ON THE BEADED CHARACTER OF THE CATHODE RAY LINE AS REVEALED BY INSTANTANEOUS PHOTOGRAPHS TAKEN AT SHORT RANGE.

By Chas. T. Knipp.

THE magnetic spectrum, so called, of cathode rays has been investigated by Birkeland, Strutt, and Thomson,[1] and is generally conceded to be due to the want of uniformity necessarily associated with the use of an induction coil. It was early shown that similar effects may be obtained by using an electrostatic instead of a magnetic field.

Recently, while photographing at short range the carriers, atomic in size, of both positive and negative electricity that accompany the cathode beam, I was impressed with the beaded character of the cathode ray line. The distinctness and regularity of the beads suggested that their origin might possibly be other than a want of uniformity that accompanies the induction coil or static machine discharge, or other than the presence of secondary rays.

Apparatus and Manipulation.

The apparatus employed was that described in a recent number of the Physical Review.[2] The modifications necessary were slight. The Wehnelt cathode was removed and in its stead an ordinary aluminum cathode was suitably mounted. The beam of cathode rays emergent from the canal passed between the nearly coterminous magnetic poles and electrostatic field plates and fell upon the photographic plate beyond. This range was about 2 centimeters. Seed's lantern slide plates were used. Mounting and exposing a plate to the action of the rays was briefly as follows: The circular plate, fastened to the movable brass disc[3] at three points by means of half and half wax, was placed in the cylindrical plateholder, which in turn slipped into position in the apparatus. After connecting the winch for turning the plate the glass containing vessel was sealed and the pump started. When the desired degree of exhaustion was reached, either with or without the aid of charcoal and liquid air, the electrostatic field was turned on and the discharge started. To get instantaneous photographs it was only necessary to rotate the plate while the discharge was passing.

[1] J. J. Thomson, Conduction of Electricity through Gases, 2d ed., p. 633.

[2] C. T. Knipp, Phys. Rev., XXXIV., March, 1912.

[3] See Fig. 1 of article referred to above.

Thus under varying conditions of deflecting fields (either magnetic, electrostatic, or both), aperture, vacuum and source of discharge, together with varying conditions of resistance, self-induction, and capacity in the circuit, photographs of great diversity were possible. The short range that the carriers traveled enabled impressions to be received and recorded on the plate that at greater distances would doubtless be lost because of absorption.

General Considerations.

The electrostatic displacement of the cathode ray particle as recorded by the photographic plate is given by the equation

$$x = \frac{Ae}{mv^2}, \tag{1}$$

while the magnetic displacement is

$$y = \frac{Be}{mv}, \tag{2}$$

where A and B are constants depending upon the strength of the two fields respectively and upon the geometrical data of the discharge vessel. From these it follows that for a given range of velocities the greatest dispersion is to be had when an electrostatic field is employed. If there are present carriers having a wide range of velocities, falling off gradually from a maximum, then the time exposures when either field is employed should appear on the plate as a straight line shading off gradually in intensity as you recede from the geometrical or undeflected spot. The character of the instantaneous photographs will depend upon whether the discharge is intermittent or not. In the former case, the case of an induction coil discharge, the instantaneous exposures will be similar in shape and shading to the time exposures, only much less intense. If, however, the discharge is continuous, such as may be had from a high potential storage battery, the instantaneous exposures should reveal a continuous uniformly drawn out band similar in shading to the time exposure only much less intense. Uniformity in the direction of rotation of the continuous band may be expected only when the plate is rotated with uniform velocity.

It would seem, then, that under the conditions just stated this arrangement of apparatus should reveal radiations that might have their origin in the discharge and possess energy enough to affect a photographic plate, as for instance (1) the presence of carriers due to ionization or secondary effects, (2) the possible emission of group velocity electrons from the surface of the cathode, or (3) group velocity electrons that may have their rise in the oscillatory character of the electric discharge.

