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"AN INVESTIGATION OF SOME WAVE-PROPERTIES OF BETA-RAYS".

by

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P R E F A C E.

The following thesis contains an account of researches performed by the author in the Research Laboratories of the Natural Philosophy Department at Glasgow University. The sequence of the experimental work is given in the order in which it was carried out, each part leading on naturally to the following one. The investigation of diffraction by methods similar to those used in cathode ray work failed to produce results, but on the other hand an effect was obtained which gave results very similar in their nature to diffraction. This was therefore investigated and thereafter attention was turned to original methods which might be utilised in the study of diffraction. As the method of detection was of fundamental importance the action of electrical counters was studied and this resulted in the discovery of new types of electrical 'counters', the detecting vessels being H.F. discharge-tubes of various kinds. Finally an entirely original method was devised to investigate diffraction and results were obtained by transmission of β -rays from radium E through films of gold and aluminium.

The author performed the experiments under the supervision of Professor E. Taylor Jones whom he thanks for the advice and encouragement which he gave throughout the course of the research. He is also much indebted to him for the many helpful suggestions which he made. The author thanks Dr. John Thomson for his interest in the work on the H.F. discharge-tube counters and for his useful suggestions in connection with it.

The diffraction of electrons is a subject which has received considerable attention, both theoretical and experimental, in recent years. Since Elsasser [1] suggested that evidence for the wave-nature of electrons would be found in their interaction with crystals considerable attention has been devoted to the matter, the fundamental principle being that strong support for the wave theory of particles would be obtained if it were possible to measure some quantity which could be regarded as a wave-length, and if it were found that the values agreed with the de Broglie [2] equation $\lambda = h/mv$ where λ is the wave-length, h is Planck's constant, m and v the mass and velocity of the particle respectively. The experiments of Davisson and Germer [3] mark the beginning of a series of investigations of the diffraction of electrons. They showed that electrons, of energy between 65 and 600 electron-volts, were diffracted by a single nickel crystal and that their measurements satisfied the equation $\lambda = h/mv$. In this work the electrons were obtained from a hot cathode, a tungsten filament. The next step was made by G. P. Thomson and A. Reid [4] who passed a beam of cathode rays from a discharge-tube through a thin celluloid film. They verified that $D\sqrt{P}$ was constant where D is the diameter of the diffraction ring (the patterns being formed on photographic plates) and P is the voltage accelerating the electrons. Results for metal films, celluloid films, mica films and so on have been obtained by these and other workers.[5] The diffraction patterns sometimes took the form of a series of concentric rings round the spot formed by the undeflected beam and in other cases the intensity was more or less concentrated in a series of spots on the circumference. The agreement in velocity between the rays forming the rings and those in the central spot was exact to well within 1%, the rings being formed by electrons which had undergone elastic collisions therefore. Rupp[6] made a series of experiments on the diffraction patterns formed by slow electrons, of energy 150 to 290 electron-volts, going through thin metal films. He used both specially sensitised photographic plates and a Faraday cylinder as detectors of the electrons. The problem of the diffraction of electrons has been studied carefully for the lower energies, corresponding to potentials from 50 to 100,000 volts, but few experiments have been tried with electrons of energy greater than 100,000 volts. The de Broglie equation $\lambda = h/mv$ has however been verified up to 250,000 volts by Rupp [7] employing the method of transmission through thin polycrystalline films with photographic detection. Kosman and Alichanian [8] obtained diffraction patterns for electrons up to 520,000 electron-volts energy without verifying the law for the wave-lengths employed. The problem of the diffraction of β-rays becomes important for two reasons:-

(1) the velocity of β-particles is normally greater than that of artificially produced cathode rays;

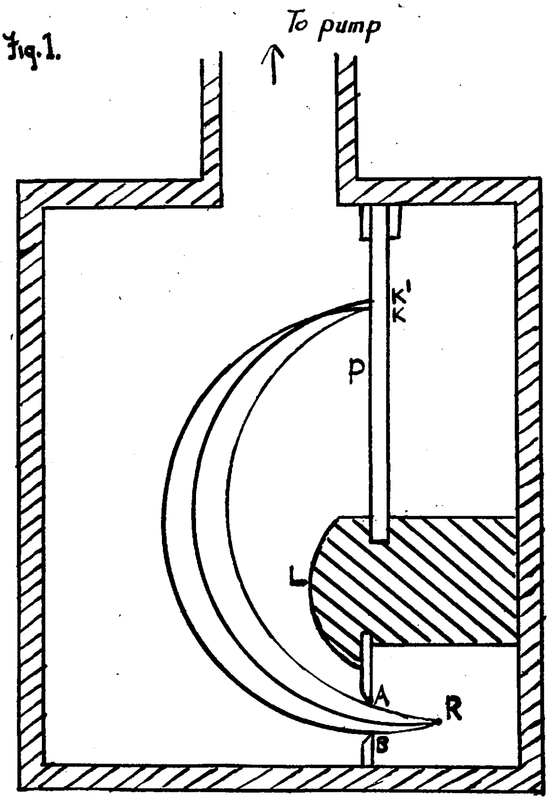
(2) it is important to co-relate the β-particle with the

electron in the property of being diffracted by crystals.

Many technical difficulties are encountered on approaching this problem. For one thing, in most experiments performed with cathode rays care is taken to make the beam homogeneous and the difficulty can be satisfactorily overcome in this case.(9) In the case of β-rays however this is a very serious difficulty. The β-radiation emitted by a radioactive source is not homogeneous and in most cases the particles have a considerable range of velocities. To obtain a homogeneous beam it is necessary to adopt some kind of resolving device such as a magnetic field with the result that the primary beam is of very low intensity. A further complication is introduced by the fact that there is generally a strong γ-radiation present emitted by the β-ray source. The measurement of a weak beam of β-particles in the presence of strong γ-radiation is a matter of some difficulty.

The first experiments were carried out with 1 mg. of radium itself but it was found that even with long exposures strong central spots could not be obtained. The rays were not homogeneous in this case as they simply passed through a system of collinear apertures and fell on a photographic plate at some distance. It was realised that work could not be advanced with a source of this strength and in the place of radium, radon capillaries, varying according to requirements from 10 to 80 millicuries in capacity were used. These were analysed by means of the semi-circular focussing apparatus (10) shown diagrammatically in fig 1.

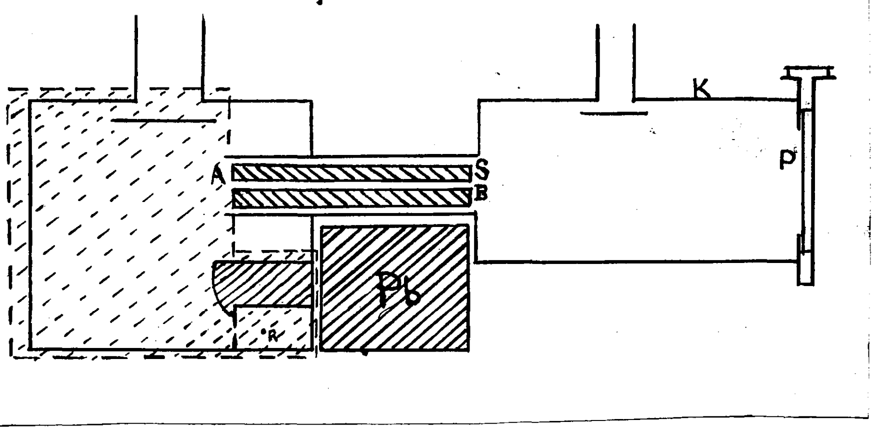
Fig.1.



It was found that the glass walls of the capillaries were sufficiently thick to cause a considerable amount of straggling of the β -rays emitted, but the more intense lines in the radium B spectrum could be picked out easily with exposures of the order of an hour. In fig. 1 R is the radon capillary, L a lead screen, P a photographic plate. The radon capillary R was usually from 0·3 to 0·5 mm. diameter externally and about 5 mm. long. AB was a slit 5 mm. long and 1·5 mm. wide and R was held on a line through the mid-point of AB perpendicular to AB and at 1 cm. from the slit. The length of R was perpendicular to the plane of the figure and the whole box was arranged to go between the large pole-faces of an electromagnet, the lines of magnetic flux being perpendicular to the plane of the figure. When the field is uniform over the area of the box particles of the same velocity describe parts of circles as shown, the radii of these circles being the same. Even with relatively wide slits rays of like velocity converge to a focus on the plate the ray passing through the centre of the slit reaching the point farthest from the source and those on either side falling at a point close below it. The edge farthest from AB , the high velocity edge of the spectral line, is therefore sharp. The electromagnet was calibrated by means of a Grassot fluxmeter, a curve of field strength and coil current being plotted.

An attempt was made to obtain a homogeneous beam of β -particles for the investigation of diffraction with the apparatus shown in fig. 2.

Fig. 2.



The resolving apparatus of fig. 1 was modified so that a tube passed through the wall and entered the box. This tube made connexion with a camera K and the tube contained a soft-iron tube S through which was bored an aperture of 1 mm. diameter. The field acted across the shaded area so that the rays falling at A passed through S being shielded from the magnetic force, and emerged at B as a homogeneous beam. A photographic plate P was put in K to detect the rays. It was found however that the beam was very weak. Using very strong radon capillaries (about 70 mc.), with exposures of 1 to 7 days, dense spots, adequate for work on diffraction, were not obtained. The lead screen marked Pb shielded the plate from γ-radiation and the most intense part of the spectrum of RaB was focussed on A.

The intensities and energies of the lines of the RaB spectrum are given in table 1, taken from Rutherford Chadwick and Ellis[10] page 362.

Table1 – The natural β-ray spectrum of radium B.

Number of line	Measured intensity	$H\rho$	Energy in volts $\times 10^{-5}$	Number of line	Measured intensity	$H\rho$	Energy in volts $\times 10^{-5}$
1	17	660.9	0.3725	17	80	1410	1.529
2	5	667.0	0.3792	18	3.9	1496	1.697
3	1	687.0	0.4016	19	2.1	1576	1.858
4	11	768.8	0.4983	20	91	1677	2.067
5	8	793.1	0.5288	21	10	1774	2.275
6	4	799.1	0.5365	22	2.5	1832	2.402
7	2	833.0	0.5806	23	0.5	1850	2.442
8	5	838.0	0.5872	24	100	1938	2.638
9	2	855.4	0.6106	25	12	2015	2.813
10	5	860.9	0.6172	26	2.1	2066	2.926
11	1.5	877.8	0.6412	27	1.5	2110	3.033
12	1.5	896.0	0.6667	28	16	2256	3.379
13	3	926.2	0.7094	29	8	2307	3.502
14	3	949.2	0.7426	30	1.5	2321	3.536
15	2	1155	1.068	31	1.5	2433	3.809
16	1	1209	1.160	32	1.5	2480	3.925

On account of the lack of intensity of the β-ray beam the method was abandoned. It had illustrated however the major difficulty of the investigation - the fact that a pencil of homogeneous β-particles is never intense when it has been obtained by some resolving device. The methods of focussing available do not produce thin pencils of β-rays, which is what is to be desired in diffraction work, and the presence of magnetic fields between the film and the plate distorts any pattern that would be formed. Thus suppose that by putting a small circular aperture at A,B (figure 1) in place of the usual slit we focussed the rays in a spot at K,K^1 and that a film was mounted at A,B. The rays diffracted on their way through the film would not form a ring round the spot owing to the action of the magnetic field on their paths.

It was decided that an attempt to show diffraction effects should be made with the non-homogeneous rays emitted by radon - the β-rays of Ra(B+C). The two elements have a continuous β-ray spectrum and a strong line spectrum superposed upon it, particularly RaB. If reference is made to Table 1 we see that a large percentage of the Line spectrum intensity is concentrated in three principal lines of the RaB spectrum - namely lines 17, 20 and 24. The total intensity of the lines between 17 and 24 =

$$80{\cdot}0 + 3{\cdot}9 + 2{\cdot}1 + 91{\cdot}0 + 10{\cdot}0 + 2{\cdot}5 + 0{\cdot}5 + 100{\cdot}0 = 280$$

The lines below line 15 do not appear in the spectrum of the radon capillaries (this was proved experimentally) being absorbed in the glass. The total β-ray intensity of the

line spectrum from line 15 to line 32 = 3·0 + 333·1 = 336·1
From Rutherford Chadwick and Ellis [10] page 364, we find RaC has a total line intensity of 18·99 + 9·98 = 29·0. The part of the spectrum whose energy lies within the range specified by lines 17 and 24 of RaB has intensity 1·6.
Hence for Ra(B+C)

Intensity in given range = 280·0+1·6

Intensity in total spectrum = 336·1+29·0

$\therefore \frac{28160}{365 \cdot 1}\% = 77\%$ of the total line spectrum

of Ra(B+C) has an energy (in volts x 10^{-5}) lying between the limits 1·529 and 2·638. This means that of the β-particles forming the total line spectra emission of Ra(B+C) 77% have energy between 152,900 and 263,800 electron volts. The continuous spectra of the elements should be considered but if we assume that their intensity is more or less uniformly distributed throughout the considerable range of energies covered by them they will not affect diffraction effects except in so far as they increase the background on the plates showing diffraction patterns. To find the diameter of the diffraction rings we have the following equations:-

$$eP/300 = m_0c^2/\sqrt{1 - v^2/c^2} - m_0c^2 \quad \dots (1)$$

$$\lambda = h\sqrt{1 - v^2/c^2}/m_0 v \quad \dots (2)$$

$\therefore$ eliminating v and approximating

$$\lambda = h\sqrt{150/ePm_0}/(1 + eP/1200m_0c^2) \quad \dots (3)$$

The symbols have the usual meanings in equations (1), (2), and (3) and eP is the energy in electron-volts.

If D = diameter of ring, L = length from film to plate, d = placing between the crystal planes

$$D = 2\lambda L/d \quad . \quad . \quad . \quad . \quad (4)$$

Hence

$$D = 2L\,h\sqrt{150/ePm_0}\Big/d(1+eP/1200\,m_0c^2) \quad . \quad . \quad (5)$$

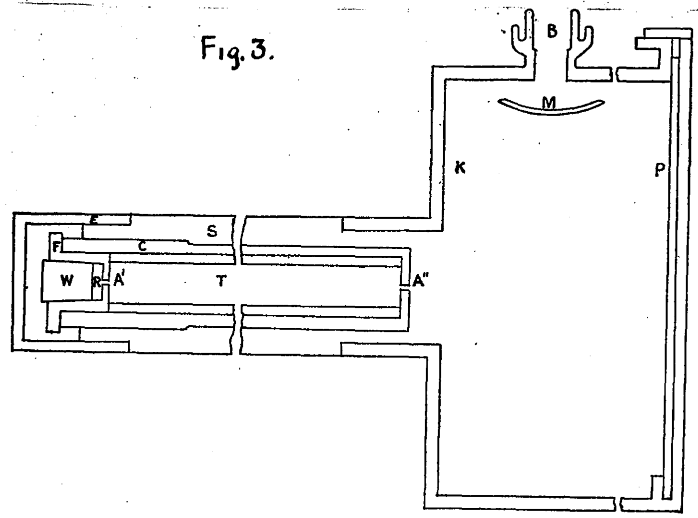
Substitution of the known values -

L = 35·0 cm., h = $6{\cdot}56.10^{-27}$ erg-sec., $e = 4{\cdot}774.10^{-10}$ e.s.u., d = 2·032 A.U. (the spacing of the (200) planes in gold i.e., one half of the side of the cubic cell from X-ray data), $m_0 = 8{\cdot}98.10^{-28}$ gm.

may be made in equation (5). When P = 153,000 volts is employed we find by calculation of (5) that D = 10·02 mm. Likewise, calculation of D for P = 264,000 volts gives D = 7·63 mm. These results, together with the above consideration of β-ray intensity in the spectra, indicate that it should be possible to detect diffraction of β-rays, employing the non-homogeneous particles emitted by radon. The diffraction ring, formed by the (200) planes of gold, should appear as a rather diffuse ring round the central spot, the inner diameter being 7·63 mm. and the outer diameter being 10·02 mm., since 77% of the rays in the line spectrum, on diffraction by the (200) planes, fall within these limits. Experiments with radon were carried out for these reasons.

