THE DIRECTION OF EJECTION OF PHOTO-ELECTRONS BY POLARIZED X-RAYS

By C. J. Pietenpol

Abstract

Variation with angle from the plane of polarization of the number of photo-electrons ejected by x-rays in lateral directions.—Bubb and Kirchner have studied the lateral distribution of photo-electrons ejected by polarized x-rays by the Wilson cloud expansion method. This method is open to objections as pointed out by Bothe, and Watson has concluded that because of scattering by neighboring atoms it is impossible to determine the exact direction of ejection of the electron from the atom. It is thus difficult to determine the mechanism of electron ejection from such data. The writer has studied the lateral distribution by means of Geiger counters which could rotate about the polarized beam. The electrons were ejected from air at a low pressure in which the mean free path of the electron is many times the distance through which the electron must move to enter the counter. Allowing for the fact that completely polarized beams are impossible to obtain in practice, the data strongly favor the cosine squared relation of Auger and Perrin rather than the relation deduced by Bubb.

THEORIES to account for the lateral spreading of photo-electrons ejected by x-rays have in general been of three kinds. Bubb[1] and Bothe[2] have attempted to account for this space distribution by compounding the momentum of the quantum in the forward direction with a random momentum of the electron in its atomic orbit. Auger and Perrin[3] have deduced a probability relationship between the direction of the electron's velocity in its orbit and the direction of the electric field of the radiation by which the electron is ejected. Results similar to Auger and Perrin's have been obtained on the basis of the new quantum mechanics by Wentzel,[4] Oppenheimer,[5] and Beck.[6] Recently Watson[7] has shown that previous experimental results can be explained by the Rutherford theory of nuclear scattering.

Experimental tests of the lateral distribution have been made by Bubb[8] and Kirchner[9] by the use of the C.T.R. Wilson cloud expansion method. This method, although used by many experimenters, is open to a number of objections. As Watson has pointed out, the whole distribution of the photo-electrons can be explained by the scattering in neighboring atoms

[1] F. W. Bubb, Phil. Mag. **49**, 824 (1925).
[2] W. Bothe, Zeits. f. Physik **26**, 74 (1924).
[3] P. Auger and F. Perrin, Comptes Rendus **180**, 1742 (1925).
[4] G. Wentzel, Zeits. f. Physik **40**, 574 (1927).
[5] J. R. Oppenheimer, Zeits. f. Physik **41**, 291 (1927).
[6] G. Beck, Zeits. f. Physik **41**, 443 (1927).
[7] E. C. Watson, Phys. Rev. **31**, 728 (1928).
[8] F. W. Bubb, Phys. Rev. **23**, 137 (1924).
[9] F. Kirchner, Ann. d. Physik **83**, 521 (1927).

when this method is used. It is thus difficult to determine the mechanism of electron ejectiom from such data.

A method employed by Bothe[10] in investigating the longitudinal distribution was that of the Geiger point-counter. A similar method has been used by the writer to determine the lateral distribution. By this method it is possible to obtain a relatively large number of counts. Thus the writer has counted 1659 photo-electrons while the paper of Bubb's indicate a total of 156 counts.

Counters of various types and forms have been used and described by Hess and Lawson,[11] Kovarik and McKeehan,[12] Bothe and Geiger[13] and others. Counters of different types were constructed during preliminary trials by the author and tested by means of a string electrometer. Best results were obtained with an electrode made by fusing a small bead of about 0.1 mm diameter on a platinum wire of approximately one half this size. This small bead was placed within 2 mm of the front of the counter. About 25 small holes were drilled in the front of the counter. A thin sheet of mica was placed over these holes and the edges sealed with soft wax to make it air-tight. A thin sheet of brass with holes drilled to coincide exactly with those in the front of the counter was placed over the mica and held tightly against it by means of screws. The counter was filled with air at atmospheric pressure.

The amplifying device used was a four-stage, transformer coupled amplifier. The counter point was connected to the grid of a special high amplifying tube and also through a water resistance to earth. The second and third tubes were similar to the first having an amplification constant of about 30. A loud speaker was connected in the plate circuit of the last tube.

The cap of the counter was connected to the positive terminal of a high voltage battery. This could be adjusted by steps of two volts to a maximum value of about 3000 volts. The voltage required on the counter depended upon the individual point used, the dimensions of the counter, and the distance between the point and the front of the counter. For the type of counter with which best results were obtained the voltage was between 1800 and 2000. The voltage of the cells could be kept constant during a run by means of a high voltage kenetron rectifier which maintained a small charging current through the battery while observations were being made.