In the first case, that of ionization, it is reasonable to expect that the photographs should show configurations that are fixed for both the time and the instantaneous exposures, but that would not necessarily be the same for a succeeding plate, and in general would not follow a definite law or sequence. In other words, the instantaneous photographs of the cathode ray line, produced by say an induction coil discharge, might show beads due to ionization and secondary effects, but it is not likely that the spacing of these beads along the line would follow any definite sequence though the spacings from instantaneous photograph to instantaneous photograph for a given plate more than likely would be the same.

In the second case if the cathode gave off group velocity electrons the effect on the plate should be marked—both for time and instantaneous exposures. Again, it does not seem clear that any definite spacing of the beads should be expected though the spacing, whatever it might have, would be characteristic of the metal. That the cathode gives off simultaneously group velocity electrons is by no means assured, though a careful study of the photographs lends that view some support.

Finally in the case of group velocity electrons that have their rise, when the discharge is intermittent, to the oscillatory character of the discharge we can foretell quite accurately what the effect on the photographic plate should be for both time and instantaneous exposures. Take the case of the discharge passing between the knobs of a static machine when the leyden jars that accompany the machine are included. The discharge obviously is oscillatory though damped rapidly. Let its general character be represented by Fig. 1, in which the ordinates repre-

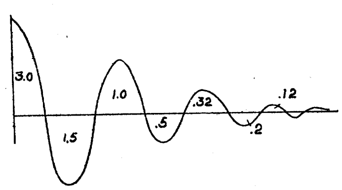


Fig. 1.

sent successive values of the quantity of electricity discharged and the abscissas the periodic time T. This period is given by the relation

$$T = 2\pi \Big/ \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}},$$

which, as R diminishes, approaches the value

$$T = 2\pi\sqrt{LC}.$$

In words, the curve approaches a simple sine wave with no damping.

If such an electrical pendulum could maintain itself in the case of our discharge vessel, the kinetic energy would remain constant and there would in consequence result but one group of group velocity electrons. This group would have the same velocity as the electrons in the case of a continuous discharge corresponding to the same discharge potential difference. If however R has a considerable value, as is the case that obtains in the ordinary operation of a discharge tube by a static machine or induction coil, the oscillations are damped as shown in Fig. 1. The successive quantities discharged through the tube fall off rapidly, and hence the energy also falls off rapidly. This results, since both e and m remain constant, in a number of groups of electrons (one group corresponding to each crest) having successively smaller and smaller velocities. Take for example the case when the successive ordinates, both positive and negative, are proportional to 3.0, 1.5, 1.0, 0.5, 0.32, 0.2, 0.12 centimeters. If, as was suggested, the velocities of the resulting electrons in the cathode beam are proportional to these ordinates we should get by equation 1, for the electrostatic displacement, distances proportional to 0.11, 1.0, 10, 25, 70. And similarly by equation 2, for the magnetic displacement, distances proportional to 0.33, 1.0, 3.3, 8.3. These displacements drawn to the same scale are set down in Fig. 2. Hence the

Fig. 2.

number of beads appearing on a given photographic plate, other conditions remaining constant, is, roughly, inversely as the damping of the oscillatory discharge which gives rise to them.

The degree of exhaustion would also have an important bearing on the appearance of the beads. For a given set of conditions, such as in the example above, we should expect that the higher the vacuum the greater the velocity of the group electrons and hence the less the displacement. However, if the vacuum is too high the oscillations after the first one may not be able to get through the discharge vessel, and for very high vacua we should expect but the one group. On the other hand if the vacuum is low the velocity of the successive groups will be low and hence the larger the displacements. The latter may be so large for group electrons corresponding to oscillations after the first that these groups may be driven off the plate by the deflecting field. For low vacua the absorption will be considerable and this may be sufficient to prevent the slower moving groups from reaching the plate, or, if they do reach it, as may be the case

TABLE I.