Apparatus.

The apparatus used in the investigation is shown diagrammatically in fig. 3. In order to show details of certain parts fig. 3 is not drawn to scale. S is a soft-iron shielding tube preventing magnetic fields



deflecting the β-particles. C is a tube of brass fitting into and held by S. It is closed by a thin brass plate, $\frac{1}{2}$ mm. thick, at its right-hand end. At the centre of the plate is a small circular aperture A^{11}, varying between 0·1 and 0·5 mm. in diameter. The left-hand side of C is occupied by a short flanged tube F having a small aperture A^{1}, similar to A^{11}. Within F is the source R, which rests in a narrow groove immediately behind A^{1}, and is held in position by the plug W. The system is closed at this end by the cap E fitting over S. The main body of the camera is denoted by K and the pump connexion by B. The latter is covered by a metal screen M to prevent light from entering the apparatus and fogging the plates. The photographic plate-holder on the extreme right contains the plate P. A remark must be made here about tube T shown in fig. 3. This tube was a later modification of the apparatus which was added in order to study the reflexion phenomenon explained below. When diffraction was being investigated it was not present, and C in this case had an inner diameter of 1·5 cm. The film holder was mounted in front of A^{11} so that rays passing through A^{1} and A^{11} passed almost normally through the film. Most of the joints are screw joints, sealed with "Picien". The chief dimensions are:- length of tube T, 8 cm; distance $A^{11}P$, 35 cm; diameter of K, 9 cm; inner diameter of C 1·5 cm. The camera was larger than required for purposes of measurement, the advantage being that the larger the dimensions the clearer the background on the plates. The pumping system consisted of a rotary oil-pump backing an oil-diffusion pump, using Apiezon oil B, and capable of producing vacua down to 10^{-7} mm. of mercury. Between the pumping system and the camera was inserted a discharge-tube for pressure measurement, it being found necessary to isolate this by means of stopcocks as running the discharge fogged the plates. The customary leak to the atmosphere was inserted between the discharge-tube and the camera. The body of the camera was held vertically, source-end uppermost, by supports not shown in the figure. A system of grooves was cut in the various parts S, C, T, W to allow free passage of air in pumping, any pressure on the capillary R, with consequent risk of breakage, being thereby avoided.

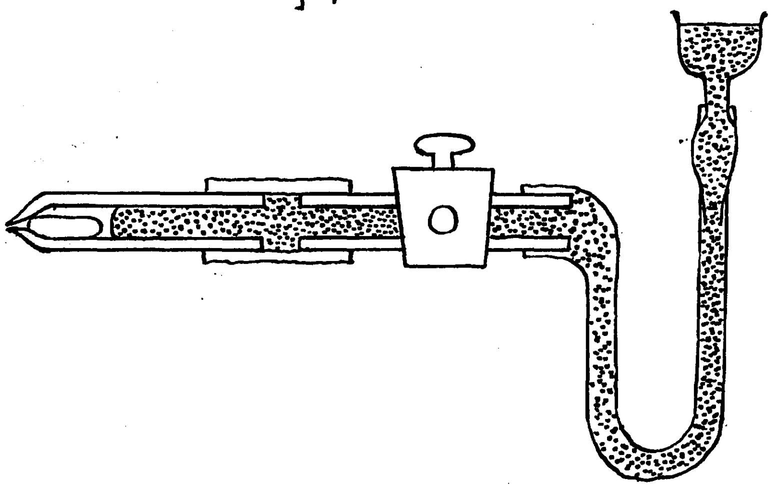
Sources of β -rays.

In work on β -radiation the sources used are of great importance and in this work various types were tried in an effort to secure the most suitable one. The chief drawback to almost all of them was lack of intensity. As mentioned above radium itself was tried but with no success as large supplies were not available. Specially prepared active deposit sources were employed also. Although these were very intense their short period of activity made their use inconvenient, a plate of the required density seldom being obtained with less than about six of these preparations. This meant that the process of taking an exposure was tedious as the system had to be let up to atmospheric pressure every time a fresh active wire was inserted. The sources which were finally adopted were radon capillaries, liberating β-rays of energy 130,000 electron-volts upwards, the range of velocity being determined by the semi-circular focussing apparatus of fig. 1. Each radon capillary could generally be used twice, its activity falling in the course of the exposures from about 60 to 40 mc. and from about 40 to 10 mc. A note will be added at this point on the method of preparation of active deposit sources as the method devised is important on its own account even though the sources were not suited to the requirements of this particular research.

Note on Activation. When a large supply of radium is not available it is not possible to adopt the usual practice of preparing bare activated sources by exposure of wires and so on to radon collected over the radium. The problem therefore arises as to the best method of activating wires, given a supply of the ordinary type of radon capillary sold commercially. Commercial capillaries are too thick-walled to allow α-rays and slow β-rays to pass through. The following simple yet efficient method was devised as a solution to the problem which becomes one of general interest when it is realised that wires coated with an active deposit of Ra A,B,C form one of the best types of sources for much of the work being done at present with α -rays in the field of artificial radioactivity and so on. It is important that it should be possible to utilise ordinary glass capillaries since large supplies of radium are in general not available. Glass radon capillaries are obtainable with capacities ranging from 10 to 100 mc. and very strong activated wires can be made from them. It is an advantage to use the strongest supplies as a larger number of strong sources are prepared from the one capillary before its activity decays to a value preventing successful activation.

About six to eight inches of thick-walled glass capillary tubing is taken - of bore approximately 1 mm. This is drawn out in a small flame at one end, this requiring to be carefully done as it has an important effect on the subsequent concentration of the radon. The bore must be kept as near 1 mm. as possible down to very near the end where it tapers sharply to a very fine opening of the order of $\frac{1}{10}$ mm. diameter. The small glass radon tube is then inserted at the other end (1 mm. diameter) and as the tubes are normally $\frac{1}{3}$ to $\frac{1}{2}$ mm. in diameter they slide easily into the glass tube after which they can be moved gently down to the narrow end where they remain fixed. Now a mercury reservoir is connected by rubber tubing to the glass tubing (see fig. 4) and when the mercury level of the reservoir is raised mercury flows up the tube forcing the air inside past the radon capillary into the atmosphere. The small stopcock inserted between the tube and the reservoir controls the mercury flow. When the mercury has almost reached the radon capillary it is stopped by closing the stopcock. A small flame is allowed to play on the narrow end, thereby effecting a seal. When the rubber tubing is disconnected

Fig. 4.



the radon capillary is held in a small cavity. The glass tube is held horizontally and a fine steel wire, not more than $\frac{1}{2}$ mm. diameter, is inserted through the mercury. The capillary being broken by bringing the wire into contact with it the radon escapes into the small pocket. The steel wire is gently withdrawn and about 50 mc. say of radon, in fairly concentrated form, is sealed off from the atmosphere by a column of mercury. The sources are obtained from this radon supply by inserting a platinum wire, a few tenths of a millimetre in diameter, through the mercury so that perhaps $\frac{1}{2}$ cm. is exposed to the radon. It is kept there for two hours being maintained at a potential of about 200 volts, negative relative to earth and the surrounding apparatus. The type of active deposit Source, whether of Radium A or of radium A, B, C in equilibrium and so on, can be determined by changing the conditions of exposures (see Rutherford, Chadwick and Ellis, [10] page 558). On withdrawing the wire and cutting off the activated end the radon supply remains intact and can be used to prepare many such sources before its activity falls below a working value. Its half-period, 3·825 days, is considerably longer than those of most of its products. Since minute quantities of radon may escape into the atmosphere on withdrawal of the wires the work should not be done near apparatus used for measurements in radioactivity. It should preferably be carried out in a place set aside for the purpose. A simple apparatus which rapidly astimates the activity of the prepared sources is an advantage and one found suitable for this purpose is that due to Chalmers [11], the microammeter reading giving a good estimate of the strength. Before use the wires should be washed in alcohol and heated to 400°C. in an evacuated quartz tube to remove radon occluded in the metal surface.

Experimental Procedure.

It has been shown that using radon as a source of β-rays and gold film as the diffracting medium a ring of external and internal diameters equal to 1·00 and 0·76 cm. respectively might be expected, and this idea was experimentally tested. The radon capillary was first placed in the holder immediately behind aperture A^1, (fig. 3) and then plug W was inserted to hold it in position. The source end of the camera was then sealed with "Picien", the plate was inserted, and the apparatus exhausted. The vacuum in the course of an exposure was usually sufficient to wipe out a discharge with 70,000 volts between the electrodes. Exposures were long, varying between one day and four days according to the initial activity of the source. The method adopted for measuring the intensity of the sources was that of Chalmers[11].

Discussion of Results.

The photographs obtained showed that a strong beam of non-homogeneous β-rays had been obtained and very good spots were formed on the photographic plates, comparable in density with those giving diffraction effects in cathode ray work. The spot was deflected by magnetic fields proving that it was formed by β-rays. Many photographs were taken with various films of celluloid, gold and aluminium over the aperture at A^{11} but no sign of diffraction rings was obtained. The background on the plates was somewhat denser than that normally encountered in the diffraction of cathode rays but it seemed clear enough to allow any pattern to show up. An experiment similar to that of E. Taylor Jones [9] with dispersed pencils of cathode rays was performed with the β-rays. They were drawn out into a short line by a magnetic field but there was no trace of a circle as in the corresponding case with cathode rays, nor was there any sign of an envelope of circles, such as might be expected if the rays of different velocities formed circles of different diameters round points on the line as centres. In this case we should expect to find lines on either side of the line formed by the primary beam.

The failure of this method of attack on diffraction seemed to indicate that new methods would have to be adopted if the problem was to be solved. The author however thought it desirable to pursue at this stage of the research an investigation into the nature of another phenomenon which had arisen in the course of the experiments and which is closely similar in its results to diffraction. The following account of it is taken largely from the author's paper on the subject ---
"An Apparent Regularity in β-ray Reflexion".

In the following pages an account is given of an effect of considerable experimental importance. It is shown to be explicable theoretically as due to reflexion of the rays by a portion of the apparatus. By the term reflexion is meant the multiple scattering of the β-rays from a surface, the reflected rays being those scattered back, away from the surface. The reflected β-particles causing the phenomenon are shown to have velocities approximately the same as the incident particles, the energy loss in the multiple scattering process being therefore small. It is shown that the photographs obtained in the investigation can be used to deduce the relative reflecting powers of various materials by a simple photographic method.

Apparatus.

The apparatus need not be described again as it was, except in certain details, the same as that used for diffraction (see figure 3).

When diffraction experiments were performed tube C was, at first, of narrow bore and tube T was absent. This arrangement gave rise to the effect which was subsequently proved to arise from reflexion at the surface of C. For this reason when working on diffraction C, as mentioned above, was made 1·5 cm. in bore the effect being absent in this case. In the present investigation however removable tubes T were used, these being made of various substances and varying in bore from .1 mm. to 6mm. The film-holder was removed and the sources used were radon capillaries.

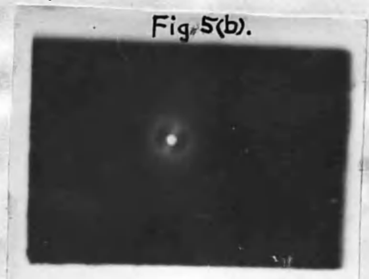
Discussion of Results.

The experimental procedure was similar to that given above in the account of the diffraction experiments. Thus when the tubes T were in position and photographs obtained, they showed a very strong central spot surrounded by a ring in all cases, the appearance of the ring suggesting that it might be due to β -ray diffraction. Fig. 5(a) is a photograph taken with a carbon tube of 4 mm. bore in the apparatus of fig. 3, and fig. 5 (b) is one taken with a brass tube in a second smaller camera. The diametral line in the

β-ray photographs : (a) with carbon tube, (b) with brass tube in smaller camera.

Fig. 5(a).

Fig. 5(b).



latter case is interesting as it arises from the fact that the groove containing the radon capillary was cut rather deep so that the very high energy β -particles were able to penetrate to a certain extent the plate at A^1. This meant that the rays formed a kind of pin-hole image of the source on the plate after passing through A^{11}.

In the first place it had to be established that it was actually the β-rays which were causing the effect as three types of radiation were present, namely, beta, gamma and light. The light referred to is the green fluorescence of the capillary. The effect of the β-rays was separated from that of the γ-rays and light by applying a very strong magnetic field across the camera. When this was done the ring was absent and a very weak central spot remained, marking the point where the fluorescent light reached the plate. (It should be mentioned here that sometimes with bright metal tubes a weak outer ring was present, formed by regular reflexion of the light at the middle portion of T). It was next proved that the ring was caused by T, this being verified by removing T and showing that the ring was then absent from the plates. To prove that T was affecting the β-particles entering at A^1 was the next step as it was possible that the circle formed by the β-rays might arise from a secondary action of the γ-radiation impinging on the surface of T and liberating β-rays by the photoelectric or the Compton effect. This was done by putting between the aperture A^1 and the tube T a thin plate of glass just sufficiently thick to absorb the β-rays while allowing the γ-rays to enter the cylinder. In this case the ring was absent and a weak central spot remained. In this case the spot was not due to β-rays as it did not deflect in a magnetic field. It was possibly due to the weak fluorescence of the source. The γ-ray effect in the apparatus was very slight.

The variation of the diameter of the circle was investigated, brass tubes of different diameters being used. In all cases it was found that the diameter of the circle varied directly as the internal diameter of the tube T as it was varied from 1 mm. to 6mm. Measurements were taken at the inner edge of the ring in this case for reasons which will appear later. In table 11 are given specimen figures for brass

Table 11.

