve cuts the axis for a thickness of aluminium corresponding to 16·9 layers of foil, which is equivalent to a distance of air equal to $(16·9-14·4)\times 0·50$, or 1·25 cms. of air beyond the distance 7·06 cms. required for complete absorption. Consequently, the velocity of the α particles which have a range r cms. in air after passing through an absorbing screen is proportional to $\sqrt{r+1·25}$. The ratio K of the velocity V of the α particle of range r to the velocity V_0 of the α particle from the bare wire is given by

$$K=\frac{r}{r_0}=\frac{\sqrt{r+1·25}}{\sqrt{7·06+1·25}}=·348\sqrt{r+1·25}.$$

For example, the range r of the α particles from radium C after passing through 8 layers of foil (equal to 4·0 cms. of air) is 3·06 cms. The ratio K is consequently ·72.

We therefore see that the velocity of the α particle of any known range in air can be deduced from a simple formula.

We shall show in a later paper that the value of e/m is the same for the α particles from radium A, radium C, and radium F (polonium). It thus appears probable that the α particles from the various radium products have all the same value of e/m. If this be the case, we are at once able to deduce from the above formula the initial velocity of the α particles expelled from a thin film of each of the radium products. The values are collected in the table given below and are expressed in terms of V_0, the initial velocity of the α particles expelled from radium C.

Product.	Range of α particles in air.	Calculated velocity.	Observed velocity.	Value $\frac{mv}{e}$.
Radium	3·50 cms.	·750 V_0	·76 V_0	$3·04 \times 10^5$
Emanation...	4·23 „	·814 „	......	$3·30 \times 10^5$
Radium A ...	4·83 „	·858 „	·88 V_0	$3·48 \times 10^5$
Radium C ...	7·06 „	1·000 „	1·00 „	$4·06 \times 10^5$
Radium F ...	3·86 „	·787 „	·81 „	$3·20 \times 10^5$

The ranges of the α particles from the radium products are taken from the paper of Bragg and Kleeman. The range of the α particles from radium F (polonium) has been found by Dr. Levin in the laboratory of the writer.

In the fourth column are given the values of $H\rho = \frac{mv}{e}$, where H is the strength of the magnetic field, ρ the radius of curvature of the path of the rays, and e, m, v have the usual signification. I have redetermined accurately the initial value of $H\rho$ for the α particles expelled from radium C and found the value $4·06 \times 10^5$, in place of the value $3·98 \times 10^5$ given in a previous paper. The values of $\frac{mv}{e}$ have been deduced from the calculated velocity and the value given above.

We shall now consider some direct experiments that have been made to determine the velocity of the α particles from some of the radium products in terms of V_0, assuming that e/m has the same value for the α particles from all products.

Magnetic Deflexion of the α Particle from Radium itself.

About one milligram of pure radium bromide, spread uniformly in a narrow groove, served as a source of α rays. The radium was heated to a sufficient temperature to drive off the emanation completely. After three hours, the products radium A and C have nearly disappeared, and the α radiation then mainly comes from radium itself. The magnetic deflexion of the pencil of rays was determined in the standard apparatus (fig. 1), using a narrow slit. The trace of the rays was first obtained without a magnetic field. The deflected traces on each side of the central band were then obtained by reversal of the magnetic field. The actual photograph obtained in this way is shown in fig. 3 (Pl. II.)

Since the layer of radium was of sensible thickness, the α particles escaped from the radium over a wide range of velocity, and the rays were unequally deflected by the magnetic field. The inner surface of the deflected bands was, however, produced by the rays of maximum velocity from the radium, which it is our object to determine. The distance, for example, from the right edge of the photographic trace, obtained without a magnetic field, to the inside of the deflected band on the left represents the deflexion of the rays of maximum velocity expelled from the radium. The deflexion was compared with that due to the rays from a bare wire coated with radium C. In this way, it was found that the initial velocity of the α particles expelled from radium is $\cdot 76 V_0$—a value which agrees closely with the value $\cdot 75\, V_0$ calculated from the formula. By observation of the outside limit of visible photographic effect, the lowest velocity of the α rays which just produced visible photographic action was found to be $\cdot 51 V_0$.