Photographic Plate.	Pressure in Mm. Hg.	Equiv. Spark in Air in Cm.	Aperture. Kind.	Aperture. Diam. in Mm.	Aperture. Length in Mm.	Electrostatic field in Volts per Cm.	Series Air Gap in Cm.	Source of Discharge.	Time Plate was Developed in Min.	Remarks.
10	——	——	Diaphragms	.2	9	2,000	1.0	8 inch Leeds coil	2	Commutated electrostatic field.
30	.004	2.5	Tube	.12	18	3,000	1.3	6 inch Kohl coil	7	Electrostatic field only.
33	.004	2.5	Tube	.12	18	3,000	1.0	6 inch Kohl coil	12	Two conditions, see discussion.
46	——	.35	Diaphragms	.2	9	3,000	1.2	8 inch Leeds coil	5	Simple connections.
47	.012	.8	Diaphragms	.2	9	3,000	1.2	8 inch Leeds coil	5	Simple connections.
48	——	1.2	Diaphragms	.2	9	3,000	1.2	8 inch Leeds coil	2	Simple connections.
65	——	.5	Diaphragms	.2	9	1,800	.5	Wehrsen Static Machine	5	Resistance, inductance and capacity.
67	——	——	Diaphragms	.2	9	1,600	1.0?	Wehrsen Static Machine	5	Static machine connected direct.
73	——	2.0	Diaphragms	.2	9	1,800	.3	Wehrsen Static Machine	5	Ditto, also interchanged connections.
76	.012	.8	Diaphragms	.2	9	1,800	1.2	8 inch Leeds coil	5	Interchanged connections.
77	.013	.85	Diaphragms	.2	9	3,000	1.2	8 inch Leeds coil	6	Interchanged connections.
81	——	——	Tube	.12	18	3,000	——	8 inch Leeds coil	8	Interchanged connections.

when the deflecting field is weak, they may not possess enough energy to affect the photographic film.

Discussion of Photographs.

As stated at the outset the beaded character of the cathode ray line was observed accidentally while working on retrograde rays. The shutter had failed to work, and in attempting an exposure on a fresh surface the plate was turned forward while the discharge was passing. The plate when developed showed, for the instantaneous exposures, a marked beading. Subsequently the beads were again noticed, especially when one or the other of the deflecting fields was zero. The beads seemed more pronounced when the deflection was due to the electrostatic field and hence most of the exposures (except a few at the beginning) were made with H equal to zero.

Some fifty plates were exposed with especial reference to this beaded effect. A number of these were selected as representative and are reproduced full size in Plates I. and II. The order of exposure is indicated on each photograph. The data relative to these photographs are collected in Table I. It may be well to state that if looking in the direction of the beam of cathode rays, the plates, in exposing, were turned counter clockwise. This makes the order on the reproduced photographs clockwise. The exposures, then, begin at the left and end after a more or less complete clockwise revolution near the beginning.

The photograph reproduced in Fig. 3 was the first to show beads. The deflections were due to both the magnetic and electrostatic fields acting simultaneously. In the first half the direction of the electrostatic field was such as to drive the cathode line away from the center. This field was reversed in the second half. The instantaneous exposures, in general, show three bright spots or beads. No record was kept of the vacuum; however, it was not high.

The reproduction shown in Fig. 4 was one of the first plates exposed in which the sole object was to get the beaded effect. During the interval the diaphragms used in Fig. 3 were replaced by a brass tube about 18 mm. long by .12 mm. internal diameter. This tube gave much sharper definition. The vacuum was high and the minimum discharge potential was equivalent to a 2.5 cm. spark in air. In this and the photographs that follow the electrostatic field only was employed. The photograph shows a series of instantaneous exposures with X (the electrostatic field) equal to zero, a time exposure of 10 or 15 seconds, followed by another series of instantaneous exposures with X = 3,000 volts per centimeter, and finally a time exposure of about one second. Many of the instan-

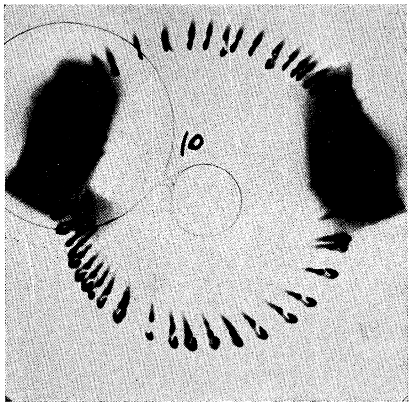


Fig. 3.