Diameter of cylinder (cm.).	Diameter of ring (cm.).
0·2	0·9
0·4	1·8
0·6	2·7

Different metals - lead, copper, iron, aluminium and also carbon were substituted for brass. The size of the β-ray ring for any one particular diameter of tube was found to be the same for the various materials but a variation in the intensity of the ring was noticed when photographs were taken under similar conditions with different substances. Finally, the constitution of the primary beam and the ring was studied and several photographs were taken with magnetic fields across the path of the beam on its way from source to plate. The central spot was drawn out into a short line with several dark maxima on it. These corresponded to the well known maxima of intensity in the β-ray spectrum of radium B - that is, those of energies $1{\cdot}529.10^5$, $2.067.10^5$, $2{\cdot}638.10^5$ electron-volts (see table 1) This showed that the spot consisted almost entirely of β -rays. At the same time the ring lost its circular form and had the appearance of two lines running parallel to the denser central line formed by the β -particles of the primary beam. The three lines were of the same form and approximately equal in length, this proving that the reflected β -rays had velocities approximately equal to those in the primary beam.

The Theory of the Effect.

Calculation showed that the ring obtained in these experiments could not be due to regular diffraction of the β-rays by the lattice planes of the metal of tube T. Thus if we consider the primary beam as striking the surface of the tube at B in fig. 6 and being diffracted in the direction BA'' we find that the observed angle of deflexion ϕ would agree with that calculated from the wave-length $\frac{h}{mv}$ and the spacing of the lattice planes (as in diffraction experiments) only if the electrons were at the most of energy 10,000 electron-volts and it would be very different from the value of ϕ for β -rays. The correct explanation of the phenomenon seems to lie in the geometrical distribution of the electrons reflected from the inner surface of the tube. Thus consider fig. 7. Suppose

Fig.6.

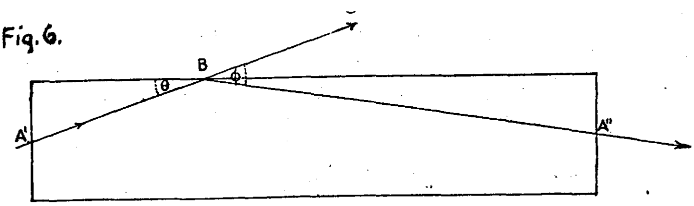
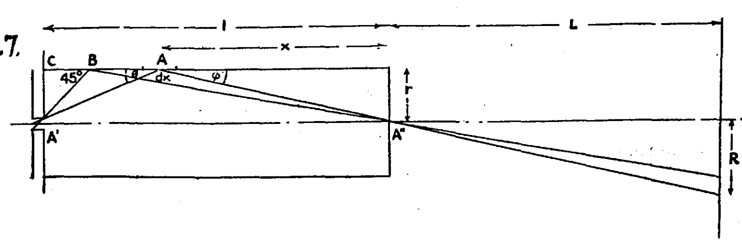


Fig.7.



a ray enters at A^1 and impinges on the cylinder at A. Let AA^1 represent a reflected β-particle leaving A and meeting the plate at a distance R from the central spot on the plate, marked by the point where A^1A^{11} meets the plate, represented by the line at distance L from A^{11}. Suppose A is distant x from A^{11} and let us consider a small element dx of the cylindrical surface around A. Let θ be the angle of incidence and ϕ the angle of the reflected ray to the surface. It is assumed that electrons impinge on the element and are diffusely reflected - that is, with equal intensity in all directions independently of the direction of incidence of the rays on any element such as that at A. AA^{11} represents one of these diffusely scattered electrons travelling in the direction required to reach the plate through A^{11}. The other reflected β-particles from the element, which is really acting as a source of reflected electrons, are absorbed for the most part by the surrounding walls of the tube. Now the number of rays from A^1 to elemental cylinder of length $dx \propto 2\pi r\, dx \sin\theta$. Hence number of reflected rays passing through A^{11} $\propto dx\sin\theta . dx\sin\phi$, in accordance with what is said above about the nature of the reflexion.

But $\tan\theta = r/(l-x)$ and $\tan\phi = r/x$

$\therefore$ number reflected

$$\propto \frac{r^2}{\sqrt{[r^2+(l-x)^2]\,[r^2+x^2]}}\cdot(dx)^2,$$

that is,

$$\propto \frac{(dx)^2}{\sqrt{[r^2+x^2][r^2+(l-x)^2]}},$$

since r is constant for any particular tube. The rays from the element dx cover an annular element of the plate whose area

$$= \pi\left[\frac{r^2L^2}{(x-\frac{dx}{2})^2} - \frac{r^2L^2}{(x+\frac{dx}{2})^2}\right] = \pi r^2 L^2 2dx/x^3$$

to a first approximation. Hence number of rays hitting unit area of the plate.

$$\propto \frac{(dx)^2}{\sqrt{[r^2+x^2][r^2+(\ell-x)^2]}}\cdot\frac{x^3}{dx}$$

that is,

$$\propto \frac{x^3\,dx}{\sqrt{[r^2+x^2][r^2+(\ell-x)^2]}}$$

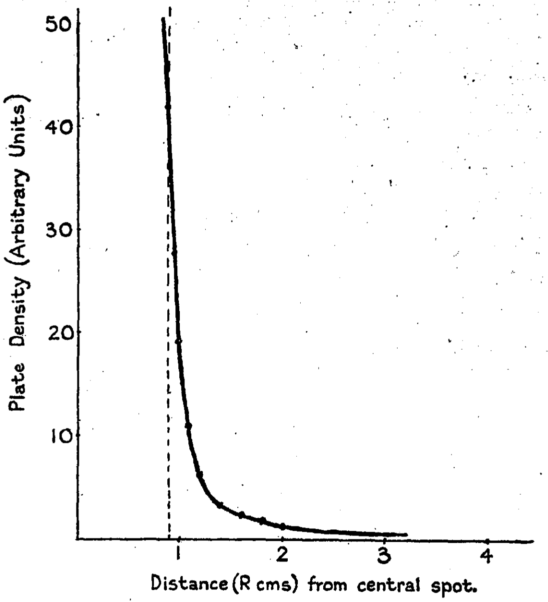
If we assume that the blackening of the plate is proportional to the number of β -particles hitting unit area [13] we obtain the function

$$I = \frac{x^3}{\sqrt{[r^2+x^2][r^2+(\ell-x)^2]}}$$

as a measure of the density of the plates for various values of x or alternatively, for various values of R since $R = r.L/x$ We are therefore in a position to plot the intensity distribution on a photographic plate by plotting the function I against R.

It is to be noticed that there is a maximum value of x corresponding to the β-ray which just enters through the aperture A^1, and since, in this experiment, it is a circular one of ½ mm. diameter in a plate ½ mm thick this limiting value corresponds to $\theta = 45^0$, as shown at B, fig. 7. This in turn determines a minimum value of R, and inside a circle of this radius no reflected β -rays are detected on the plate. To take a particular case: suppose the function I is graphed against R, as in fig. 8, for a tube of $r = 0{\cdot}2$ cm, where L = 35·0 cm., and $\ell = 8$ cm. The minimum value of R in this case is that for $x = (8{\cdot}0 - 0{\cdot}2)$ cm., i.e. for $x = 7{\cdot}8$ cm., and $= 0{\cdot}2.35{\cdot}0/7{\cdot}8$cm.

Fig. 8.



= 0·90 cm. This is indicated by the broken line in the figure. The function

$$I = \frac{x^3}{\sqrt{[0{\cdot}2^2 + x^2][0{\cdot}2^2 + (8{\cdot}0 - x)^2]}}$$

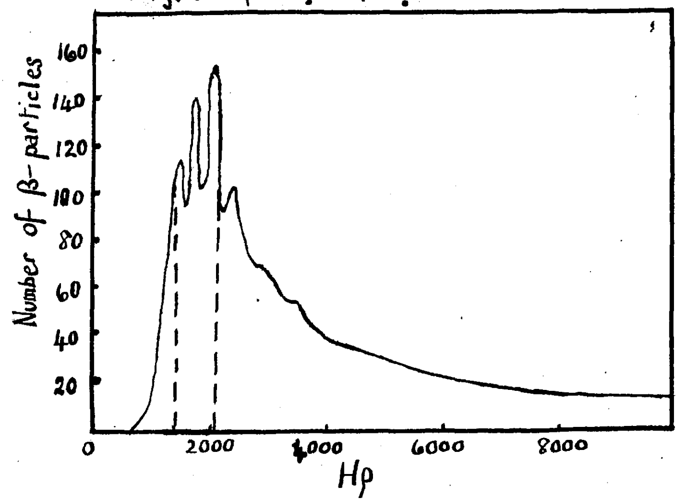
for this value of r, and it is seen that, starting at R = 0·9cm. the curve falls very rapidly, indicating that the plate density will decrease rapidly outside of R = 0·9 cm; and, since there are no reflected β-particles inside this radius, we have a sudden increase in plate density at R = 0·9 cm., with a rapid decrease for greater values of R. This exactly corresponds to the density distribution on the plates obtained in the experiment, in the case r = 0·2 cm. for example, the inner edge of the ring was at a distance R = 0·9 cm. from the central spot, and it was sharply defined while the outer edge of the ring was more diffuse. The equation $R = r.L/x$ shows that the inner edge of the circle, corresponding approximately to $x = l$, neglecting the end-correction BC discussed above (fig. 7) should vary directly as r since we have $R = r.L/l$, and this agrees with the measurements given in table II.

A remark should be added on the other experimental observation, the difference in intensity of the rings with tubes of different materials under similar conditions of exposure. The method can be utilised as a convenient means of measuring the relative reflecting powers of the different substances composing the tubes with the β-rays. By photometry we can find the ratio of the maximum intensity in the ring to the intensity of the central spot and this figure gives a measure of the reflecting powers of the various substances. The strength of the source and other variables are taken into account automatically by this device and the only error is the slight background effect produced by light and γ-radiation. This error can be eliminated by subtracting the background intensity from the other measurements if greater accuracy is desired. The method is free from the difficulties associated with delta rays etc. in the electrical methods of determining reflecting powers.

The above investigation being brought to a satisfactory conclusion attention was again directed towards the problem of diffraction. It is difficult to understand why the method described above, in which the non-homogeneous β-rays emitted by Ra(B+C) were used, should have failed to produce results. One explanation of this may be that of the total β-ray emission from a radon source a part only is found in the line-spectra, the greater part of the emission being found in the continuous spectrum. Thus, although 77% of the line-spectra should produce diffraction effects, this diffraction may be masked by the diffraction of rays forming the continuous spectrum, contrary to the assumption made above.

If we take the curve due to Chadwick[14] for the number of β -rays emitted by radon, shown in fig. 9 (taken from Rutherford, Chadwick and Ellis[10] p. 400. curve B), we see

Fig. 9 — β-rays of radon.

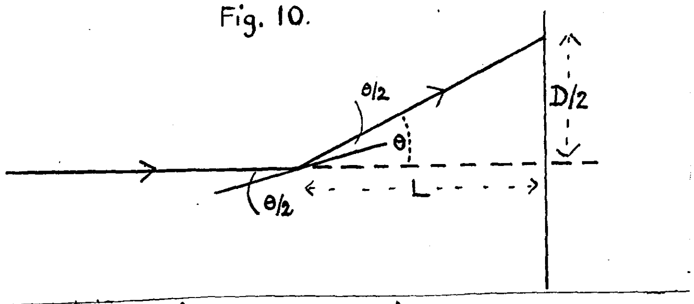


that the area under the part of the curve enclosed by the two dotted lines represents the electrons which we have considered. This area is approximately that between the ordinates at $H\rho$ = 1400 and at $H\rho$ = 2000. The area under the total length of the curve represents the complete emission of the source. Calculation of these two areas shows that the ratio of the first to the second is approximately 0·23. In other words it is found that the useful part of the β -ray emission, so far as diffraction is concerned, is only 23% of the total emission of the source. Perhaps this affords some explanation of the apparent difference between β-rays and cathode rays in diffraction. There is no theoretical reason for the diffraction patterns formed by β -rays being less intense than those formed by slower cathode rays. This can be proved by reference to the theoretical values for the intensities of the parts of an electron diffraction pattern.. From Mott [15] we have the result that the fraction of the incident beam scattered into the solid angle dw, in direction making an angle θ with the direction of incidence is $$\{I(\theta)\}^2 d\omega$$

where
$$I(\theta) = \frac{e^2}{2mv^2} \cdot \frac{Z-F}{\sin^2\theta/2} \quad . \quad . \quad . \quad . \quad (6)$$

and $-e$, m, v are the charge, mass, and velocity of an electron Z is the atomic number of the atom, and the X-ray **form** factor.
$$F(\theta) = \int_0^\infty \frac{\sin \mu r}{\mu r}\, 4\pi \rho(r)\, r^2 dr \quad . \quad . \quad . \quad (7)$$
where $u = \frac{4\pi \sin\theta}{\lambda}$, λ being the de Broglie wave-length, and $\rho(r)$ the density of electrons. Now from

Fig. 10.



the Bragg condition (see fig. 10).
$$2d \sin\theta/2 = n\lambda \quad . \quad . \quad . \quad . \quad (8)$$
Hence for a particular order n and a particular spacing d, θ being small we have
$$\sin\theta/\lambda = 2\sin\theta/2\,/\lambda = n/d = \text{constant}.$$
$$\therefore\ F(\theta) = \int_0^\infty \frac{\sin\left(\frac{4\pi n}{d}.\, r\right)}{\frac{4\pi n}{d}.\, r} \cdot 4\pi\rho(r)\, r^2 dr = \text{constant}$$

for a particular diffracting medium.
$$\therefore\ I(\theta) = \frac{e^2}{2mv^2} \cdot \frac{Z-F}{\sin^2\theta/2} = \frac{e^2}{2m h^2/m^2\lambda^2} \cdot \frac{Z-F}{n^2\lambda^2/4d^2} = \frac{e^2(Z-F)2m^2d^2}{m h^2 n^2}$$
is constant also under the same conditions. This shows that corresponding parts of diffraction patterns due to fast β-rays and slower cathode rays should be equally intense since I(θ) is snown to be independent of v. For example the first ring in diffraction patterns formed by a gold film should be equally

intense where the central spots are equally intense.

Longer exposures failed to produce diffraction results, the background density merely increasing in proportion to the length of exposure. It was felt that if further progress was to be made attention should be paid to different methods of detection. The photographic plate did not seem to be as sensitive to the β -rays as might be desired, even though various types were tried in an effort to secure denser central spots and clearer backgrounds (mostly due to γ -radiation). Schumann, Process, and other types were used but those which seemed less affected by γ-rays were at the same time less affected by β -rays. Of course this almost follows from the fact that most of the action of γ -radiation on the plate comes through a secondary action of the rays which liberate β -particle when they impinge on any material in their path. The direct action of the γ -radiation itself on a photographic emulsion is so small as to be almost negligible. The plates generally used were Imperial Eclipse, H. and D. 850. The scintillation method, so powerful for work with weak sources of α -particles is not applicable and indeed it was found impossible to detect the strongest beams of β -rays obtainable on a fluorescent screen. This is an illustration of the very considerable difference in intensity of the cathode ray beams normally employed in diffraction experiments and the β -ray beams used in radioactivity. One of the most sensitive forms of instrument devised is the electrical 'counter' and it was decided that in this a more sensitive detector than the photographic plate would be found. Preliminary experiments with various forms of counters showed that the action of many of these was erratic unless great care was taken in the matter of the high voltage control, the electrode treatment and so on. Attention was therefore paid to the possible use of high-frequency discharge-tubes as electrical counters and a successful investigation of this question was made. The new types of counter evolved in this research have many points in their favour in comparison with the more standard types of D.C. counters. The following account of their properties and of their mode of action is taken from the author's paper (16) on the subject "The Use of High-Frequency Discharge-tubes as Electrical Counters"

Introduction.