Each counter was tested by the use of β-rays from radium. The voltage on the counter was raised until the clicks in the loud speaker became clear and distinct. The radium was then removed and the counter tested for spontaneous discharges. If a counter showed more than two spontaneous discharges for a time of about three minutes, it was not used. Considerable trouble was found in the construction of counters which would count a large

[10] W. Bothe, Zeits. f. Physik **26,** 59 (1924).
[11] V. F. Hess and R. W. Lawson, Wiener Ber. **127,** 405 (1918).
[12] A. F. Kovarik and L. W. McKeehan, Phys. Rev. **8,** 574 (1916).
[13] W. Bothe and H. Geiger, Zeits. f. Physik **32,** 639 (1925).

number of β-rays and still not give spontaneous discharges. Points of different types were tried in an effort to obtain the best counter. It was found that steel needles ground to a sharp point by means of an oil stone gave fair results, provided the steel point was heated to a dull red in a gas flame. The spontaneous discharges were, however, more numerous with that type of point than with a small sphere fused on the end of a fine platinum wire. Sharp tungsten points or platinum spheres of considerable size were not found satisfactory.

The source of x-rays was a Coolidge 30-milliampere, 20-second tube. The voltage across the tube was supplied by a transformer of approximately 60,000 volts. The x-ray tube was placed in a box lined with 1/4″ lead and the transformers, placed below the tube, were completely surrounded by 1/32″ tin plate which was grounded. The lead box in which the tube was placed was also grounded. This was done to prevent stray fields which might affect the counter or amplifying system. A second lead box, closed on the top, bottom and three sides, was placed in contact with the first lead box. This contained the scattering block. The scattering block was placed at an angle of 45° with the direction of the primary rays. The rays scattered from this substance at 90° with the direction of the primary rays passed through an opening in the side of the box and then a brass cylinder holding the counter. The details of this cylinder are shown in Fig. 1. Inside the brass cylinder there was placed another coaxial cylinder of lead L held tightly in place by friction. Small circular apertures J, 5 mm in diameter and 6.8 cm apart, were made in the two ends. This served to constrict the beam of x-rays, thus rendering them more nearly parallel and also prevented in large measure any stray x-rays from entering the counter. Since the apertures J were accurately constructed to be along the axis of the tube H, any rotation of the tube H did not in any way alter the x-ray beam passing through it, and consequently the face of the counter was always at the same distance from the x-ray beam. This distance was 2.6 cm. The faces of the tube H were closed by sheets of mica I about 1/2 mm thick and were made air-tight by wax joints. A side tube M allowed a connection to be made to the vacuum pump. The whole tube could be rotated about its axis by being placed upon two semi-circular bearings near the two ends.

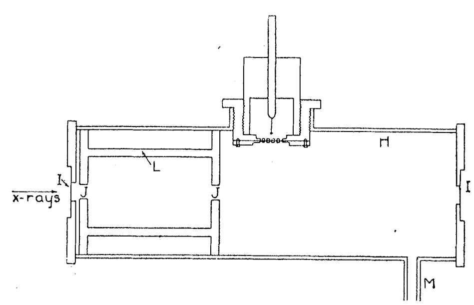

Fig. 1. Diagram of apparatus.

Compton and Hagenow[14] have shown that x-rays scattered at right angles are nearly completely polarized as the thickness of the scattering

[14] A. H. Compton and C. F. Hagenow, J.O.S.A. **8**, 487 (1924).

substance is decreased. For paper having a thickness of 0.25 cm there is almost complete polarization. This is the type of scattering block used in this experiment.

After counters had been tested by the β-rays of radium for constancy of number of discharges per minute, they were placed in the apparatus and the joints made air-tight by soft wax. The apparatus was then evacuated to about 0.004 mm of mercury. The filament rheostat was regulated for constant current through the tube. It was possible to run the tube for only 20 seconds at a time since it was not of the continuously operating type. It was necessary to wait for about one or two minutes between each interval that the tube was in use to allow cooling of the tube. The number of photo-electrons entering the counter during the 20 seconds of operation was counted by means of the loud speaker.

It was found that many counters which worked well for β-rays failed to register any photo-electrons. Some counters caused registrations which were either so weak or so few in number as to make them worthless. Each counter was repeatedly tested for spontaneous discharges. Unless a counter showed at least four counts per 20 seconds when in the plane of the electric vector and no spontaneous ones in a time of three minutes, it was not used. Although all counter points were constructed in the same way, there was a very marked difference in their behavior.

The cylindrical tube containing the counter was rotated until the counter was in the plane of the electric vector. Usually three sets of 20 second intervals were taken before the counter was rotated out of this plane. It was then set at 30° with the plane of the electric vector and another set of three counts taken. Similar observations were made then for 60°, 90°, 180°, and 270°. The counts at 180° and 270° were made simply to check the counts at 0° and 90°. Each run was continued as long as the apparatus operated properly. Ther terminations of the runs were due to the following reasons: (1) the ceasing of the counter to register photo-electrons, (2) the development of spontaneous discharges by the counter, (3) a defect in the x-ray apparatus which made it impossible to keep a steady current through the tube, (4) defects in the vacuum system which developed in rotating the cylinder containing the counter.