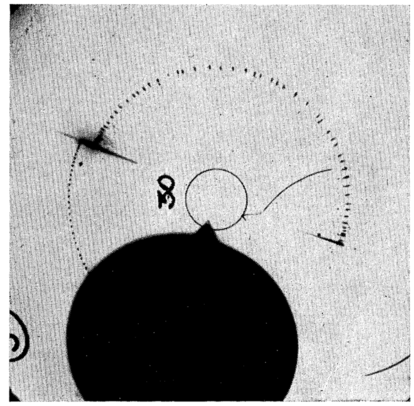


Fig. 4.

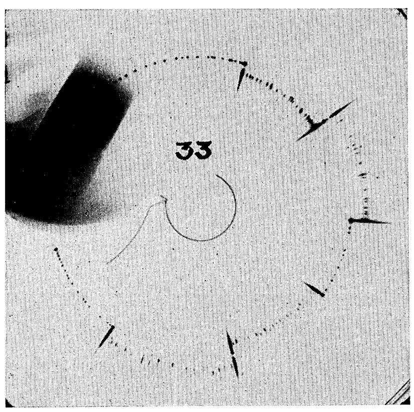


Fig. 5.

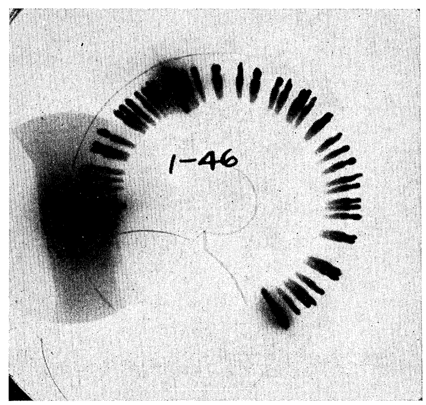


Fig. 7.

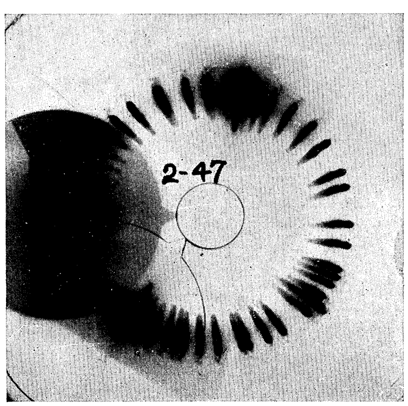


Fig. 8.

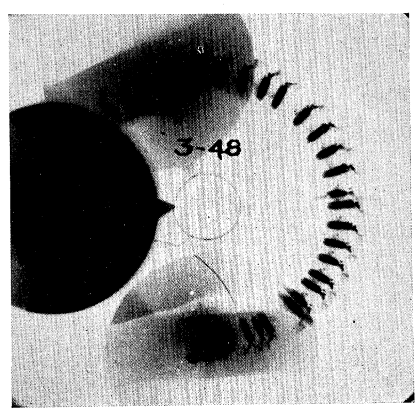


Fig. 9.

Plate I.

CHAS. T. KNIPP.

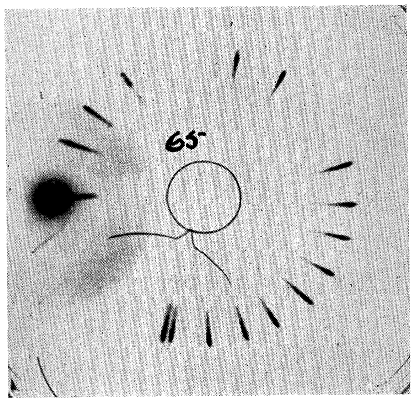


Fig. 10.

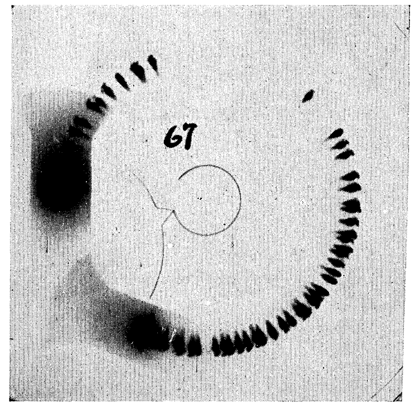


Fig. 12.