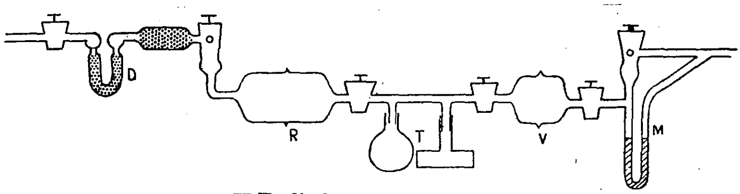
The subject of the electrical counter is one which has received considerable attention since it was described in its first form by Rutherford and Geiger (17) and various modifications and improvements have been made by numerous investigators from time to time. The principle embodies in the different types is the same - when the potential applied to a discharge-tube is less than that required for sparking, the entry of a single ionizing particle will cause, under certain conditions, the momentary passage of a detectable current. In the prototype of the electrical counter, as described by Rutherford and Geiger (17) one electrode was the wall of the cylindrical vessel and the other was a fine axial wire. This was changed to a hemispherical vessel with a central small ball by Geiger and Rutherford (18) later, and to a cylinder and sharp point by Geiger (19). The sharp point in the last case was specially sensitised before use. In nearly all the earlier types of counter what takes place is simply magnification of the ionization currents by collision in the strong electric field between the electrodes [20] and no "trigger action", in which the energy stored in the capacity of the counting vessel is released by the entry of the particle, takes place. This means, in these cases, that the currents to be detected are extremely small, and considerable amplification has to be effected. Even in the point-cylinder type of counter working on the principle of "trigger action" the currents passing through the tube are still of the order of a few microamperes at the most, and amplification is required to make them audible in a loud-speaker for instance. The small area over which the rays can enter and be effectively counted is for many purposes a disadvantage of the point-cylinder type, and recently some experimenters have reverted to the wire type[21], which can be used for X-rays and γ-rays as well as α-particles and β-particles, the rays entering through the sides of the tube. In addition, it has been found possible to use plane parallel electrode tubes as counters [22] a steady potential being maintained across the electrodes. These tubes are erratic in their behaviour and have not the required stability of action.

In the following pages an account is given of experiments carried out on high-frequency discharge-tubes of various kinds, in which it has been found that such tubes can be adapted so that they act very efficiently as electrical counters of good sensitivity, and in which the "energy trigger ratio" is so large that a small loudspeaker may be included in the oscillator circuit to detect the counts as audible clicks. The use of the H.F. potentials in place of the D.C. potentials makes it possible to work the counter from a D.C. supply of 400 volts or even less, and thus the use of high steady potentials required in most other counters is avoided. The erratic behaviour associated with some D.C. discharge-tubes is absent for reasons given later, and the effective counting area for these tubes is very large.

Apparatus.

The pumping system consisted of a rotary oil-pump backing an oil-diffusion pump, using Apiezon oil B, and capable of producing a vacuum of the order of 10^{-7} mm. of mercury. It was attached to a manometer and various tubes shown in diagrammatic form in fig. 11. The gases admitted to the tubes were passed through a drying system of calcium chloride and phosphorous pentoxide.

Fig. 11.



H.F. discharge-tube system.

In fig. 11 D represents the drying tubes, the gas being passed into the system at the left hand side of the figure. R is a large reservoir for storing the dried gas and for use in adjusting the gas pressure in the discharge-tubes T and V, these being separated to allow for pressure variation in the manner described by Thomson (23). The manometer M contains Apiezon oil B of very low vapour-pressure. Suppose V_A is the volume of V and V_B is the volume of T, and the manometer, when pumped out completely on the right hand side, records a pressure P_0 cm. of mercury, as read by a travelling microscope. T is cut off from V. V is pumped out, and the gas in T is then shared between the vessels T and V. If the resulting pressure is p_1 cm. of mercury, then

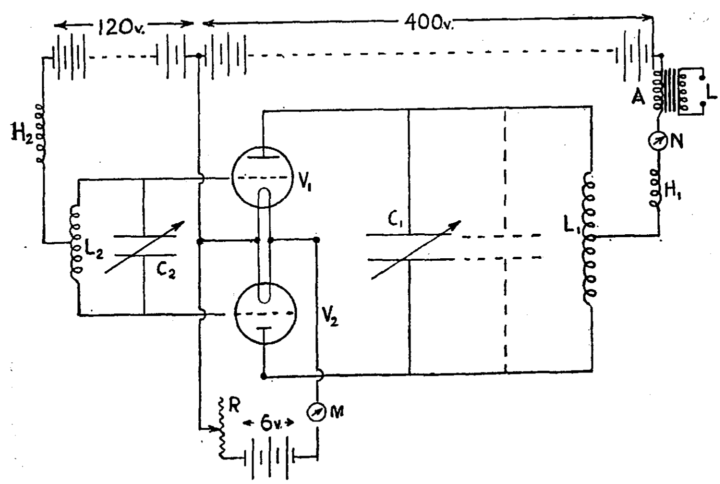
$$P_1 (V_A + V_B) = P_0 V_B$$

$$\text{i.e.} \quad P_1 = P_0 \frac{V_B}{V_A + V_B} = k P_0 \text{ say.}$$

Thus k is determined from readings p_1 and p_0, and proceeding with the same process, subsequent pressures, $p_2 = kp_1 = k^2p_o$. $p_3 = k^3p_o, \ldots\ldots\ldots\ldots\ldots, p_n = k^np_o$, can all be calculated. The highest pressure which could be measured directly on M was 22 cm. of oil or 1.41 cm. Hg., but by starting at higher pressures and taking the readings p_m and $p_m + 1$ when they were below this value, pressures ranging from 7 cm. to 0·001 mm. of mercury were recorded.

The oscillator used for the generation of the H.F. potentials was of the push-pull type shown in fig. 12.

Fig. 12.

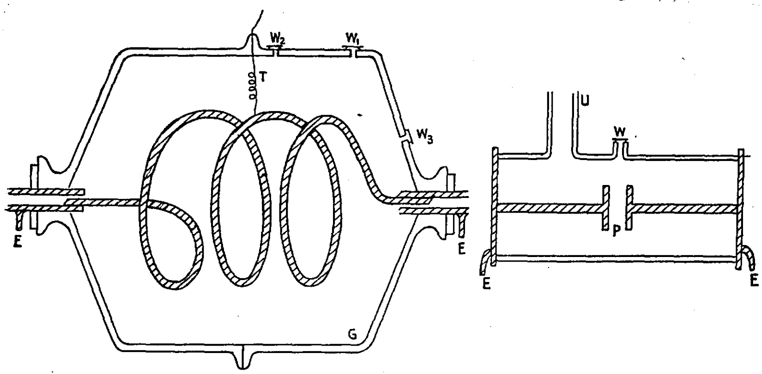


H.F. push-pull oscillator.

The matched values V_1 and V_2 were Marconi-Osram L.S.6A, dissipating about 25 watts each. The oscillatory circuit L_1C_1, was tuned to the grid circuit L_2C_2 by variation of the capacity C_1 or C_2 according as circumstances required. H_1 and H_2 are two high-frequency chokes, A is an audio-frequency transformer, L is the loudspeaker, M is an ammeter measuring filament current, N is a milliammeter measuring plate current, and R is a pair of variable resistances giving fine adjustment of the output of the oscillator.

Three of the discharge-tubes, which were found to act as electrical counters, will be described, though several others were used in an attempt to find those most suitable for this purpose.

Fig. 13 (a). Fig. 13(b).



Discharge-tube number I. Discharge-tube number II.

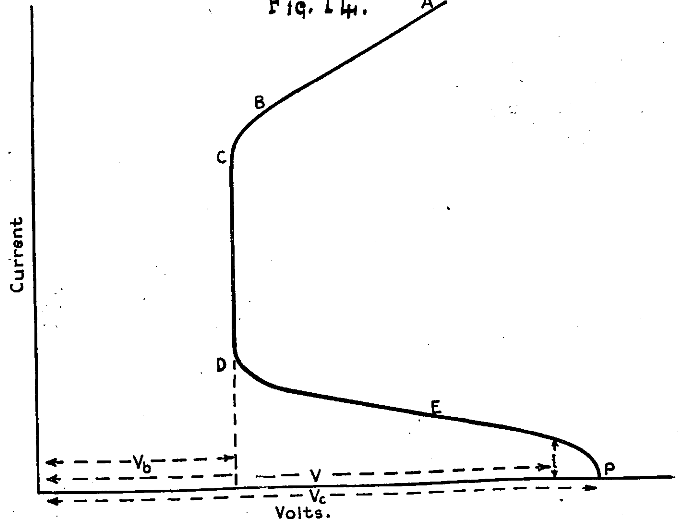
Fig. 13 (a) is a sketch of tube 1. This consisted of a large glass vessel G consisting of two parts sealed together along ground flanges. Copper tubes bearing terminals E passed through the ends and were connected by a coil of copper wire consisting of three turns with a fine centre-tapping wire T connected to it, and passing through the side of the vessel at the joint. Three small windows through the glass wall, W_1, W_2 and W_3, were covered by thin sheets of mica. The vessel G was 13 cm. in diameter and 15 cm. long. The total length of the coil was 80 cm. and the wire had a cross-section of diameter 2·5 mm. Fig. 13(b) shows tube 11, which consisted of a glass vessel 20 cm. long, closed at its ends by two metal plates bearing terminals E and two rods, which supported two copper plates P of 2 cm. diameter at a distance apart of 3 mm. The vessel was provided with a window W covered with mica and a pumping tube U. Tube III was exactly similar to tube I, except that in place of a coil and centre-tapping T there were two large copper plates supported in the centre of the vessel, at a distance of 1 mm. from each other. Their diameters were 7·8 cm. each. It is to be noticed that in using tube I the coil L_1 was replaced by the coil of the discharge-tube, the centre-tapping T going through H_1 to +400 volts. With this voltage across the valves it was possible to generate a peak potential of 1000 volts across the ends of the coil. When tube II was used it was connected across L_1 as indicated by dotted lines in Fig. 12. L_1 in this case was a coil of 20 turns, each turn 2.5 cm. in diameter, and of total length 8 cm. L_2 was usually a coil of 12 turns, each turn 5·6 cm. in diameter, the total length being 8·5 cm. while C_1 and C_2 were 100 μF variable condensers. When tube III was used the condenser C_1 was removed and the discharge-tube connected across L_1. The capacity between the plates was about 40 μF, and tuning was carried out by means of C_2. It was possible to have a peak potential of 1000 volts across tube III in this case.

Measurements of voltage across the tubes were seldom required in absolute values so a method giving relative values quickly and accurately was usually adopted. A loop of thick copper wire about 15 cm. in diameter was connected to the heater terminals of a vacuum thermo-couple, which was in turn connected to a microammeter. It can be proved that the heater current set up in the loop when it is placed near the oscillator is proportional to the voltage generated, and therefore from a calibration curve connecting heater current and the current in microamperes in the thermo-couple circuit it is possible to find relative values of the voltages from readings of the microammeter. This method has the additional advantage that the oscillator is unaffected in taking readings. In the case of the highest frequency employed, $2{\cdot}3.10^7$ cycles per second, the use of an electrostatic voltmeter is not feasible because of the capacity it introduces into the system, but in several cases readings of the sparking potentials etc. were taken with the electrostatic voltmeter when working at frequencies of the order of 10^7 c/s. These were taken by connecting an electrostatic voltmeter, in series with a diode valve, across the electrodes of the tubes.

Theoretical Discussion.

Several investigators have studied the mode of action of various forms of electrical counters, in the elucidation of which many problems arise. The mode of action of the H.F. tubes can be best explained by comparison with that of the standard point-cylinder type. Appleton, Emeléus and Barnett (24) carried out a series of experiments on this subject, and suggested the idea of threshold current. This idea was experimentally verified by Taylor (25) who carried their explanation a step further.

Fig. 14.



General volts-amperes characteristic.

Thus suppose ABCDEP in Fig. 14 is the general volts-amperes characteristic of a discharge tube, where AB is the statical boundary condition, CD is the region of normal cathode fall, and DP is the corona characteristic. Taylor showed that DP the corona characteristic, is the same as the region of threshold current proposed by Appleton, Emeléus and Barnett, in their explanation of the action of the counter, and his explanation of the counting action is that "if in a discharge tube having a voltage V across the electrodes, a threshold current i is produced either by external or internal ionizing factors, a self-sustained discharge will be initiated if, and only if the voltage V across the electrodes is equal to, or greater than, the voltage on the corona characteristic corresponding to the current i" (26). The threshold current is, of course, the current set up by magnification of ionization by collision in the electric field between the electrodes. This explains how the point-cylinder vessel works, since in this case the corona characteristic DEP lies very close to the axis near P before it finally cuts it there. Thus a small threshold current can have a considerable effect, allowing a discharge to be initiated at the potential V instead of V_c. With plane parallel electrode tubes the corona characteristic rises rather perpendicularly to the axis at P, and Taylor considers the threshold currents are insufficient to allow the discharge to pass at some potential V less than V_c. The action in this case is therefore considered to depend on polarisation of the electrodes rather than on the shape of the volts-amperes characteristic near P, and since such polarisation layers are erratic in their behaviour, these counters are not very stable in their action. Electron liberation at the cathode causes neutralisation of the charged layer locally and consequent lowering of the sparking potential to a value at which a flash may occur with the existing potential across the tube. Suppose now we consider a discharge-tube such as that of fig. 13(a) or fig. 13(b) with a high-frequency potential across the electrodes E. It appears that when such tubes act as counters either of the two actions described above must take place. Polarisation effects in such H.F. tubes are very slight compared with those in D.C. tubes (27), and it would seem to be necessary to explain the action of such tubes on the basis of corona currents. The corona regime has not been systematically investigated for the H.F. discharge, but Thomson (23) has produced evidence of its existence. Now it is probable that here as in D.C. parallel plate discharge-tubes the corona characteristic rises steeply from the voltage axis at P, fig. 14, and the question is whether the threshold currents set up by collision on the entry of an ionizing particle are sufficiently large to bring about what is virtually a lowering of the sparking potential of the H.F. discharge tube. For a tube such as that of fig. 13(b) with a steady potential across the electrodes such an action is not possible, but the threshold currents brought about by ionization by collision when the steady potential is changed to a high-frequency potential might conceivably be of much greater magnitude since in this case the ions oscillate to and fro under the influence of the alternating electric field. The opportunities for collisions in a very short interval of time in a field of frequency of the order of 10^7 c/s. are increased in this way, provided that the conditions are such that the loss of ions by contact with the electrodes etc. during the interval is small. It is possible that these conditions can be fulfilled and the experiments on the H.F. tubes supported this conclusion. In this connection mention may be made of an experiment of Sir. J. J. Thomson [28] who showed that it is possible to light an electrodeless discharge by passing ultra-violet light through the discharge-tube when it is critically adjusted for sparking. This lends additional support to the hypothesis that some such action as that dwscribed above is responsible for bringing about a discharge on the entry of an ionizing particle into tube I. Since then it is unusual to have polarisation effects greater than 1 or 2 volts in a H.F. discharge-tube, it seems reasonable to conclude that the initial action of an ionizing particle on entry is to cause a building up of the threshold current to a value equal to that of some part of the corona current characteristic, and that this process results in a glow discharge. Such an explanation does not preclude, however, the possibility that a very slight polarisation of the electrodes, or an alteration in the field distribution of the electric force due to the existence of corona currents, plays some part in the mechanism of the flashing also. Indeed, it is quite possible that the action is a combination of both effects, just as Taylor concludes that in the case of the point-cylinder counter, although the corona can explain the action, it does not preclude the chance of both processes being involved to a greater or lesser degree.

