THE VELOCITY AND NUMBER OF THE PHOTO-ELECTRONS EJECTED BY X-RAYS AS A FUNCTION OF THE ANGLE OF EMISSION

By E. C. Watson

Abstract

Magnetic spectra of the electrons ejected by x-rays from thin metallic films at angles ranging from 0° to 180° with the direction of the x-ray beam have been obtained by the method of Robinson, de Broglie, and Whiddington. To the degree of accuracy of the measurements (one-half of one percent) the maximum velocity of ejection is exactly the same in all directions. With thin foils of the heavier elements the number of electrons leaving the foil with this maximum velocity in the various directions (determined by the intensity of the edges) is approximately the same. With radiators of small density, or with sputtered films so thin that Wentzel's criterion for "single" scattering holds, the number of electrons leaving the foil is greatest in a direction a little forward of perpendicular to the direction of the x-ray beam. Rutherford's theory of nuclear scattering applied to electrons gives an explanation of these results if the assumption is made that all the electrons start out from the atom in the same direction.

1. Introduction

WHILE the work of Seitz[1] has shown that the greater ionization on the emergence side of a thin plate traversed by x-rays than on the incidence side observed by Beatty,[2] Cooksey,[3] Seitz,[4] and others is caused by more *high-speed photo-electrons* leaving the emergence side of the plate than leave the incidence side, nevertheless the question whether the velocity of ejection is *exactly* the same in the two directions has not been answered at all conclusively. Beatty's[5] discovery that the absorption coefficients in air are the same whether the electrons come from the emergence or incidence side of the plate shows that the velocities are at least approximately equal in the forward and backward directions, and the expansion-chamber photographs of C. T. R. Wilson,[6] Bubb,[7] Loughridge,[8] and others show that the forward and backward electron tracks have very nearly the same average range, but neither of these methods is sufficiently accurate to detect small velocity differences.

That the velocity of ejection of the photo-electrons is exactly the same in all directions has been tacitly assumed in all the experimental tests which

[1] W. Seitz. Ann. d. Physik **73,** 182 (1924); Phys. Zeits. **25,** 546 (1924), and **26,** 610 (1925).
[2] R. T. Beatty, Proc. Camb. Phil. Soc. **15,** 492 (1910).
[3] C. D. Cooksey, Nature **77,** 509 (1908), and Phil. Mag. **24,** 37 (1912).
[4] W. Seitz, Ann. d. Physik **73,** 182 (1924).
[5] R. T. Beatty, Phil. Mag. **20,** 329 (1910).
[6] C. T. R. Wilson, Proc. Roy. Soc. **104,** 1 and 192 (1923).
[7] F. W. Bubb, Phys. Rev. **23,** 137 (1924).
[8] D. H. Loughridge, Phys. Rev. **26,** 697 (1925).

have been made of the Einstein photo-electric equation. In fact, the best evidence that the velocities of ejection are the same in all directions is the fact that this equation has been shown by de Broglie,[9] Whiddington,[10] and Robinson[11] to hold so exactly. Actually, however, in the case of x-rays the equation has been tested only for electrons ejected approximately at right angles to the x-ray beam (de Broglie and Robinson) and for those leaving in the forward direction of the x-ray beam (Whiddington).

But even if the electron does always leave the *individual atom* with the velocity given by the Einstein equation, the work of Bothe,[12] Auger,[13] and Loughridge,[14] which shows that the vast majority of the photo-electrons are ejected at an angle a little forward (10 to 20 degrees) of the perpendicular to the x-ray beam, would lead one to expect that the velocities of the electrons which are scattered sufficiently to leave a thin plate in the forward or backward direction would be diminished because of that scattering and moreover that those which leave the plate in the backward direction, having been scattered through a larger angle, would be slower than those which leave in the forward direction. In view of these considerations it seemed desirable to determine as accurately as possible the velocity of the photo-electrons leaving a thin plate at a number of different angles.