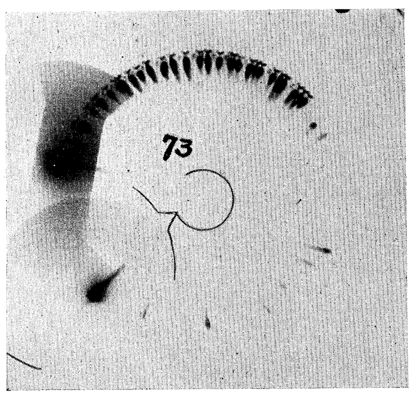


Fig. 13.

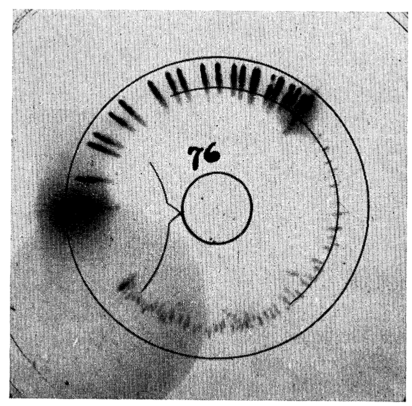


Fig. 14.

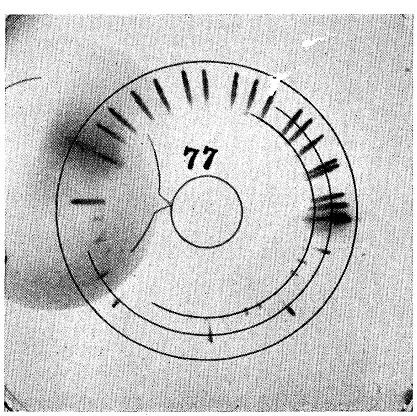


Fig. 15.

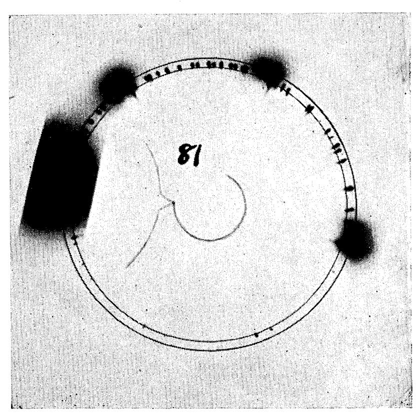


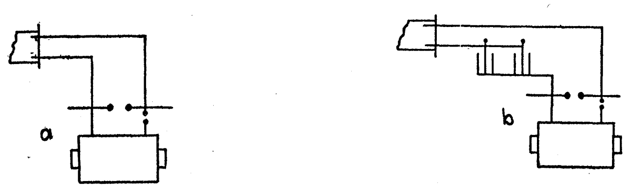
Fig. 16.

Plate II.

CHAS. T. KNIPP.

taneous exposures show a second and several a third dot in the direction towards the center of the plate. It is interesting in this connection to note that the first time exposure also shows the retrograde rays, *i. e.*, carriers atomic in size and charged positively and hence deflected, in this photograph, away from the center.

The conditions for Fig. 5 were nearly the same as in Fig. 4, except in the second half of the revolution a capacity of two leyden jars was included as shown in *b*, Fig. 6. The connections for the first half are shown in *a* of the same figure. The undeflected spots are first shown, then the plate was turned through an arc during which the deflecting field X was on, after which X was reversed for a time and then again reduced to zero. The leyden jars were now included, as shown in Fig. 6, *b*, and



a *b*

Fig. 6.

the sequence of exposures repeated. Unfortunately the reproduction does not show all of the finer markings of the negative. A number of the exposures on the negative show as many as four beads.