Magnetic Deflexion of the α Particles from Radium A.

Since the activity of radium A decreases to half value in 3 minutes, an accurate measurement of the magnetic deflexion of its rays by the photographic method was a matter of some difficulty. The radium A was collected on a thin wire by exposing it for 3 minutes in the presence of a large quantity of emanation. Before the introduction of the wire, the emanation had been exposed to a strong electric field so as to remove as much as possible of the radium C which has a tendency to collect in the emanation vessel. During the time of exposure, 3 minutes, the wire collects one half of the equilibrium amount of radium A upon it and very little radium C. A photographic plate was first placed in position in the apparatus shown in fig. 1. The active wire was then quickly removed, placed in position, and the cover fixed on. Not more than half a minute elapsed after the removal of the wire before the apparatus was in position between the poles of the magnet, and the vessel exhausted to a pressure of a few millimetres of mercury. The field was reversed every half minute for six minutes, when the plate was removed and developed.

After intensification, the deflected bands were sufficiently clearly defined to be measured. The amount of magnetic deflexion was 1·14 times as great as for a bare wire coated with radium C exposed under the same conditions. This makes the observed value of the velocity of the α particles of radium A $\cdot 88 V_0$, which is in good agreement with the value $\cdot 86 V_0$, previously deduced from its known range in air.

Another photograph was taken in which the active wire was covered with a layer of mica equivalent in stopping power to 3·5 cms. of air. The measurements in this case were complicated by the fact that the rays from radium C on the wire produced also a comparable photographic effect. Two broad bands were consequently obtained, the outer parts of which were due to the rays from radium A. Allowing for the known width of the trace of the undeflected pencil, the velocity of the α particles from radium A after passing through 3·5 cms. of air was found to be $\cdot 54 V_0$. The value deduced from measurement of the range of the rays in air, viz. 1·3 cm., is $\cdot 56 V_0$. Considering the difficulty of measuring such weak photographs, the observed and calculated values are in as good agreement as could be expected.

Radium F.

It has not been thought necessary to determine directly the magnetic deflexion of the α rays from radium F (polonium), for this has already been done with accuracy by Mackenzie (*loc. cit*). Using a rod covered with a thin film of polonium, he found the value of $H\rho$ for the polonium rays to be $3{\cdot}30 \times 10^5$. The value (see previous table) deduced from the range and known value of $H\rho$ for radium C is $3{\cdot}20 \times 10^5$, which is in substantial agreement with the value determined by Mackenzie.

I have not so far separately determined the magnetic deflexion of the rays from the emanation. I think, however, that there can be little doubt that the velocity $\cdot 81 V_0$, deduced from the known range of the rays, is close to the true value. Experiments are in progress to obtain if possible on a single photographic plate the separate traces of the rays from each of the four α ray products of radium in equilibrium. This should be theoretically possible using a very thin film of radium in equilibrium as a source of rays. It is doubtful, however, whether it will be practically possible to obtain a complete separation of the traces due to the rays from the emanation and radium A, on account of their velocities of projection being nearly the same.

Scattering of the α Rays.

When Bragg first put forward his theory of the absorption of the α rays, which has received such a remarkable measure of verification in the last two years, he pointed out that on general theoretical considerations there should be a marked difference in the character of the absorption of α and β rays by matter. Although the β particle is in most cases projected at a much greater velocity than the α particle, yet, on account of its very small mass, its kinetic energy is much less than that of the α particle. Since the atom is the seat of intense electrical forces, the β particle in passing through matter should be much more easily deflected from its path than the massive α particle. We know experimentally that this is the case. A narrow pencil of β rays, incident on matter, emerges as a diffuse ill-defined cone of rays. This scattering of the β rays, as Bragg pointed out, probably accounts for the exponential law of absorption of homogeneous β rays by matter.