II. Apparatus and Method

The apparatus used is shown in Fig. 1. It enables the method of Robinson, de Broglie, and Whiddington to be applied to the determination of the maximum velocity of ejection *in any given direction*.

A parallel beam of x-rays from a tube with water-cooled molybdenum target driven at approximately 25 milliamperes and 30,000 volts, a potential high enough to excite the K lines strongly, enters the vacuum chamber through the slit S which is covered by a thin sheet of mica and after traversing the radiator R leaves through the plate glass window W. The radiator R from which the electrons are ejected consists of thin metal foil supported on an aluminum frame at the exact center of the apparatus and capable of being set so as to make any given angle with the x-ray beam.

The whole apparatus is placed at the center of a solenoid 10 inches in internal diameter and 4 feet long, which produces a uniform magnetic field of 25.56 gauss per ampere of current. The electrons ejected by the x-rays are bent in circles by the magnetic field and recorded on the photographic plates, pp, as shown. The width of the x-ray beam where it strikes the metal foil is approximately 4 mm and all the electrons of a given velocity ejected from the foil through an angle of approximately 10° pass through the narrow slits (0.04 cm wide) in the quadrants 1 and 2 and are focused in a line on the

[9] M. de Broglie, Jour. de phys. et rad. **2,** 265 (1921).
[10] R. Whiddington, Phil. Mag. **43,** 1116 (1922).
[11] H. R. Robinson, Proc. Roy. Soc. **104,** 455 (1923).
[12] W. Bothe, Zeits. f. Physik **26,** 59 (1924).
[13] P. Auger, Comptes rendus, **178,** 929 (1924).
[14] D. H. Loughridge, Loc. cit.

photographic plates. The nature of the "spectra" thus obtained and the method of calculating the velocity of the electrons from measurements of the radius of curvature and magnetic field strength are too well known to