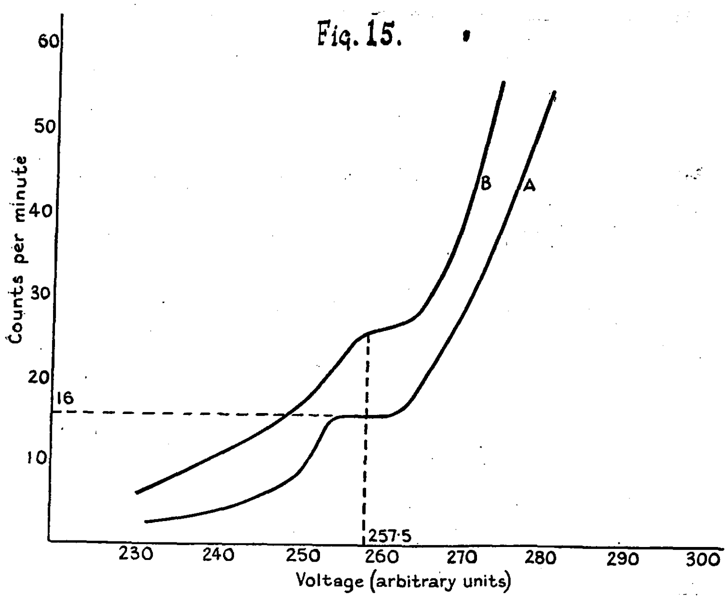
This bwings us to the second important point in the working of any counter - the self-restoring property. The action in the case of the point-cylinder or the D.C. plane parallel electrode tube depends in an intimate way on the presence of large resistance in the circuit [25]. The self-restoring property of the H.F. discharge-tybe must be altogether different therefore, and is as follows. When a discharge passes through the tube its capacity is altered, and this has a decided effect on the tuning of the oscillator. The effect is equivalent to adding capacity to the anode oscillatory circuit. Thus when the counter is working the passage of a current is the same as the sudden addition of capacity to the oscillatory circuit with consequent detuning. If this is sufficient to lower the oscillatory voltage across the ends of the tube to a momentary value below that of the maintenance potential of the tube, then the discharge ceases to pass, and a flash takes place. This was found to occur in practice, being especially marked at the lower pressures, and when it did not occur it was usually possible to obtain a flashing state of the discharge either by increasing the capacity C_1 or by decreasing the capacity C_2 (see fig. 12). Thus to take an example, in one case the oscillator when tuned to resonance had a frequency of $1{\cdot}11.10^7$ c/s and the frequency when it was detuned to act as a counter giving flashes was $1{\cdot}07.10^7$ c/s.

Experimental Procedure and Results.

Before using any of the tubes they were "conditioned". The vessel was pumped out to as low a pressure as the pumps were capable of producing. It was then allowed to stand for some hours, and the pumping was resumed. This was repeated at intervals for a few days. The gas to be used was next passed through the drying system into the thoroughly evacuated discharge-tube, and the pressure was adjusted so that when the glow discharge was running it covered the plates in the case of tube II or tube III. In the case of tube I the discharge was run also. After passing the discharge for a few hours the tube was again exhausted, fresh gas passed in and the whole process repeated. This was done several times before the tubes were used as counters. In the case of the parallel plate tubes, tubes II and III, this "conditioning" was found to have a material effect in improving the action. The plates were carefully cleaned and heated for some time in a Bunsen flame before assembly in the glass vessels.

Experiments carried out with tube I, which became L_1 of fig. 12, showed that with the 3 turn loosely wound coil the gas pressures at which discharges could be obtained were low. The range of pressure investigated was from 0·27 mm. Hg. to 0·001 mm. Hg. (Experiments with other coils, for instance one of 20 turns about 10 cm. long, showed that although higher gas pressures could be used, they did not give a good counting state.) A curve of sparking potential against pressure was determined for this range, and was of the usual form, showing the characteristic straight portion falling to either a single minimum [23] or in some cases to two minima. It was found that the tube acted as a counter on either side of the critical pressure, 0·02 mm. Hg. with air as the filling gas. With the oscillator adjusted so that the frequency was $2 \cdot 0 . 10^7$ c/s. and with the pressure of the gas at 0·05 mm. Hg., a characteristic curve of counts per minute against voltage across the ends of the coil was plotted as shown in fig. 15. The voltage was determined in relative values only by the thermo-couple and galvanometer method described above The voltage was raised slowly by adjustment of the filament resistance R of fig. 12, and at a certain value counts began to be heard. The discharges giving rise to these could scarcely be seen in a lighted room. With air they took the form of a dull blue flash confined almost entirely within the coil at the pressure 0·05 mm. Hg., in the neighbourhood of which tube I was normally used. As the voltage was still further increased the number of counts per minute slowly increased, and finally the discharge became intermittent, flashing so rapidly that it produced a howl in the loudspeaker. This behaviour is exactly similar to that of the point-cylinder type. It is seen from fig. 15 that there is a part of the curve approximately parallel to the voltage axis, the counts per minute remaining steady through the range of voltage corresponding to 255 to 260. Thus the correct operating voltage of the tube is about the mid-point of this range, and is seen from fig. 15, curve A, to be at 257·5. From this part of curve A, we can determine the natural count for tube I. this being 16 per minute.

Fig. 15.



Characteristic curve for tube I.

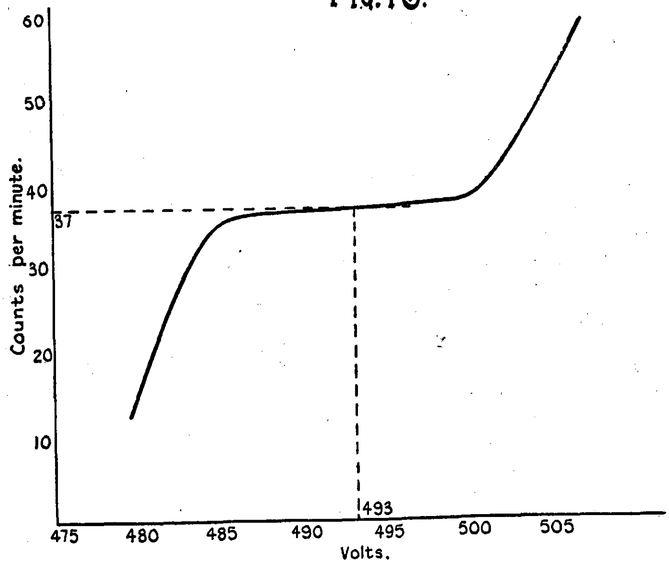
Curve A was determined when there were no radioactive substances present, but curve B was plotted with a weak source placed at a distance from the counter. As is to be expected curve B lies above curve A, the flattened portion being not so well defined. It is seen from the two curves that the source has brought about 10 additional counts per minute. Tube I was tested for radiation by bringing a radon capillary containing 1 millicurie into its vicinity. As it was brought nearer the rate of counting rose very rapidly and attained a high value. If we define the sensitivity of the counter to be measured by the distance at which 1 millicurie doubles the natural count, then for tube 1 it is 3·5 metres. The counter was used to detect α-rays and β-rays also, these passing into the vessel through the mica windows.

Experiments on tube II were carried out on the same lines. It was found that with argon as the filling gas the tube could be struck between the pressures 4·5 cm. Hg., and 0·05 mm. Hg. approximately when it was connected across the oscillatory circuit, as shown by the broken lines of fig. 12. The reaction of the passing of a discharge on the oscillatory circuit was not large enough at the upper end of the pressure range to make it possible to attain a counting state. This is to say at the higher pressures the self-restoring property required in a counting tube was absent, the discharge staying in once it was struck. At the lower end of the pressure range the self-restoring property of the system was effective, the glow taking the form of a sudden flash. The tube at pressures of the order of 0·10 mm. Hg. acted as a counter quite efficiently, the natural count being determined as 9 per minute.

In order to increase the reaction on the oscillatory circuit due to the passage of a discharge, tube III was constructed, as it was hoped that with the plates of the tube in place of the condenser C_1 of fig. 12, the self-restoring property would be present at higher pressures than those used with tubes

I and II. It was found that discharges could be obtained in tube III with air as the filling gas over a range of pressures from 0·01 mm. Hg. to 7·00 cm. Hg. at least. It was found also that the tube did act as a counter at the high pressure of 7·00 cm. Hg., each discharge taking the form of a very fine bright line between the plates, while at the lower end of the pressure range the discharge was a dull glow spread round the edges of the electrodes. The tube was usually worked at the low pressures because in this region it was steadier in its action, the variations at pressures around 7·00 cm. Hg. being possibly due to the fact that the line discharge was inclined to wander between different points on the plates. The characteristic curve for tube III was determined with the oscillation frequency at $1 \cdot 10 . 10^7$ c/s. by means of an electrostatic voltmeter.

Fig.16.



Characteristic curve for tube III.

The chief difference in the case of tube III was that the natural count was much higher than that of either of tubes

I or II. This is to be expected since the surface area of the electrodes of tube III and the volume of the containing vessel are larger, this giving an increased chance of radiations falling on the walls, the containing gas, and the electrodes causing the ejection of electrons etc., While considering the natural count, which is seen from fig. 16 to be 37, it is well to point out that the characteristic curve had to be taken in the dark, or with the vessel screened from light, as this was found to increase the count by a Photoelectric action. Thus a 100 watt lamp at 1 metre from the counter doubles the natural rate of counting. Experiments performed with a D.C. tube acting as a detector, the tube being an ordinary Osglim beehive lamp showed that the photoelectric effect in these tubes was of much greater magnitude, a lighted match held near being sufficient to cause very rapid discharging. From the curve of fig. 16, we see that the working potential of tube III is 493 volts, the gas pressure being 0·05 mm. Hg., and the voltage requires to be adjusted at this value within the limits $\pm$ 7 volts. A test carried out with tube III to test its sensitivity to γ-rays showed that the natural count was doubled when 1 millicurie of radon was placed at 4·5 metres from the counter.

Experiments carried out with a beam of γ-rays, defined by means of lead blocks, showed that detection of the γ-rays was effected when the γ-rays passed through the contained gas or when they impinged on the electrodes. The effect was greatest when the beam fell directly on the metal surface. It would appear that when the counters are detecting the γ-radiation most of the action is due to the γ-rays ejecting electrons from the metal these producing ionization when they oscillate in the H.F. field of electric force. This conclusion is supported by comparison of the sensitivities of tubes I and III with the surface areas of the coil of tube I and the plates of tube III.

Thus $\dfrac{\text{Sensitivity of tube I}}{\text{Sensitivity of tube III}} = \dfrac{3\cdot5^2}{4\cdot5^2} = 0\cdot61$

Surface area of coil of tube I $= \pi.0\cdot25.80 = 63$ sq. cm.

Surface area of plates of tube III $= 2\pi r^2 = 2\pi(3\cdot9)^2 = 94$ sq. cm.

$\therefore$ Ratio of surface areas $= 0\cdot67$.

Comparison of the figures 0·61 and 0·67 supports the view that the γ-rays act for the most part on the metal surfaces.

The "energy trigger ratio" of a counter is the ratio of the energy of the discharge to the energy of the ionizing particle. The energy of the discharge in the H.F. tubes is $\int_0^T i\,V dt$ where i is of the order of 10 milliamps, and V of the order of 10^2 to 10^3 volts. The integral cannot be evaluated, but the effective ratio for the H.F. tubes must be large compared with that of the point-cylinder type, 10^5 to 10^9, as determined by Appleton, Emeléus and Barnett (24), since a small loudspeaker could be included in the circuit. The "energy trigger ratio" of the parallel plate D.C. tube may be higher than that of the point-cylinder type, but some of the faults of this type of detector mentioned above and encountered in some experiments with it make it inferior in its action to the H.F. tubes. As has been said its action depends on polarisation layers, and these give rise to erratic behaviour. For instance a relatively intense source of radon brought up close to an Osglim lamp acting as a detector sometimes stopped it working altogether. This agrees with two observations of Taylor. Taylor shows that with continued flashing polarisation in some tubes can amount to values in the region of 60 volts (29). He finds, moreover, that a D.C. tube cannot act as a counter when the polarisation is much greater than about 3 volts[25]. The explanation of the above phenomenon would seem to be that the initial rapid flashing of the tube raises the polarisation to considerable values and prevents the subsequent action of the tube as a counter. Another fact noted with the D.C. tube was that after a certain maximum the counting rate could not be increased by increasing the radiation intensity. This follows from the fact that there is a time period $t = CR \log \frac{E-V_c}{E-V_b}$ associated with the electrical circuit, where E is the potential applied to the tube, V_b is the potential at which discharge occurs when radiation falls on the detector, V_c the minimum maintenance potential. This means there is a certain minimum time interval between individual discharges, and shows that the maximum rate at which particles can be recorded is determined by the time constant CR of the circuit. If two particles enter the chamber in rapid succession the second cannot initiate a discharge unless the battery has had time to recharge the condenser to a sufficiently high voltage. In the case of the point-cylinder counter this is true also, though CR is usually smaller in value. With the H.F. discharge-tubes there is no such time constant associated with the circuit limiting the rate of counting, as was proved by the high rates of counting obtained with strong radiation intensities.

The question of the reduction of the sparking potential of the tubes was studied. A weak source of radon held near an Osglim beehive lamp showed that the sparking potential fell from 162 volts to 159 volts. If any meaning has to be attached to such results readings have to be determined in a certain way. Considering the beehive tube, if it is put at a definite potential of 160 volts, read on an accurate electrostatic voltmeter, it will not show flashes if there is no radiation present. Keeping it at this steady potential, and bringing radon near to it, a discharge is observed between the electrodes (either continuous or flashing). The behaviour of tube II may be contrasted with this. It was found that when the potential across the electrodes was increased extremely slowly the discharge commenced at very nearly the same value whether radiation fell on the tube or did not. When the potential was increased more rapidly, however, there was a difference between the values at which discharge commenced of the order of 5 to 10% of the sparking potential. Also, if the tube was set at an intermediate value of potential the discharge came in after some delay in the absence of γ-radiation, but it came in as soon as radon was put near the vessel. The filling gas was argon at a pressure of 4·00 cm. Hg., and with air at a pressure of 1·31 cm. Hg. the results were much the same. The same type of behaviour was found with tube I. The potential at which the discharge commenced was the same in the presence or absence of radon, the potential being increased very slowly. An increase of the order of 5% was recorded when it was raised more rapidly. For tube III, filled with air at 6·80 cm.Hg. pressure, the counting commenced at very nearly the same values when the potential was increased slowly, it being a very occasional flash without radiation and rapid flashing with radon. More rapid increase gave differences of the order of 3% to 5% however. There was evidence in some cases for all the tubes of a small reduction in the sparking potential for a very slow rate of increase of potential, but it was of the order of 1% and was near the limit of accuracy of the measurements. Thus specimen readings are given in the table III (in arbitary values only).