On the other hand, the α particle, on account of its enormous energy of motion, plunges through the atoms of matter without suffering much deflexion from its path. As I pointed out in a previous paper, there is, however, an undoubted slight scattering or deflexion of the path of the α particle in passing through matter. This is clearly seen from the two photographs shown in fig. 3 (Pl. II.). The space between the radiant source and the photographic plate (see fig. 1) was divided into two parts by a mica screen. An active wire coated with radium C was used as a source of rays. One half of the top of the slit was covered with a plate of mica equivalent in stopping power to 3·5 cms. of air. The dark well-defined band in one photograph (fig. 3 A) represents the trace of the rays which have not passed through the mica, the diffuse band the trace of the rays after passing through the mica. If there were no scattering of the rays, the two bands should be equally well defined. A very similar scattering is observed in a strong magnetic field (see fig. 3 B), showing that the effect produced cannot be ascribed to the slow-velocity electrons which are so copiously emitted by matter through which the α particles pass, for these would be bent away from the photographic plate by the strong magnetic field.

This broadening of the photographic trace is naturally not exhibited if the absorbing screen is placed over the source instead of over the slit.

From measurements of the width of the band due to the scattered α rays, it is easy to show that some of the α rays in passing through the mica have been deflected from their course through an angle of about 2°. It is possible that some were deflected through a considerably greater angle; but, if so, their photographic action was too weak to detect on the plate.

This scattering of the α particles increases, as we should expect, with the decrease of velocity of the α particle. From the values of e/m and V for the α particle, given in the next paper, it can easily be calculated that the change of direction of 2° in the direction of motion of some of the α particles in passing through the thickness of mica (·003 cm.) would require over that distance an average transverse electric field of about 100 million volts per cm. Such a result brings out clearly the fact that the atoms of matter must be the seat of very intense electrical forces—a deduction in harmony with the electronic theory of matter.

Discussion of Results.

The α particles from a thin layer of one kind of radioactive matter are all expelled with the same velocity, and after passing through an absorbing screen, all emerge with the same, though diminished velocity. We have already drawn attention to the rapid decrease of photographic effect due to a pencil of rays from an active wire when the rays pass through an absorbing screen. The photographic effect of the α particles towards the end of their path in air certainly decreases far more rapidly than the kinetic energy of the α particles themselves.

This rapid decrease of the photographic effect is not to be ascribed to a decrease of the number of α particles falling on the plate, but to a decrease of the photographic effect produced by each α particle. The general results of my experiments have led me to conclude that the photographic effect due to an α particle is approximately proportional to its range in air. On this hypothesis, the α rays from an active wire coated with radium C (range 7 cms.) produce, at a given distance in a vacuum, seven times the photographic effect of the same pencil of rays after passing through an absorbing layer equivalent to 6·0 cms. of air.

The range of the α particles after emerging from the screen is in this case 1 cm. On this view, the α particle from radium itself (range 3·5 cms.) only produces half of the photographic effect of the α particle from radium C.

In a similar way, I have observed that the brilliancy of the scintillations produced by the α rays in zinc sulphide decreases rapidly as the range of the α particles is cut down by the use of absorbing screens. Experiments are in progress to test quantitatively whether the intensity of the luminosity produced in a zinc-sulphide screen, as well as of the photographic effect, is directly proportional to the range of the α particles in air. Such a connexion is to be expected if both the photographic and luminous effects are directly or indirectly due to ionization by the α particles of the substances involved.

In regard to the question whether the α particle has a "critical" velocity, below which it is unable to produce its characteristic effects, it is difficult to give a definite answer. The α particle certainly appears to have such a "critical" velocity, but there appears to be no obvious reason why the α particle should suddenly lose its ionizing power when its velocity is still very great. Bronson has made an investigation to see whether the α particle produced any appreciable ionization beyond its normal range of strong ionization in air, but with negative results. We have to conclude either that there is a definite critical velocity (about ·4 of the maximum velocity of the α particle from radium C), or that the velocity of the α particle decreases very rapidly when it falls below that amount. The question is complicated by the slight scattering of the α particles in passing through matter, for this makes definite deductions from the experiments very difficult. I hope to make further experiments to throw light on this important question.