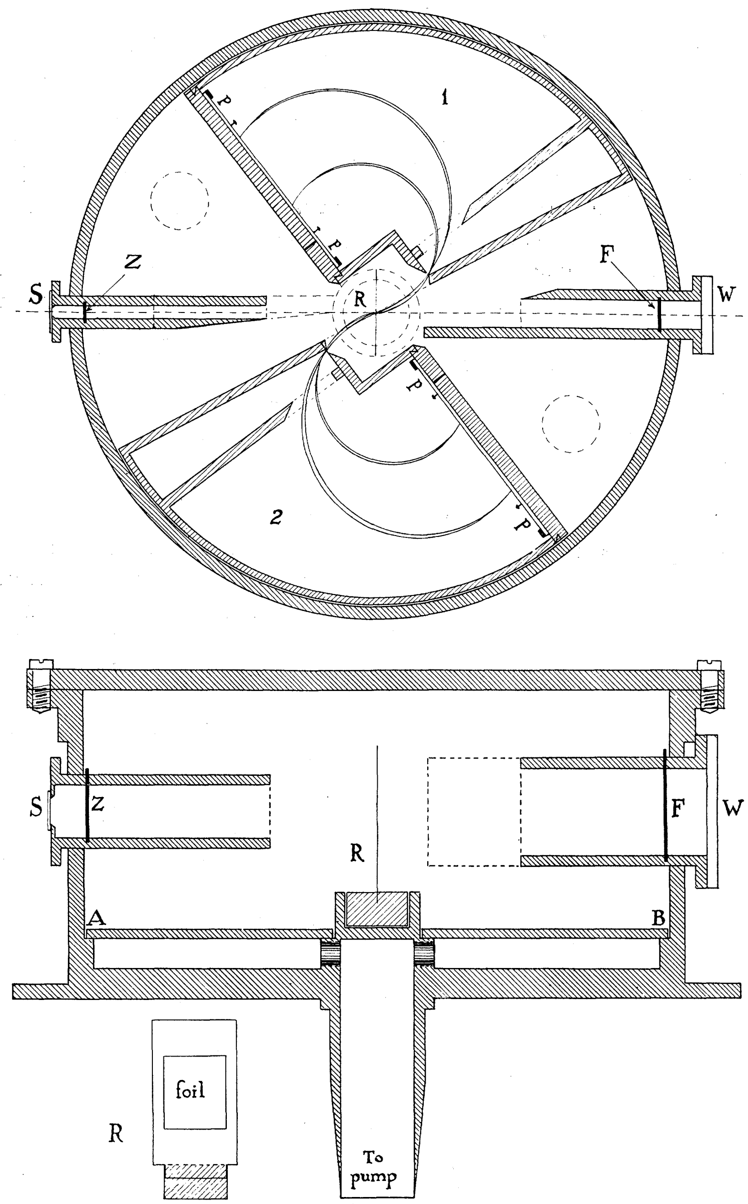

Fig. 1. Diagram of apparatus.

need further description here. Quadrants 1 and 2 are carried on the plate *AB* and may be rotated so that by a suitable adjustment of magnetic field and position of the quadrants, the velocities of electrons ejected in any direction from 0° to 360° may be studied. Quadrant 1 records the emergence electrons and quadrant 2 simultaneously the incidence electrons. The whole inside of the vacuum chamber is lined with black paper to cut down any stray emission from the walls.

Z is a removable zirconium oxide filter to isolate the $K\alpha$ lines of molybdenum. It was not used in the experiments described in this paper, but instead was replaced by a strip of black paper to prevent light from entering the apparatus. F is a removable fluorescent screen to facilitate the alinement of the x-ray beam and radiator. The vacuum chamber is connected through a liquid-air trap to a two-stage mercury diffusion pump which is kept running continuously during an exposure. Exposures of from 50 to 100 hours are necessary to bring out the weak edges. Both Eastman x-ray plates and Hilger Schumann plates sensitized for cathode rays were used. For values of $H\rho$ greater than 300 both types of plate are satisfactory. For small electron velocities the Schumann plates are much superior. This is well shown in Fig. 2, the lower reproduction being from an Eastman x-ray plate, the four upper ones from Schumann plates.

III. Results

In Fig. 2 are reproduced two 100-hour exposures made on Schumann plates using ordinary gold foil as radiator. The magnetic field was held constant to better than 0.5% during the two runs and the quadrants were set so as to receive on the center of the photographic plates electrons emitted at approximately the angles indicated (namely 45°, 135°, 0°, and 180° with the forward direction of the x-ray beam). Because the radius of curvature is different for electrons of different velocities, the angles of emission of the electrons recorded at the two ends of the plate will differ by as much as 10° from these values and for electrons of intermediate velocities by corresponding amounts. The origin of the electrons responsible for the various edges is given in the subscript. The lower reproduction is a similar exposure taken on an Eastman x-ray plate in order to compare the relative sensitiveness of the two kinds of plates to electrons of different velocities. The spot at the left end of each spectrum is a fiducial mark for use in measuring up the plates.

These spectra and many others taken at different angles and with different materials as radiator have been measured with a comparator and the positions of the corresponding edges on various plates found to be exactly the same to the degree of accuracy with which the measurements can be made and duplicated, namely one-half of one percent. *We conclude therefore that the maximum velocity of ejection is the same in all directions.* This conclusion was to have been expected, but it is satisfactory to have this much abused question settled in so decisive a manner.

The surprising feature of the spectra obtained with gold foil is that the intensities of corresponding edges are nearly the same in the various directions. Some variations do appear in the reproductions, but they are due to irregularities in the emulsions of the Schumann plates and are not reproducible.