Table III

	Radium Present	Radium Absent
Very slow increase	49·3	49.7
More rapid increase	49·3	52·7

The action of the radiation on the H.F. tubes seems to be essentially a reduction of the time-lag in the passing of a discharge. For instance, with tube II which has a natural count of 9 per minute, there exists on the average a period of 7 seconds between individual counts, but this interval is reduced by the action of the radiation, becoming smaller and smaller with stronger and stronger intensities. The difference in the readings 52·7 and 49·7 is due to the rise in potential which takes place during the 7 seconds in which no ionizing particles enter the counter, there being no radiation present except the normal cosmic radiation etc. present in any room. The different action of radiations on the H.F. discharge-tubes and on D.C. tubes was noticed in the fact that the D.C. tube could be adjusted at a potential at which no flashes took place under normal conditions, although the tube flashed when γ-radiation fell on it. It was found on the other hand that radiation had no effect on the H.F. tube unless this was adjusted at such a voltage that an occasional flash was taking place. These results agree with those given above for the effect of γ-radiation on the sparking potential of both types of tube, and prove that the D.C. tube may be adjusted at a potential such that it detects γ-radiation but does not detect the cosmic radiation etc. present under normal conditions. For a true counter we should expect the few radiations normally present to have the same effect as strong γ-radiation and to be equally capable of affecting the counter, and this is true of the H.F. tubes described above.

A few remarks may be added here on several other points connected with the working of the H.F. discharge tubes. The filling gas was found to have no material effect on their behaviour though this may have been due to the fact that the purity was not very high. Commercial argon, 99·5% pure, was used, and the hydrogen was passed direct from a Hoffmann apparatus into the drying tubes and then into the discharge tubes. The shape of the coil of tube I is not critical, but it was found to be the best of those tried, while the electrode disposition of tubes II and III may be varied considerably. Tube III, forming part of the H.F. circuit seemed to be the best arrangement however. This brings in one of the disadvantages of this system, the fact that capacity effects from surrounding objects may alter the voltage generated across the tubes by the high-frequency oscillator and thus affect the results. This can be guarded against in practice. It may be noted that an attempt to use an electrodeless discharge, with the coil outside the containing vessel instead of inside as in tube I, proved unsuccessful. Many causes may explain this result - the long life of an ion in the glass vessel being a probable one.

The work on the H.F. counters being advanced to a satisfactory stage it was decided that further attacks should be made on the diffraction problem with a counter as the detector of the β-rays since it was obvious that 'counting' was much more sensitive than photographic detection. In the meantime results on β-ray diffraction had appeared. Hughes[30] claimed to have diffracted β-rays from radon for values of the momentum ranging from $H\rho = 1938$ to $H\rho = 4866$, where H is the value of the magnetic field and ρ is the radius of curvature of the path described in the field H. The sizes of the diffraction rings obtained agreed with those expected from de Broglie's equation to within 5%. His method depends on the principle of focussing the β-rays and selecting those of a particular velocity. It is a modification of a method proposed by Lebedeff (31) and it suffers from two serious objections:-

(1) β-rays of slightly different energy from those focussed at the centre form a background on the plate;

(2) large thin films, about 5 cm. across and extremely difficult to prepare, are required.

Hughes obtained photographs whose background density was so great that prints could not be made from the plates. Only one type of film could be employed - gold sputtered on a gelatine base. For these reasons it seemed desirable to pursue the problem further, using the more sensitive electrical method of detection which is found in the counter.

The preliminary attempt with the new method of detection was analogous to the first experiments with photographic detection. A special type of 'monochromator' was devised to give a homogeneous beam of β-rays and since the principle embodied in this is original a short explanation of it is given. Suppose R is a radioactive source (fig. 17) and that the rays emanating from R are to be sorted out into a beam of a certain discrete velocity and detected in the detector D (a counter in this instance). Let an aperture be fixed at A in a rectangular box, situated in a magnetic field whose lines are perpendicular to the plane of the figure. The beam has to be moving in the fixed direction BD after passing through the aperture at B.

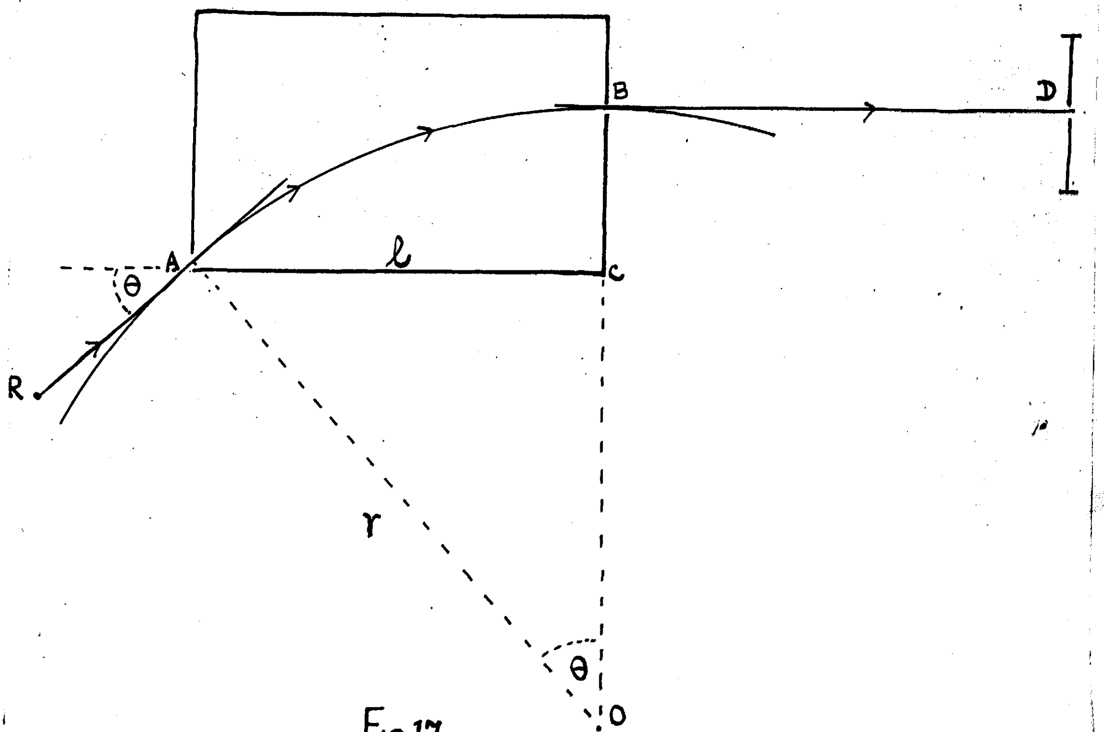


Fig.17.

Then we find that there is a particular value of BC such that, no matter what the strength of the magnetic field may be, the beam passes through B and travels in the direction BD. Otherwise, the 'monochromator' is such that variation of the magnetic field strength brings rays of different velocity to the detector fixed at D.

Draw AO $\perp$ RA and produce BC which is $\perp$ BD to meet AO in O. Then if BO = AO, O is the centre of a circle with radius AO and rays leave the magnetic field at B in a direction perpendicular to the radius BO, that is, in the direction BD. Let θ = the fixed angle of deflection of the rays (20^{o} in this instance), let l = the fixed length of the side of the box, and let r = radius of the circle.

Then

$$\angle AOC = \theta$$

$$r = l \operatorname{cosec} \theta$$

$$OC = l \cot \theta$$

$$\therefore \quad BC = l(\operatorname{cosec} \theta - \cot \theta) \qquad --- \qquad (9)$$

This is the condition that must be fulfilled in the construction of the resolving box if the action is to be as described. It includes as a particular case the arrangement commonly used for both β -ray and cathode ray work, namely $\theta = 90^{\circ}$ when BC $= 1$. With a 'monochromator' designed for $\theta = 20^{\circ}$ and a counter at D, 20 cm. from B, a weak beam of β -particles was obtained with 50 mc. of radon as the source R. With more than 10 cm. of lead shielding, the count due to γ -rays was 24 per minute and with the magnetic field adjusted for maximum β -count only 12 additional counts per minute were obtained even with a subsidiary field between B and D for finer control. It was realised that the problem could not be solved by this method since the β -ray beam was too weak to show small variations in intensity against a stronger background of γ -ray counts.

One of the chief difficulties in using a counter as the detector in β -ray work is the disturbing action of γ-radiation. This cannot be entirely eliminated in any β -ray counter since the γ-rays are detected because they form secondary β -rays in passing through material in their path. Thus when they fall on the walls of the counter or pass through the contained gas they liberate electrons. Any counter which responds to β -radiation will therefore respond to γ-radiation. The action of the γ-radiation can however be minimised by the choice of material for the counter walls, electrode shape and dispostion etc. It is generally the case that radioactive sources which liberate β -rays liberate γ-rays. There is however an important exception to this general statement, namely radium E. This element emits a normal continuous spectrum of β -rays or disintegration electrons (32) whose energy limits correspond to $H\rho = 1600$ and $H\rho = 5000$. The spectrum has a single maximum of intensity at $H\rho = 2100$. There are no homogeneous groups of electrons superimposed in the form of a line-spectrum and no γ-radiation is emitted (actually an extremely small quantity is emitted but it can be neglected in practice). It was decided that RaE was the best source for this work because of these unique properties which it possesses and experiments carried out with a specially prepared source were the first to give evidence of diffraction.

Apparatus.

(a) The Counter. Since the β-rays in a narrow pencil emitted from RaE were to be detected the Geiger counter was chosen in preference to other types. The effective counting volume in this form is limited to a small narrow cone (33) with its apex at the point and its base on the metal front, close to the small mica window. (this is only true if the point is nearer the front than the sides of the vessel and this arrangement was adopted). One result of this is that the natural count is small - an important thing in measuring weak sources of β-radiation accurately. The efficiency of this type for γ-rays is lower than for most other types and it may be reduced to extremely low values by using an ebonite cylinder(34). The counter described below had a low γ-ray efficiency and this seemed to depend on the sharpness of the point and its position in the cylinder. The most suitable values were determined experimentally to be those given below (fig. 18). The γ-ray response itself is not of any importance in work with RaE which does not emit γ-radiation. The small window of the Geiger type of counter suited the experimental conditions imposed in the diffraction investigation. The Geiger counter is shown in fig. 18. The chief dimensions are:- length, 8 cm; distance from point to face 0· 8 cm; distance from point to side, 1·0cm; aperture, 0·8 mm. diameter. The cylinder was of copper and the face screwed into position. A thin mica window covered the aperture. The seals were effected with a mixture of beeswax and resin. A copper rod, 0·5 cm. diameter, passed through an ebonite insulating plug, corrugated along its surface to increase its resistance. It supported a short steel needle whose shape was ground to the form suggested by Emeléus [35]. The form of the point and its treatment are important and the views of various experimenters do not agree on this subject. Thus heat treatment is sometimes said to be more important than form or polish [33] but it was found by the author that with steel points (prepared from gramophone needles) heat treatment was detrimental in its action since it seemed to produce irregularities on the surface. A smoothly ground point washed in alcohol and given no other treatment worked very satisfactorily. Contrary to some views it was found that sharpness of the point was an important factor. Thus with the point approximately hemispherical in shape, tests were made with points of diameters equal to 0·01 cm, 0·03 cm, 0·06 cm. and the 0·06 cm. point was found to be much more regular in its response. Very sharp points (diameter less than 0·01 cm) were erratic in behaviour. This is probably due to the fact that spurious discharges were much more liable to pass between small projections on the point and the cylinder in the very strong electric field which exists in the neighbourhood of a very sharp point. The inner surface of the copper vessel had to be polished and washed in absolute alcohol as otherwise the

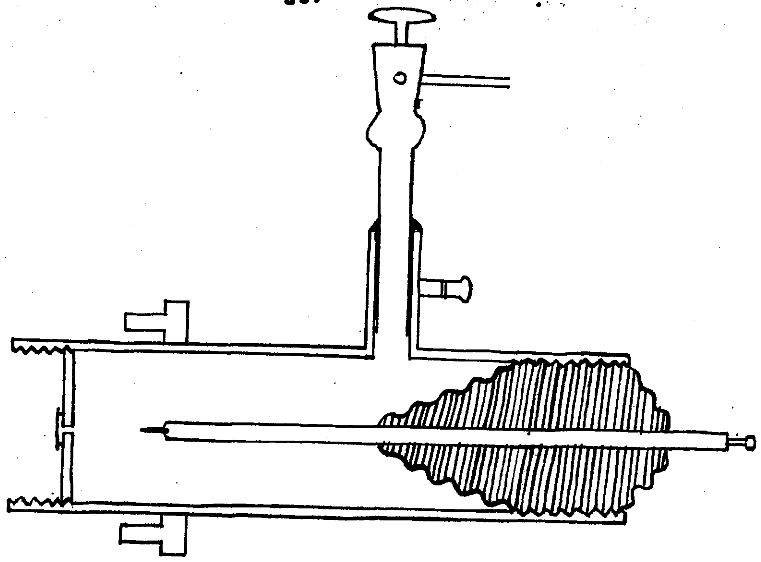


Fig. 18 Geiger Counter.

tube usually failed to act as a counter. An alternative method found even more suitable was to heat the copper tube in a Bunsen flame and to immerse it in alcohol.. This leaves a bright clean copper surface when the reaction is complete. In this connection a remark may be made on the fact that on many occasions the counter seemed to act on assembly without any external ionising agent being present and in some instances the counts were inclined to take place in small bursts. The effect seemed to be most marked after the copper vessel had been most carefully polished and it was not so prominent when the surface was heated and cleaned by reduction in alcohol. This effect usually disappeared with time and an increase in the voltage applied to the counter had to be made to bring it to the correct steady working state. These observations agree with those of Lewis and Burcham(36) who explain their results in terms of surface reaction (probably oxidation) accompanied by ionization. The counter should therefore be given some time to settle if it is assembled in the above way. The vessel was filled with dry air by means of the drying system indicated in fig. 19. Liquid air was used instead of the more usual calcium chloride and phosphorous pentoxide. Five stopcocks divide the system into four parts. First it was evacuated and then gas was