We have seen that it is possible to determine with accuracy the value of $\frac{mv}{e}$ for the α particles emitted by radium, radium A, and radium F by measurements of the retardation of the α particles of the single product radium C in passing through matter. Such a result affords an almost certain proof that the value of e/m is the same for the α particles expelled from each of these products; for while the measurement of the magnetic deflexion of the rays gives the momentum of the α particle, the range of the particle *plus* a constant is proportional to the kinetic energy of the α particle. Unless e/m is the same for each product, we should not expect the observed and calculated values of $\frac{mv}{e}$ to agree.

It will be shown in a future paper, that this conclusion has been confirmed by direct measurement of the value of e/m for the particles expelled from the various radium products.

McGill University, Montreal,
June 14, 1906.

Fig. 3 b.

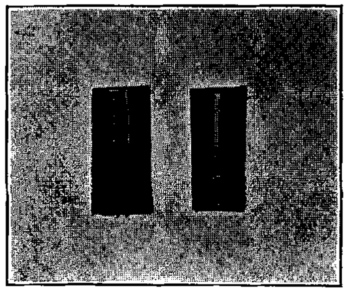
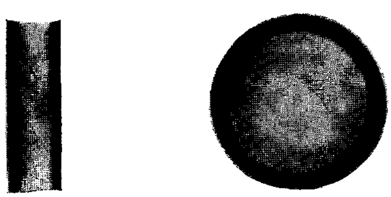


Fig. 3 a.

Fig. 1



A. B.

Fig. 4.

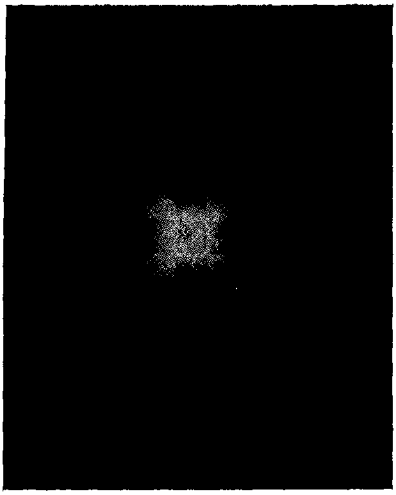


Fig. 6.

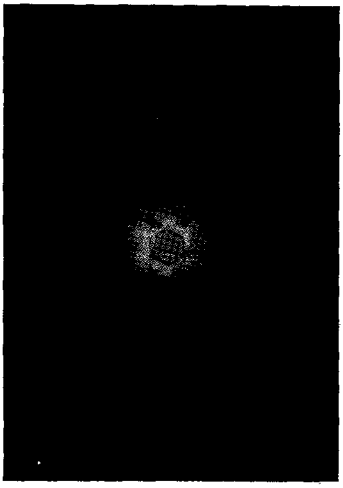


Fig. 5.

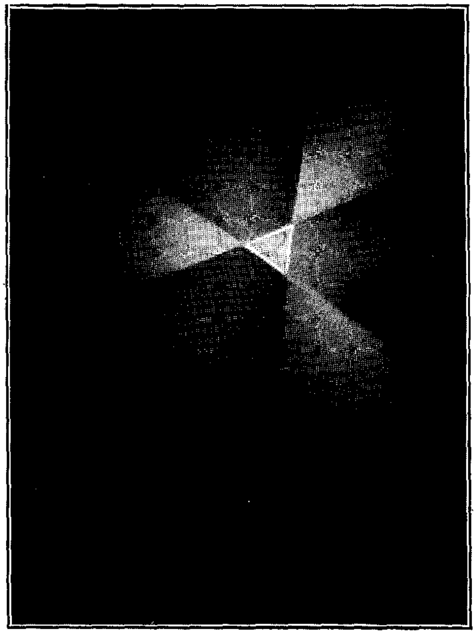


Fig. 8.