This result can be reconciled with the expansion-chamber results of Loughridge and Auger, who found a great preponderance of photo-electrons at from 70 to 80 degrees, only if a large fraction of the electrons have their directions changed in getting out of the foil without a corresponding loss in

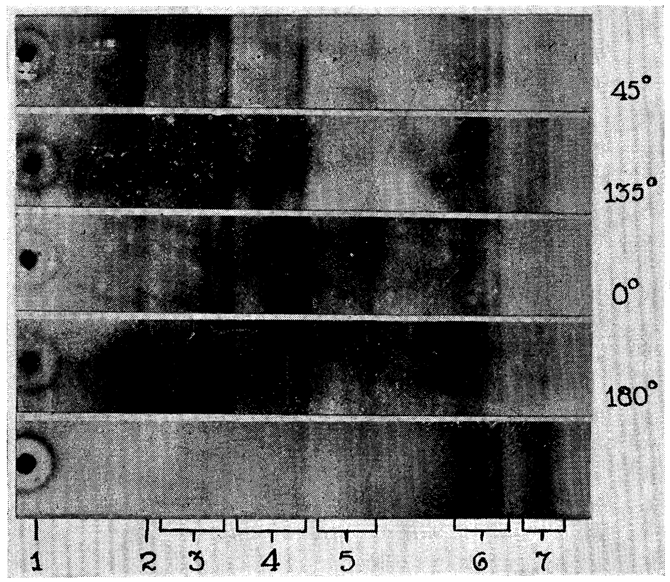

Fig. 2. Magnetic spectra of electrons emerging at various angles from gold leaf traversed by primary x-rays from molybdenum. 1, L_{II} electrons ejected by Mo $K\alpha$; 2, L_{III} electrons ejected by Mo $K\alpha$; 3, M electrons ejected by Au $L\alpha_1$; 4, M electrons ejected by Au $L\beta_1$; 5, M electrons ejected by Au $L\gamma_1$; 6, M electrons ejected by Mo $K\alpha$; 7, N and O electrons ejected by Mo $K\alpha$.

velocity, i.e. only if the nuclear scattering is large. To test whether this is the case similar expeiiments were made using still thinner films of gold obtained by cathodic sputtering on celluloid and also foils of the light elements such as aluminum. In these cases the nuclear scattering should be

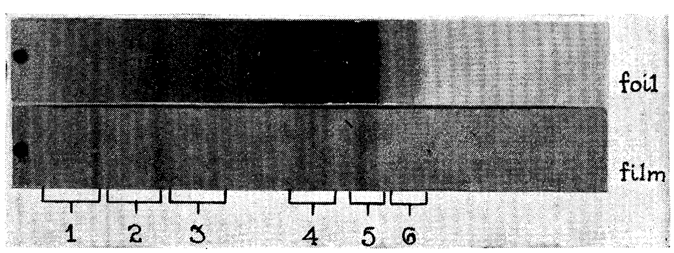

Fig. 3. Comparison of magnetic spectra of electrons from gold foil and sputtered gold film. 1, M electrons ejected by Au $L\alpha_1$; 2, M electrons ejected by Au $L\beta_1$; 3, M electrons ejected by Au $L\gamma_1$; 4, M electrons ejected by Mo $K\alpha$; 5, N and O electrons ejected by Mo $K\alpha$; 6, N and O electrons ejected by Mo $K\beta$.

less and directional effects are to be expected if the electrons are really emitted more copiously in one direction than in another.

With a sputtered film of gold so thin that it transmitted more than half the light which fell upon it, fairly sharp lines were obtained upon the photographic plate instead of edges which are sharp on the high velocity side and trail off on the low velocity side. This is well shown in Fig. 3 in which the

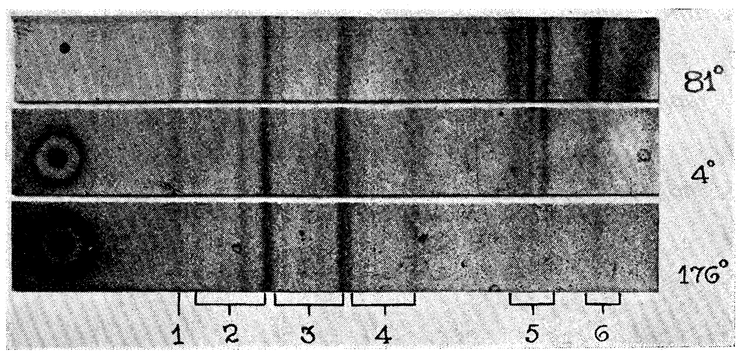

Fig. 4. Magnetic spectra of electrons emerging at various angles from a thin sputtered film of gold traversed by primary x-rays from molybdenum. 1, L_{III} electrons ejected by Mo $K\alpha$; 2, M electrons ejected by Au $L\alpha_1$; 3, M electrons ejected by Au $L\beta_1$; 4, M electrons ejected by Au $L\gamma_1$; 5, M electrons ejected by Mo $K\alpha$; 6, N and O electrons ejected by Mo $K\alpha$.