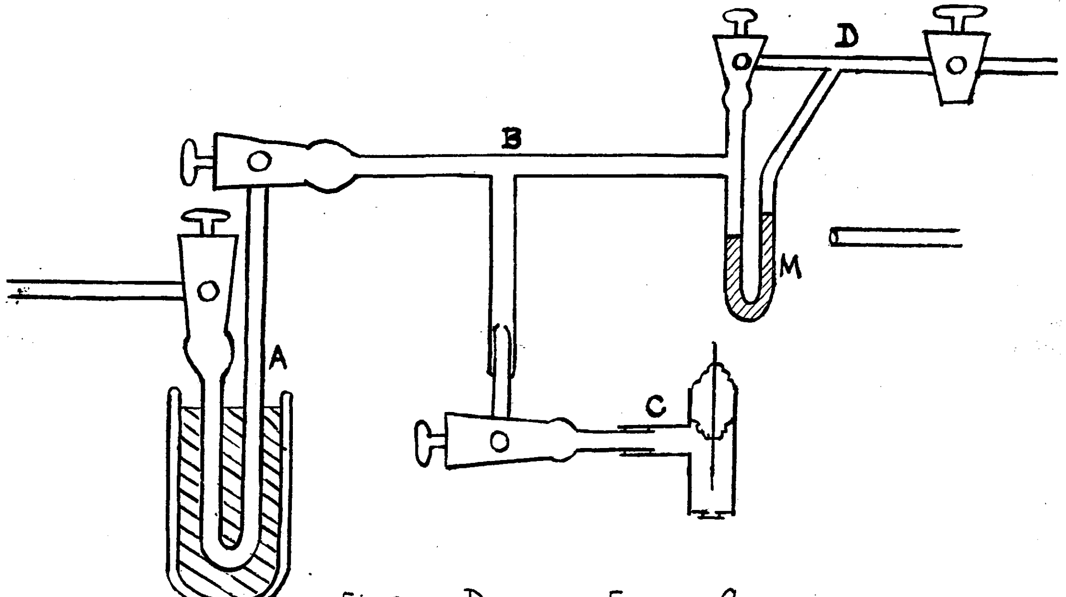


Fig. 19. DRYING AND FILLING SYSTEM.

passed into the part A round which liquid air was kept for several hours. The dry gas from A was passed into the counter C. By exhausting various parts of the system and sharing the gas the pressure in the counter could be adjusted at practically any value (as read by the mercury manometer M). The counter when removed was ready for use. The pressure was varied considerably at different times, values between 2 cm. and atmospheric being used but normally 7 cm. was the pressure of the filling gas. Before use the counter was adjusted to the correct operating voltage. The positive potential on the case was gradually raised by regular steps and the total number of counts due to cosmic rays etc. determined over a fixed interval of time, say 10 minutes, for each value of the potential (the counts being registered as described below). A typical set of readings taken in this way is graphed in fig. 20. We see that between 1345 volts and 1390 volts the curve is approximately parallel to the voltage axis. For the maximum efficiency of counting

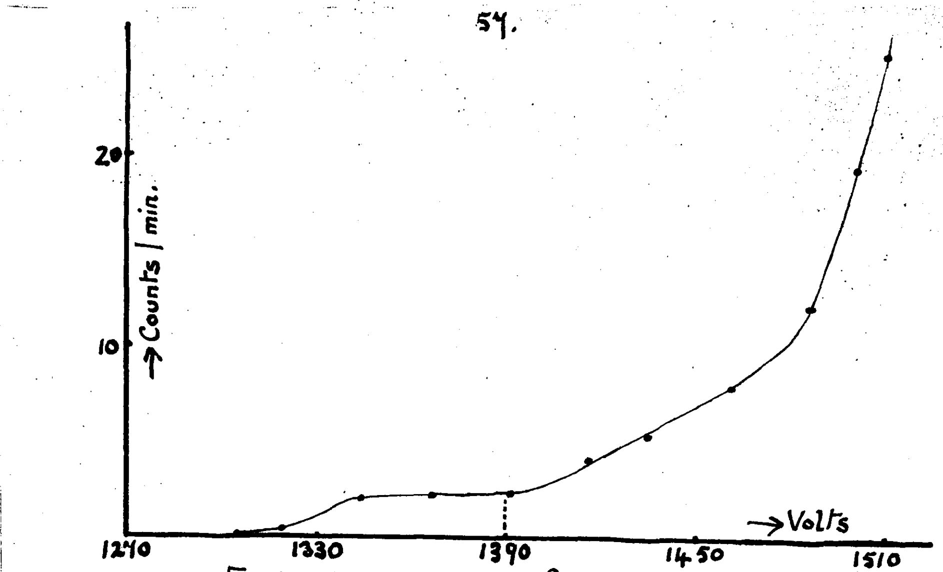


Fig20. Characteristic Curve.

the voltage on the case should be 1390 volts and this was the potential applied in this instance. Higher potentials give spurious counts while below 1350 volts a considerable number of particles can be missed in counting. From the curve the natural count is seen to be 2·4 per minute. This low value agrees with the observed fact that this counter was relatively insensitive to γ-rays. The importance of determining the correct voltage is seen from table IV giving counts against voltages over a considerable range of values. It was determined with a source of RaE near the counter and it shows a continuous variation.

Table IV.

Volts	1272	1296	1320	1344	1368	1392	1416	1437	1452	1480
Counts/ min.	0:00	112	276	332	374	397	420	440	456	472

Before use a counter should be tested for the probable error in any reading due to statistical fluctuations in the number of counts recorded. The counter was tested for this by placing a weak source of RaE near the window and taking a number of readings over 10 min. intervals. Thus four separate total counts for 10 min. were found to be 2442, 2418, 2424, 2445, which gives an average count of 243·2 per min. Taking 2432 as the correct result, the maximum error in the determination is seen to be 14, which means that any one of the counts can be taken as correct to within ± 14 in. 2432. This proves that in taking any count of the order of 2500 the result can be taken as correct to within ± 0·58%.

(b) The Amplifier and Register. Several good amplifiers (37) for use with D.C. counters have been described. The amplifier used in the present work differs in some ways from these. The circuit is shown in fig. 21. The complete amplifier was enclosed in an earthed metal shield indicated by the broken lines.

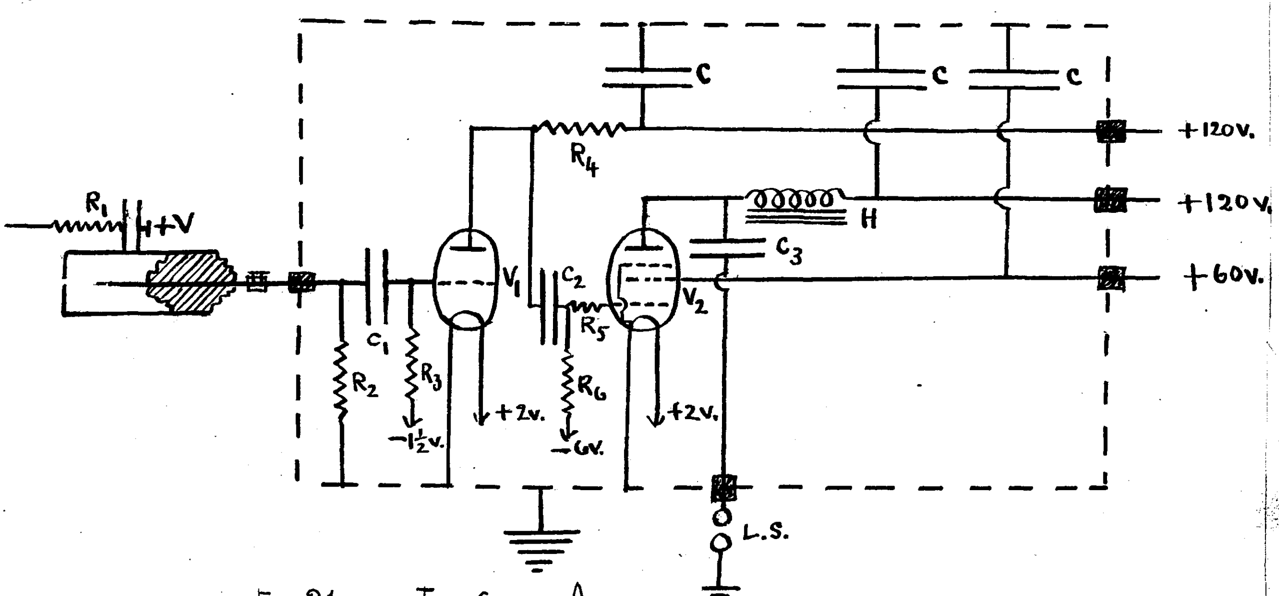


Fig.21. Two-Stage Amplifier.

The values of the various components were:-

(1) $R_1 = 10^9$w, $R_2 = 3{\cdot}0.10^7$w, $R_3 = 2{\cdot}0.10^6$w, $R_4 = 10^5$w,
$R_5 = 5{\cdot}0.10^4$w, $R_6 = 10^6$w.

(2) $C_1 = 0{\cdot}002\mu F$, $C_2 = 0{\cdot}003\mu F$, $C_3 = 0{\cdot}01\mu F$, $C = 2\mu F$.

(3) H = 30 henries.

L.S. denotes a speaker, V_1 a 210 HF Cossor valve, V_2 a 220 HPT Cossor valve. The resistances R_1 and R_2 were of

$\frac{1}{4}$" diameter pyrex tubing about 6" long with tungsten electrodes and filled with the correct mixture of absolute alcohol and zylol (or benzol) to give the proper values to the resistances.[38] They were carefully mounted on ebonite insulating stands.

For counting at a considerable speed or for long periods of counting it is necessary to couple the amplifier to a thyratron valve controlling an automatic register. In the

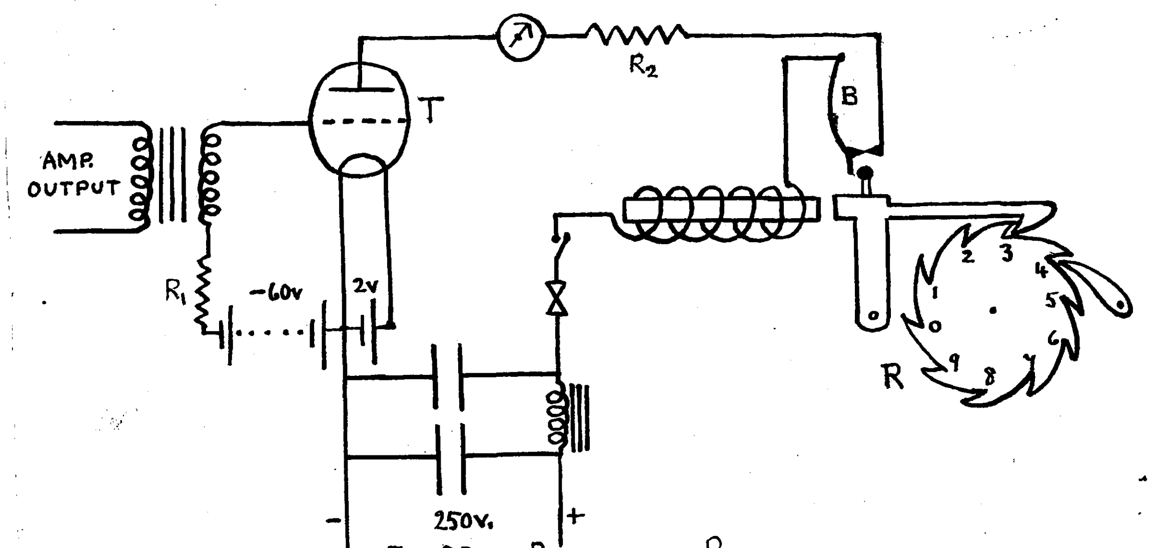
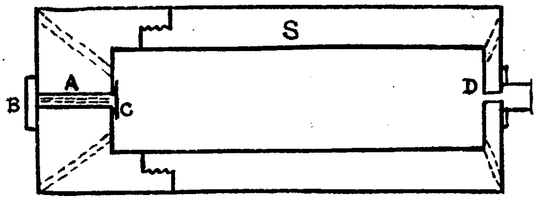


Fig. 22. Relay and Register.

present instance the method of recording due to Wynn-Williams[39] was adopted. In fig. 22 T is the thyratron valve and B a flat spring contact-breaker wired in series with the magnet of the register R which was modified so that the pawls were spring controlled instead of gravity controlled. The thyratron was coupled to the amplifier by a transformer. In fig. 22 R_1 = 25000 w, and R_2 = 1000 w. Counting at 500 per minute very few particles were missed by the register.

(c) The Source and Source-Holder. The source of β -rays was specially prepared from old glass radon capillaries. Twelve of these, which had each contained from 60 to 80 mc. of radon originally but which had decayed for periods between 2 and 3 years were opened and mounted in a small cylindrical cavity 0·6 mm. in diameter and 1·5 cm. long as shown at A in fig. 23. They were

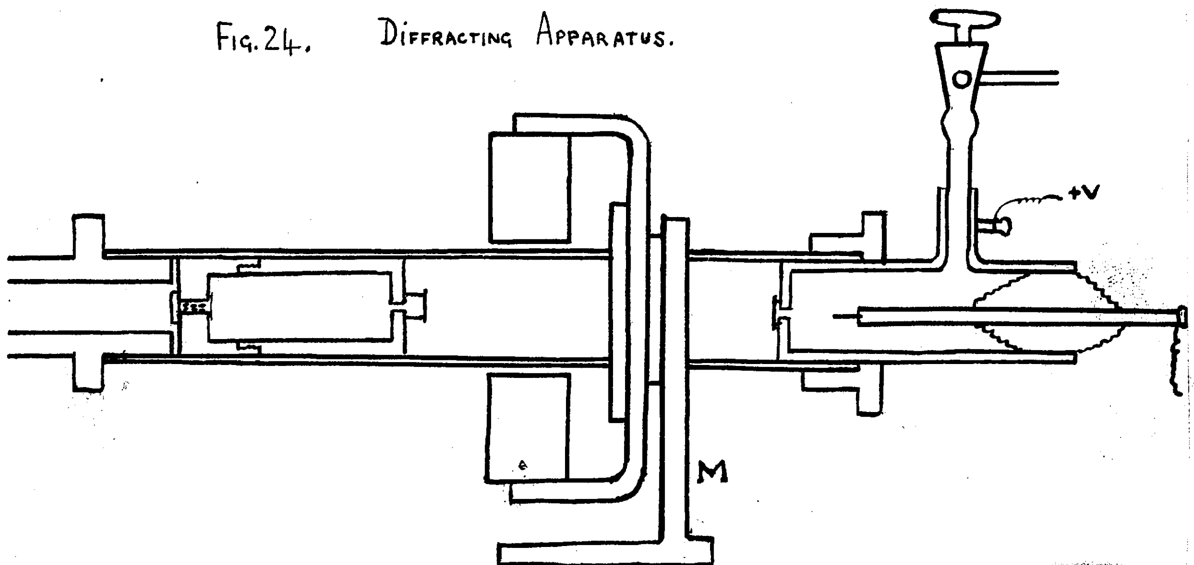
Fig. 23. Source - Holder.



held in position by the metal cap B and the thin mica film at C. The source was on the axis of a cylinder S of 2·4 cm. external diameter, 1·5 cm. internal diameter. It was closed at both ends and was made in two sections. The aperture D was of 0·5 mm. diameter and in front of it was the film-holder. Air passages were cut in the walls.