In the succeeding photographs the tube was replaced by the objective containing the diaphragms. The three photographs, Figs. 7, 8, 9, constitute a series of instantaneous exposures in which all the conditions were kept constant except the vacuum. In these an 8 inch Leeds coil was substituted for the 6 inch Kohl coil. The connections were those of *a*, Fig. 6. The method of exposing each plate was to give the plate a quarter turn, then stop for a few seconds before proceeding on round. The first photograph, Fig. 7, shows the beads in a striking manner. In the second, Fig. 8, the vacuum was some higher and hence the displacement of the first group is less. The exposures on this plate show peculiar markings in the neighborhood of the undeflected point which may be due to ionization or secondary effects. These markings together with others that appear at the side of each instantaneous photograph are distinctly shown in the third photograph of this series, Fig. 9. The effect of an increasing vacuum is to cut off the subsequent groups. Traces of retrograde rays are visible in nearly all of the time exposures on these three plates.

In the next three photographs, Figs. 10, 12, and 13, the induction coil was replaced by a Wehrsen static machine. Smaller values of X were also used. In Fig. 10 the connections were made as sketched in Fig. 11. As is readily seen the discharge takes place at B without preparation whenever a spark passes at A. The volume of the discharge was considerable. Most every instantaneous exposure on the negative shows

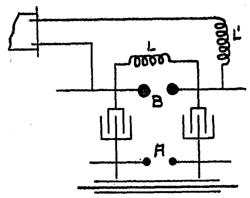


Fig. 11.

beads. In the photograph reproduced in Fig. 12 the inductances and leyden jars were removed and connections were made direct. The vacuum was quite high. The peculiar markings shown in Figs. 8 and 9 again appear. These markings also appear very distinctly in the first half of Fig. 13. It would thus seem that they are not dependent upon the source of the discharge.

To get still further evidence on the possible cause of the beads that so persistently appear on the cathode ray line I followed a suggestion made by Mr. O. H. Smith, graduate student in physics, and who assisted me in making a number of the exposures. If these beads are due to the oscillatory discharge then possibly additional evidence may be had by photographing simultaneously the *negative* crest. This could be done by mounting two exactly similar canals with their attending equal electrostatic fields diametrically opposite in the apparatus, so that either in turn may serve as the cathode. The plate with this arrangement to be turned but a half revolution. The negative crests (corresponding to the troughs in Fig. 1) should appear on the plate as instantaneous photographs diametrically opposite to the corresponding photograph for the positive crests. Indeed, this point may be tested with the apparatus as originally constructed by giving the photographic plate a half turn then interchange the connections after which the turn is completed. A plate thus exposed should show negative crests, obviously not simultaneously with the positive crests, but negative crests due to oscillations accompanying a series of later discharges, and, so far as comparing the position of the negative crest with the positive trough is concerned, should answer equally well.

The second half of Fig. 13 was taken under the above conditions. It shows that cathode rays *do proceed* from the anode. Their presence and position may be accounted for by the negative crests of the damped oscillatory discharge. In this photograph they did not, however, accompany each discharge, but only about every fourth one, though careful measurements show that the groups that are recorded correspond in general to the troughs in the first half.

In Fig. 14 the static machine was replaced by the 8 inch Leeds induction coil, the vacuum was rather low, and X was made 1,800 volts (see Table I.). On this plate the negative crests appeared in great numbers due in part to the plate being turned more slowly in the second half. For the most part their positions correspond to a trough in the first half, as may be seen by the arc drawn on the photograph. It seems strange, however, that this photograph shows no negative crests corresponding to the fiıst trough. In the next, Fig. 15, X was made 3,000, otherwise the conditions were the same as in the preceding photograph. In this negative crests appear in the second half corresponding to two troughs in the first half.

In the last photograph exposed, Fig. 16, the tube was again inserted. The vacuum though not recorded was high. In turning the plate it was halted twice, possibly for one or two seconds, in each half turn. Again the points appearing in the second half correspond to carriers having a lower velocity than in the first half. In comparison with Figs. 4 and 5 it is evident that the vacuum was too high, since apparently only the first positive and first negative group electrons were formed.

Conclusion.

It appears from the photographs reproduced in this paper that in most cases the beaded effect of the cathode ray line may be accounted for by the oscillatory character of the electric discharge. However a number of the photographs show beads whose spacing along the cathode line is not in agreement with that that should follow for damped oscillations. These may be due to ionization or secondary effects, or possibly due to group velocity electrons given off by the cathode. The position of the cathode seems to have but little or no effect upon the general character of the beads.