spectra obtained with the gold foil and the sputtered gold films are compared. Eastman x-ray plates were used in these experiments and in those which follow because they are far more uniform and dependable for intensity measurements.

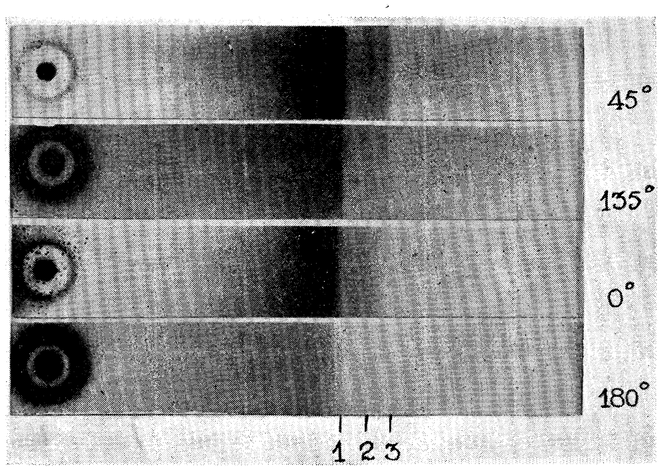

Fig. 5. Magnetic spectra of electrons emerging at various angles from aluminum foil traversed by primary x-rays from molybdenum. 1, K electrons ejected by Mo $K\alpha$; 2, L electrons ejected by Mo $K\alpha$; 3, K electrons ejected by Mo $K\beta$.

As was anticipated the intensity of the lines obtained with the sputtered film varied with the angle at which the electrons were emitted. Thus in Fig. 4, which shows results obtained at three different angles, the lines are all relatively strong in the spectrum taken at 81°, i.e. a little forward of perpendicular to the x-ray beam. At 4° all the lines (except those due to the fluorescent radiation of the gold itself which should be the same in all directions) are much weaker and at 176° they have practically disappeared.

The results with aluminum foil are also of interest. They are shown in Fig. 5. Here again edges are obtained instead of lines. These edges are strong and sharp when the electrons leave the foil at 45° with the direction of the x-ray beam. In the forward and backward directions they become weak and fuzzy and they are always less sharp in spectra taken in the backward direction than they are in spectra taken at corresponding angles in the forward direction. If the angles are measured from the 80° position instead of from the forward direction of the x-ray beam, the edges become systematically less sharp as the angle becomes greater. Also the position of the edges as measured on the comparator seems to shift systematically towards the left (i.e. towards smaller velocities) as the angle increases, so that the velocity seems measurably greater in the forward direction than it is in the backward direction. Photometer curves of the original plates show, however, that all the corresponding edges really start at the same distance from the fiducial mark and that it is the intensity maximum which shifts towards smaller velocities as the angle departs from the 80° position.

IV. Discussions of Results

The fact that with the thin sputtered film or the aluminum foil the lines or edges are always weaker or less sharp in the backward direction than they are for corresponding angles in the forward direction shows that the most probable direction of emission of the photo-electrons is forward of perpendicular to the direction of the x-ray beam in agreement with the results obtained by the expansion-chamber method. The measurements are not yet accurate enough, however, to determine precisely what this most probable direction is.