During one run a sheet of lead was placed over the slit in the x-ray box so as to cut off the x-ray beam. It was found that there was no indication of counts. This was done to make sure that the operation of the counter was not due to any external fields.

A counter which operated well for photo-electrons was taken out of the apparatus and a thick sheet of mica placed over the holes in the counter. When it was put back in the apparatus it showed no counts whatever although the counter continued to operate when the mica sheet was removed. This sheet was of such thickness that photo-electrons could not penetrate it. On the other hand it was not so great that x-rays were absorbed in it. This indicates that the number of stray x-rays which could enter the counter was exceedingly small.

Although many runs were started with counters which showed a relatively large number of photo-electrons, the actual number of runs which gave self-consistent results for any length of time were few. Those which showed that the counter was not behaving properly have been discarded only after a careful investigation which showed that there was somethings wrong with the apparatus. Those which were self-consistent for such a period that it was possible to obtain a good average result for the number ejected in the different directions are tabulated below. The corresponding times are given in seconds.

TABLE I. *Number of photo-electrons ejected at various angles with plane of polarization in plane perpendicular to x-ray beam.*

0°		30°		60°		90°		180°		270°	
No.	Time	No.	Time	No.	Time	No.	Time	No.	Time	No.	Time
98	340					15	340				
148	480					11	480				
14	120	12	120	9	120	2	120	8	60	0	60
61	300	64	420	30	420	8	360	30	120	5	120
241	600	229	720	93	720	40	600	42	120	6	120
65	180	31	120	11	120	1	120	42	120	5	120
98	420	70	420	28	420	10	420	112	420	20	240

If the number of counts is added for all runs and then reduced for equal times and expressed in terms of 100 in the 0° direction we get,

0°	30*	60°	90°	180°	270°
100	76.0	37.2	12.0	93.7	14.4

If the 0° and 180° directions and the 90° and 270° directions are combined and then reduced as before for equal times and expressed in terms of 100 in the plane of the electric vector $(0-180)$ we get the following results.

0°-180°	30°	60°	90°-270°
100	76.7	32.5	12.8

The fact that for 100 counts in the plane of the electric vector there are 12.8 at right angles to this plane may have four causes other than the ejection of photoelectrons in a plane perpendicular to the electric vector. First, the scattering did not all occur at 90° because of the fact that a beam of rays was used instead of a line. Since the distances from the target to the scattering block and from the scattering block to the counter together with the size of the apertures are known, it is possible to calculate the greatest deviation of a scattered ray from 90°. This was found to be about 3°. Second, the beam is not completely polarized because of the fact that the scattering block has a thickness greater than one layer of molecules. Although Compton and Hagenow have shown that this effect is not greater for thin substances, there is nevertheless a certain amount of unpolarized radiation. A third reason for expecting some electrons to appear at this setting is that some are deflected from their original direction by collision. For the pressures used in this experiment a high speed electron should have a theoretical mean path of about 12 cm. The face of the counter was 2.6 cm from the x-ray beam. The probability of collision is thus small, the more so as the experiments of Langmuir[15] have shown that the actual mean free path is considerably greater than that predicted by theory. A fourth reason lies in the fact that the effective area of the face of the counter covered about 4°. Thus with the counter set at the 90° position it actually covered the space between 88° and 92°.

The experimental points are plotted in Fig. 2 together with the theoretical curves of Bubb and Auger and Perrin. The curve of Bubb is based on an incident frequency of the $K\alpha$ line of tungsten and an ejected electron from the K shell of oxygen and nitrogen, averaged to give one value for computation. For this frequency there should, by Bubb's theory, be no photoelectrons ejected beyond 5° from the electric vector. It is to be noticed that the experimental points fit the curve of Auger and Perrin more closely than the curve of Bubb.

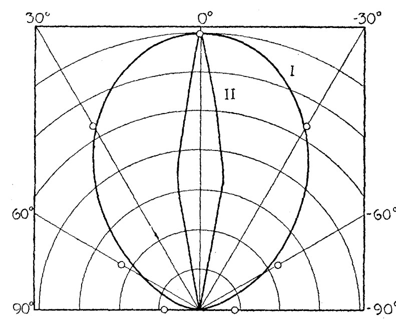

Fig. 2. Lateral distribution of photo-electrons. The points are experimental. Curve I is Auger and Perrin's theoretical curve: Curve II is Bubb's theoretical curve. The electric vector of the polarized x-rays is vertical.

The writer wishes to express his sincere thanks to Professor J. C. Hubbard of the Johns Hopkins University for suggesting the problem and to Professors W. A. Lynch and R. T. Cox for their constant aid and interest during the investigation.

NEW YORK UNIVERSITY,
UNIVERSITY HEIGHTS, N. Y.
June 19, 1928.

[15] See Dushman, High Vacuum