The strongest, and in some respects the most convincing evidence pointing to the oscillatory discharge as the origin of the beads is furnished by the photographs showing the negative crests. These crests in most every instance correspond to the troughs in the beaded line as shown in Figs. 13, 14, 15, and 16.

Admitting that the evidence submitted is sufficient to show that an oscillatory electric discharge under proper conditions (conditions which were met in a number of the foregoing photographs) results in a beaded cathode ray line, it seems that we have here a possible explanation of the beading of J. J. Thomson's molecular lines.[1] This conclusion, it seems to me, follows naturally because of the intimate relation that exists between the cathode rays and the positive rays which form the molecular line.

LABORATORY OF PHYSICS,
UNIVERSITY OF ILLINOIS,
March, 1913.

[1] Philosophical Magazine, August, 1912, p. 237.

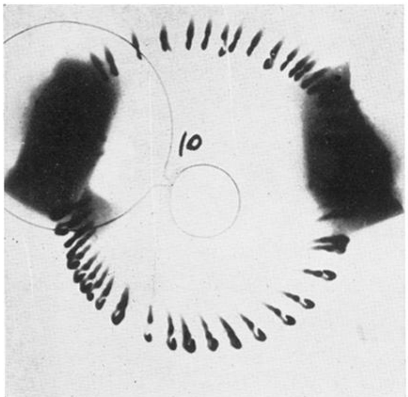


Fig. 3.

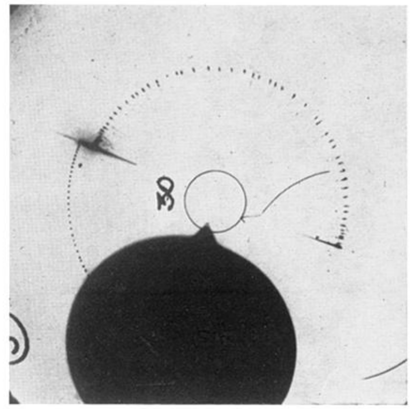


Fig. 4.

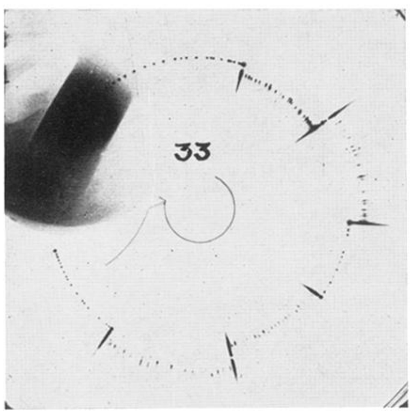


Fig. 5.

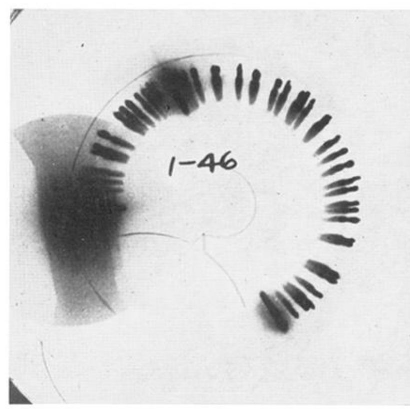


Fig. 7.

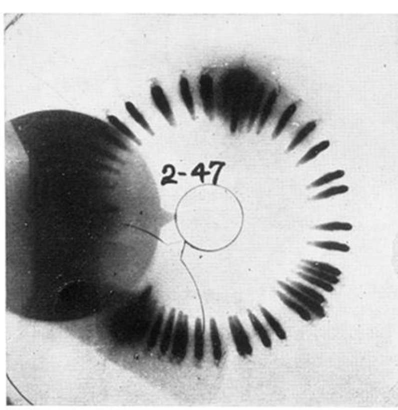


Fig. 8.