The theory of nuclear scattering developed by Rutherford for α-particles and applied by Crowther and Schonland,[15] Chadwick and Mercier,[16] and Schonland[17] to the case of beta-rays enables the relative intensities at various angles of corresponding lines in the spectra obtained with sputtered gold film to be calculated provided the assumption is made that all the electrons start out from the atom at approximately 80° with the direction of the x-ray beam. Intensity measurements have not yet been made with sufficient accuracy, however, to decide whether such nuclear scattering is sufficient to account for the whole of the angular distribution or not, but the fact that

[15] J. A. Crowther and B. F. J. Schonland, Proc. Roy. Soc. **100**, 526 (1922).
[16] J. Chadwick and P. H. Mercier, Phil. Mag. **50**, 208 (1925).
[17] B. F. J. Schonland, Proc. Roy. Soc. **113**, 87 (1926).

the intensity of the lines in spectra taken at angles other than 80° diminishes as the thickness of the radiator is decreased gives a strong presumption that this is the case.

The theory of nuclear scattering also explains very simply the results obtained with aluminum foil and the differences between these results and those obtained with the gold foil and film. The theory applies directly to the case of the sputtered gold film because its thickness is so small that the electrons experience only single collisions with atomic nuclei in getting out. Now Wentzel[18] has given a criterion for "single" scattering which enables the critical thickness which must not be exceeded if there is to be no more than one nuclear collision to be calculated and the change in velocity which electrons experience in passing through this critical thickness of foil can be computed by means of Whiddington's[19] fourth-power law. For the gold foil this change in velocity is less than 0.3% even for electrons emitted at 180°; i.e. it is less than the accuracy with which the edges can be measured. There is therefore no variation in the structure of the edges as the angle is changed. In the case of aluminum, however, the loss in velocity is 0.2% for electrons leaving at 45 and 0.6%, 1.1%, and 1.8% for those leaving at 135°, 0°, and 180° respectively, which agrees very satisfactorily with the apparent shift of the edges as measured with the comparator. This means that the electrons which are recorded on the plate close to the high velocity edges are electrons which have suffered at most one nuclear collision and therefore the intensity of this portion of the edge varies with the angle as does the intensity of the lines in the spectra obtained with thin sputtered films. Electrons coming from deeper layers in the foil will experience more than one such collision and so will be scattered to such an extent that there will be no change in intensity with angle of the part of the edge to which they contribute. All this is of course on the assumption that all the electrons start out at 80° with the direction of the x-ray beam and the success of this assumption is further argument for its correctness.

V. Conclusions

The conclusions which may then be drawn from these experiments are: (1) that most (probably all) of the photo-electrons ejected by x-rays from thin metallic radiators start out from the individual atoms in a direction a little forward of perpendicular to the direction of the x-ray beam with the velocity given by the Einstein equation; (2) that due to collisions with atomic nuclei some (many, if the radiator is thick and heavy) have their direction changed without a corresponding loss in velocity and so electrons leave the radiator in all directions with the same velocity; (3) that if precise results are to be obtained by the method of Robinson, de Broglie, and Whiddington on the velocity of ejection of x-ray electrons from radiators of small density, the apparatus must be so arranged as to focus upon the photographic plate

[18] G. Wentzel, Ann. d. Physik. 69, 335 (1923). See also Chadwick and Mercier, Loc. cit., and Schonland, Loc. cit.

[19] R. Whiddington, Proc. Roy. Soc. **86**, 360 (1912).

electrons which leave the radiator in a direction a little forward of perpendicular to the direction of the x-ray beam. The velocities of electrons leaving in other directions may appear to be as much as one or more percent too small because the majority of them come from considerable depths in the radiator.

This work further emphasizes the importance of nuclear scattering in all experiments on the angular distribution of electrons ejected by radiation of any sort. It shows that essential features may be entirely obscured and wrong conclusions arrived at unless care is taken to work under conditions such that Wentzel's criterion for "single" scattering holds and allowance can be made for the effect of scattering.

Finally the writer desires to express his thanks to Dr. I. S. Bowen for his kind assistance many times in maintaining constant conditions during the long and tedious exposures necessary in this work; to Dr. R. M. Badger for sputtering the gold films used; to Mr. J. A. Van den Akker for his care in making the reproductions which accompany this article; and to Professor R. A. Millikan for his enthusiastic interest and constant encouragement during the course of the work. The investigation has been carried out with the aid of funds provided by the Carnegie Corporation of New York.