(d) The Experimental Arrangement. The assembly of the various parts is indicated in fig. 24. The source-holder and the Geiger counter were mounted in a Pyrex glasstube which was 20 cm. long, the distance from the film to the aperture of the

Fig. 24. Diffracting Apparatus.



counter being 10·0cm. A small electromagnet M was arranged so that it could be rotated round the axis of the camera. It was used for magnetic deflection of the β -ray beam on its way from film to counter. Its pole-faces were 2 cm. in diameter. The pumps were connected on the extreme left of the figure as indicated and the counter was connected to the amplifier, which controlled the thyratron-register arrangement of fig. 22.

Experimental.

Owing to the fact that the source consisted of decayed radon tubes the active material was of radium (D + E + F), the quantities of the last two being to within 2% in their equilibrium ratio(40). The β-radiation from radium D is very soft(41) and is unable to pass through the mica window of the counter. Radium D is therefore neglected. Radium F emits α-rays and these were detected when they fell on the window of the counter. Emeléus(42) has shown that in this case theoretically to every 17·1 α-particles from the source there are 24·5 β-particles To prevent some reduction in β-count the α-rays were not absorbed by films. They do not influence the results since with the magnetic fields used the α-rays suffered no deviation and any part of the total count due to these remained constant. The α-particle count and the natural count due to cosmic rays etc. made simply a constant background to the experimental readings. These varied only with a change in the number of β-particles from radium E reaching the counter. The principle of the method

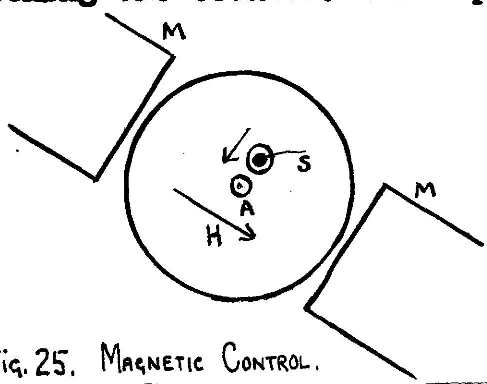


Fig. 25. Magnetic Control.

is illustrated in fig. 25. Suppose M represents the poles of the magnet producing a field H and let the front of the counter be as indicated, the aperture A being shown (looking along the axis of the camera). Suppose the β-rays fall at S. They will not be registered. At a certain value of H (with the pole-faces in the setting shown) S will be coincident with A and they will be detected. Now if diffraction at the film takes place a ring will be formed round S and the β-rays in this ring, passing across A under the influence of H, will be observed as an increase in the count. From the different values of the deflecting field-strength H the displacements of the beam at the counter are calculable and the diameter of the diffraction ring obtained. It is important to note that the method depends largely on the fact that RaE has no line-spectrum. This would complicate matters as variations in count due to different lines crossing A would be recorded. RaE has a single large maximum of β-ray intensity at $H\rho = 2100$. In this connection it may be mentioned that the apparatus was tested with a very weak source of Ra(B+C). The four principal maxima in the RaB spectrum were recorded as they passed across the aperture A. They correspond to line 17, intensity 80, at $H\rho = 1410$ (see table I); lines (20,21), intensities (91,10), weighted mean value $H\rho = 1687$; lines (24,25), intensities (100,12), weighted $H\rho = 1946$; lines (28,29) intensities (16,8), weighted $H\rho = 2273$. The separation of these maxima was approximately as expected from theory. The magnetic control does not lend itself to accurate determination of ring diameters since the field between the poles, which were 2 cm. in diameter and at a distance apart of 2·5 cm., is not uniform. The fact that non-homogeneous rays from RaE were used made this of little moment since approximate values only were expected. In view of the difficulties encountered above with β-rays as compared with cathode rays even qualitative results for diffraction of β-rays are of considerable value. Actually fairly good agreement in numerical values is obtained by the method. Calculation showed that electrostatic control of the beam, though preferable in many ways, required large voltages and it was not adopted for this reason.

Discussion of Results.

Consider an electron moving across the magnetic field whose area is bounded by the circle ACD. Let AB be the undeflected path of the electron along a diameter of the circle and suppose the lines of the magnetic field, of strength H, are perpendicular to the plane of the figure. Assume the field-strength H is uniform over the area of the circle, of diameter AC = l. The displacement x = BE of the electron from B, at distance L from C, where BE is perpendicular to AB, is required. The electron describes an arc AD of a circle and leaves in the direction DE, a tangent at D to the circle described. The radii of this circle, AO perp. to AB and DO perp. to DE, meet in O. Let

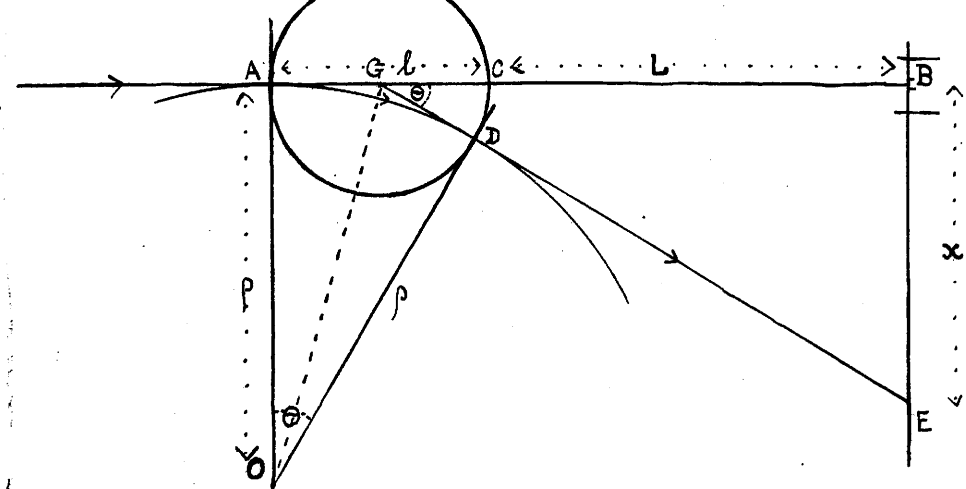


Fig 26. Magnetic Deflection of β-ray Beam.

ED meet AC in G. Then G is the centre of the circle ACD because AG = GD (tangents), and G is on a diameter.

Thus GB = GC + CB = L + $l/2$

but x = GB tan θ, where θ = $\angle$AOD = $\angle$BGE

and tan $\theta/2$ = $l/2\rho$, where ρ = radius AO.

Hence $x = (L + l/2) \tan \theta$.

$$\therefore x = (L + l/2) l/\rho \Big/ (1 - l^2/4\rho^2)$$

For rays of given momentum $H\rho = k$ we have

$$x = (L + l/2) l H \Big/ k (1 - l^2 H^2 / 4k^2).$$

Here $H\rho = k = 2100$, $L = 5{\cdot}6$ cm, $l = 2{\cdot}0$ cm.,

$$\therefore x = 0{\cdot}0063 H \Big/ (1 - H^2/2100^2)$$

Since H is seldon greater than 40 we have as a very good approximation

$$x = 0{\cdot}0063\ H$$

For changes in displacement corresponding to changes in H we have

$$\delta x = 0{\cdot}0063\ \delta H. \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Counts were made at different settings of the magnet and with different field-strengths till the setting and the value of H giving a maximum were obtained. This meant the maximum number of β-rays was entering the counter, that is, the rays of $H\rho = 2100$ in the spot S of fig. 25 were now deflected to enter at A. This search for the beam was the most difficult part of the whole process and when the correct position of the magnet was obtained it was clamped in position and counts taken over long periods for different values of field current in the neighbourhood of the value for which the count was a maximum. The minimum counting period for each value of H was 10 minutes. The results were graphed, field current being plotted against count. The count includes the natural count and the α-rays from RaF which enter the counter in addition to the variable part due to the β-rays deflected by the magnetic field. With no film in the camera the curve took the form shown in fig. 27, A, being a smooth curve with a single large maximum. With a film present two very small maxima were detected on either side of the

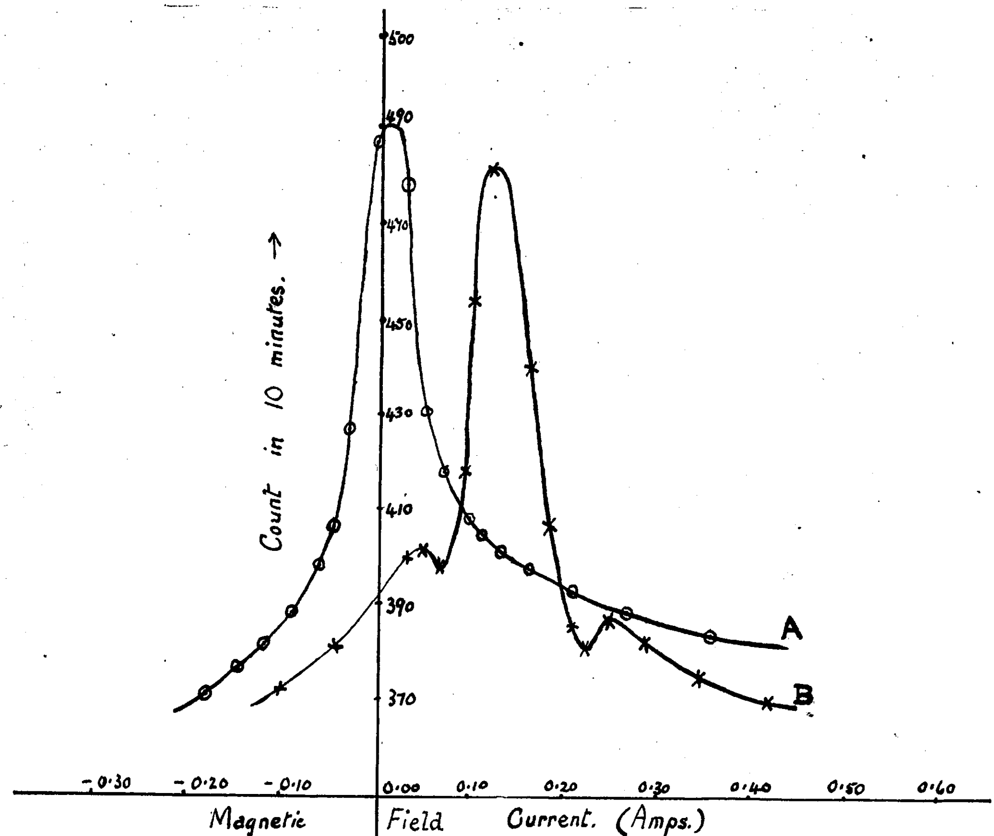


Fig. 27. A, no film present. B, with aluminium film.

principal maximum. Curve B, fig. 27 is for an aluminium film. The small maxima are at i_1 = 0·25 amp, i_2 = 0·05 amp.,

$\therefore$ Change in field current = δi = 0·20 amp. The corresponding value of δH from the calibration curve for the magnet = 34·6 gauss

$\therefore$ δx = 0·0063. 34·6 cm = 0·22 cm.

Thus, from the curve, for the diffraction of aluminium we have the diameter D of the first ring given by D = 0·22 cm.

But from equation (5) we find by calculation for $H\rho$ = 2100 (i.e. P = 300,700 volts) that D for the (2,o,o) ring = 0·193 cm. This is very satisfactory agreement between theoretical and experimental values when the small size of the diffraction pattern, the non-uniformity of the magnetic field, and the non-homogeneity of the β-rays are present as factors which detract from the accuracy of the result.

For P = 300,700 volts eqiation (5) gives for the (2,o,o) ring with gold the result D = 1·92 mm. From the curve of fig. 28, δi corresponding to the shift from one diffraction maximum to the other = 0·19 amp. Hence δx = 0·21 cm. is the diameter D of the diffraction ring obtained experimentally

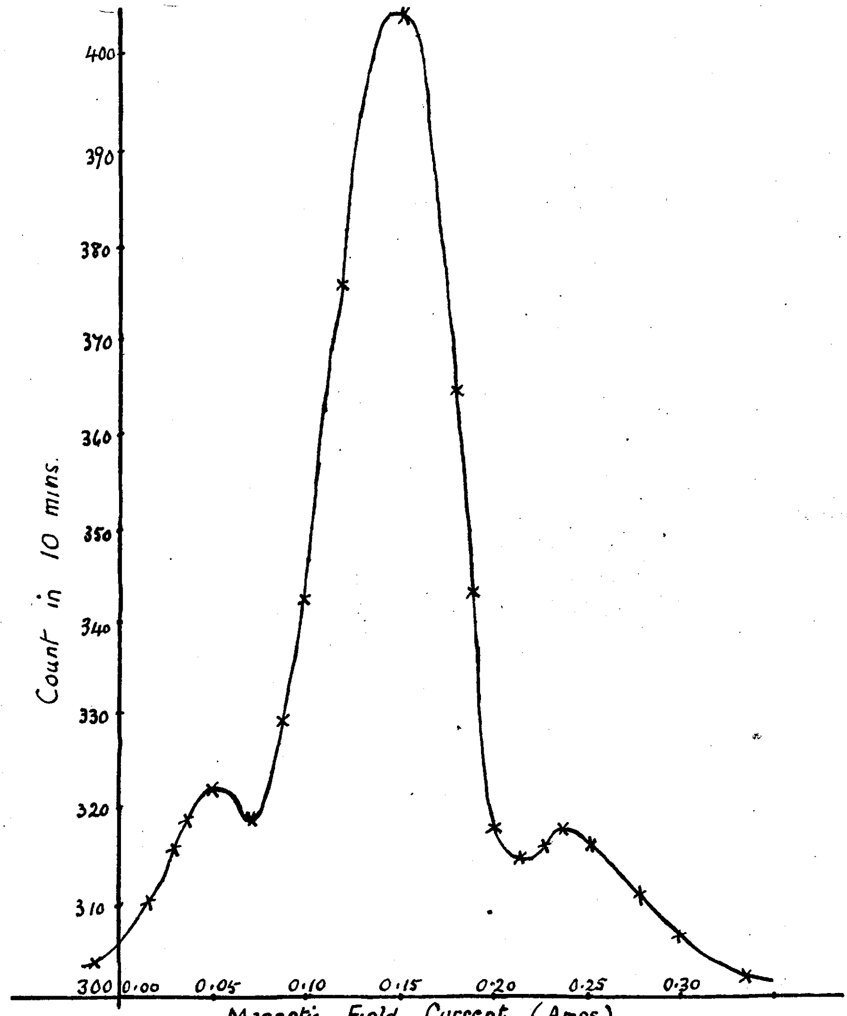


Fig. 28. Diffraction Curve for Gold film.

In the curves of figs. 27 and 28 each value of the ordinates was the average of a number of separate 10 minute counts.

Diffraction experiments with celluloid films failed to produce definite results. The smallness of the pattern in this case would explain the failure however as the instrument is not capable of resolving the different maxima when they occur so close to one another. Higher resolution might be obtained with smaller apertures but this reduces the number of counts and adds to the experimental difficulties very considerably.

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