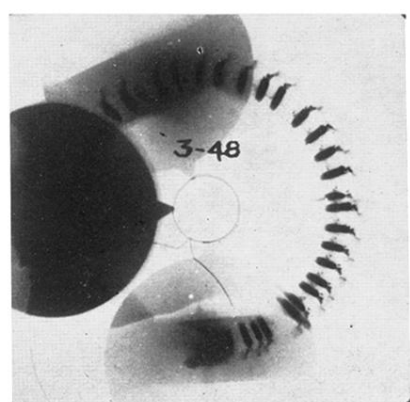


Fig. 9.

Plate I.

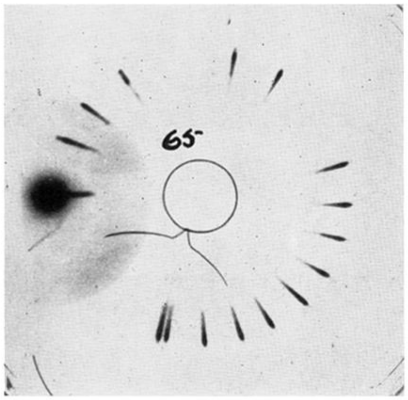


Fig. 10.

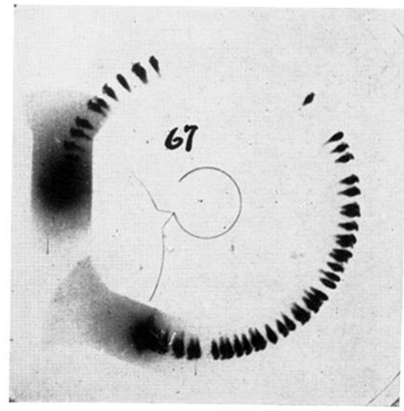


Fig. 12.

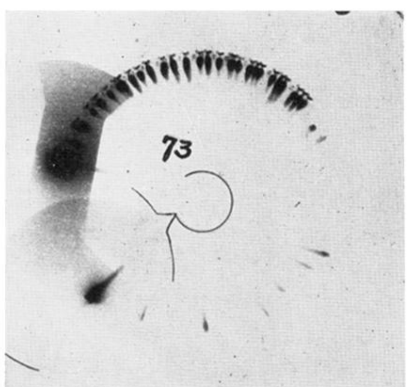


Fig. 13.

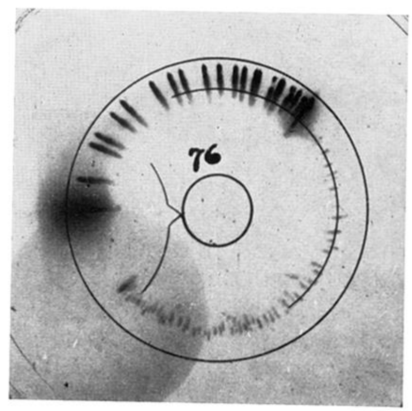


Fig. 14.

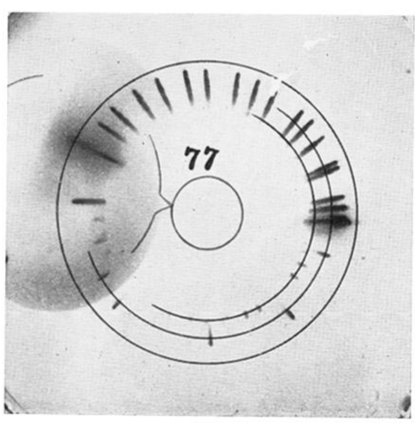


Fig. 15.

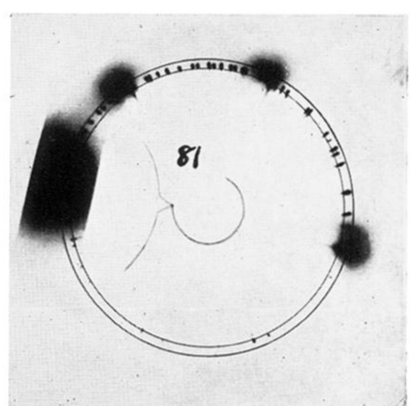


Fig. 16.

PLATE II.