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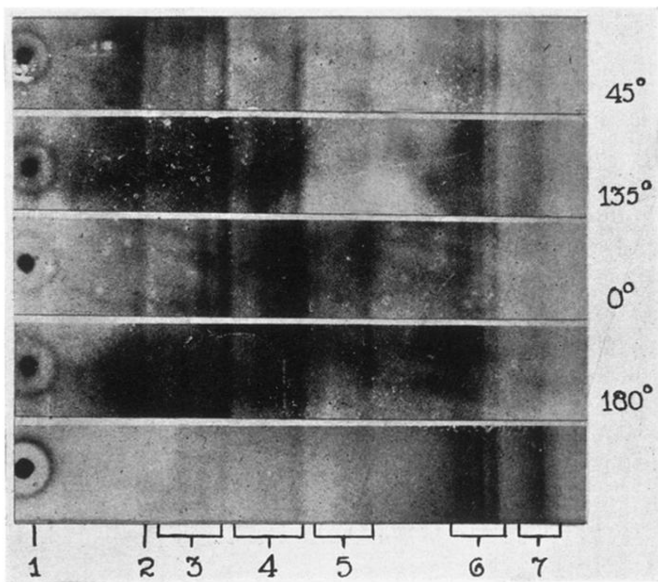

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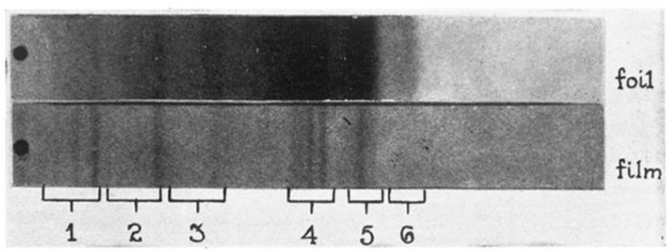

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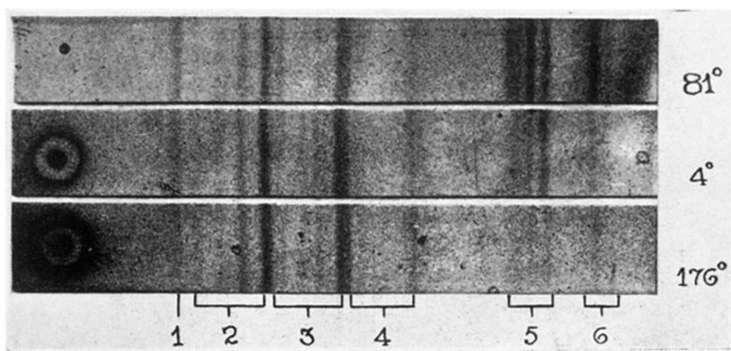

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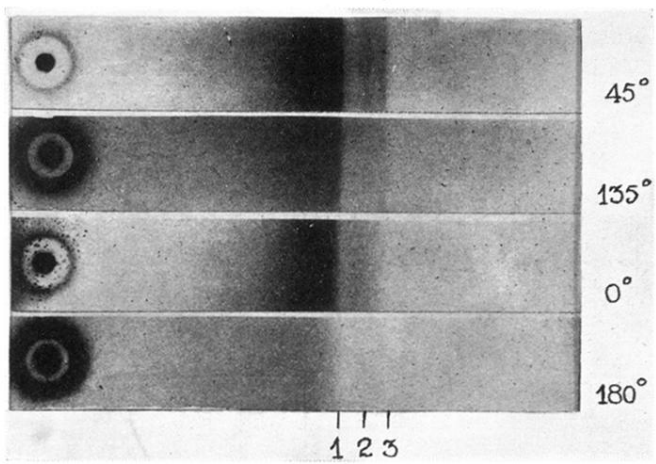

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