PROCEEDINGS
OF THE
NATIONAL ACADEMY OF SCIENCES

Volume 15 November 15, 1929 Number 11

ON THE POLARIZATION OF X-RADIATION

By William Duane

Department of Physics, Harvard University

Communicated October 4, 1929

In recent papers,[1] experiments on the general x-radiation produced by the impacts of high-speed electrons against the free atoms of mercury vapor have been described. In these experiments all the electrons had substantially the same velocity, as the difference of potential between the electrodes of the x-ray tube came from a high-tension storage battery. The absorption of the radiation in successive sheets of aluminum indicated that the radiation had the spectral distribution predicted by certain theories, in which distribution the intensity of the radiation has its maximum value at the short wave-length limit, given by the quantum relation, and then decreases beyond the limit toward longer wave-lengths inversely as the square of the wave-length.[2] It appeared, also, that the radiation had the same distribution whether it proceeded from the points of impact of the electrons in the direction of their motion or at right angles to this direction.

In a paper presented at the recent meeting of the American Physical Society in Washington the writer described experiments on the polarization of the radiation coming from the impacts of electrons against the mercury atoms. (See *Physical Review*, June, 1929, p. 1089.) The experiments indicated that the general (not the characteristic) x-radiation was largely but not completely polarized. This note describes the polarization experiments in greater detail and states some of the conclusions that may be drawn from them.

The x-ray tube employed to generate the radiation from the mercury vapor atoms differs from those previously employed only in a few details, chief among them being the fact that the mercury vapor is condensed by liquid air instead of by a water-cooling system. Figure 1 represents the glass x-ray tube. Electrons come from a Coolidge cathode, A, and pass through a circular opening into the anode, BB'. Metal rods, indicated by broken lines, connect the two metal parts of the anode, B and B'. Another rod connects the anode to a water-cooled cap, G, at the end of the tube, this cap being metallically connected to earth. The cathode, A, is connected to a point on a manganine wire circuit having a total resistance of over 6,000,000 ohms (not shown in the figure). One end of this resistance is metallically joined to earth and, therefore, to the metal cap, G, and to the anode, BB'; the other end is connected to part of the high-tension storage battery. During the experiments to be described the voltage of this part of the battery amounted to approximately 18,000 volts, and the resistance of the manganine wire circuit was so regulated that a current of 2.90 milliamperes passed through it to the ground. The resistance of the manganine wire circuit between the point at which the cathode, A, was attached and the ground (i. e., the resistance of the circuit in parallel with the x-ray tube) amounted to 4,023,000 ohms and, therefore, the

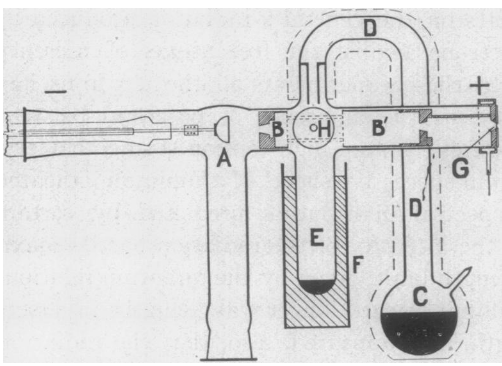


FIGURE 1

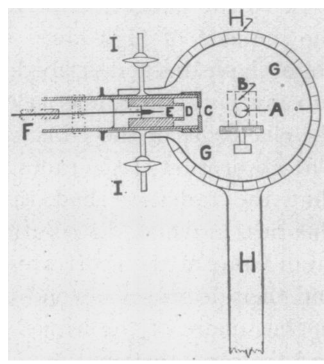
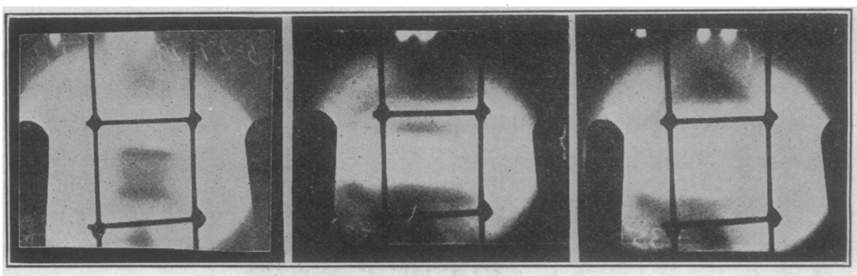


FIGURE 2

battery produced a constant difference of potential of 11,670 volts between the cathode and the anode. This voltage cannot produce any of the L series lines in the x-ray spectrum of mercury, for the generation of these L series lines requires at least 12,290 volts. The M series lines have such long wave-lengths (in the neighborhood of 6 Ångströms) and such large coefficients of absorption that they do not come through the windows of the x-ray tube with perceptible intensity. The spectrum of the radiation observed in the experiment, therefore, contained none of the x-ray lines and consisted of general or continuous spectrum radiation only. The reservoir, C, contains pure mercury, that is heated and vaporized by an electric furnace (not shown in the figure) upon which the reservoir rests. The mercury vapor passes up and over through the tube, D, and down through a constricted portion, as represented. The entire tube, D, is heated by means of an electric current flowing through a wire wound in asbestos around it. The coils of this wire lie considerably closer together near the constricted portion of the tube, which insures super-heating of the mercury vapor and prevents the formation of drops of mercury in the central portion of the tube. From D the stream of mercury vapor passes down into the reservoir, E, where it is condensed by means of liquid air in the flask, F. With this arrangement of apparatus, a horizontal stream of high-speed electrons passes through a vertical stream of mercury atoms in the middle portion of the anode. The radiation coming from the impacts of the electrons against the mercury atoms in the direction of motion of the electron stream can be observed through the thin window, G. This window consists of a thin sheet of cellophane paper, which absorbs less than one per cent of the x-radiation. A magnet (not shown in the figure) produces a magnetic field in the region, B', of the anode, which deflects the electrons so that they do not strike the window, G, itself. The circles, H, represent a wide tube extending out toward the front of the diagram at right angles to the main tube. This tube carries a cellophane window similar to G through which the radiation coming from the mercury atoms in a direction perpendicular to the electron stream can be observed. The window, H, lies about 9 cm. from the axis of the electron beam. In the researches I am describing, the polarization of this radiation in the direction at right angles to the electron stream has been investigated. During the experiments, as high a vacuum as possible was maintained by means of a three-stage mercury vapor pump (not shown in the figure) on which the x-ray tube rested. Contact with this pump was made at the lower end of the tube, below A.

The polarization of the radiation has been examined by means of the scattered radiation coming from a block of carbon upon which the primary radiation impinged. Figure 2 represents the apparatus for detecting the scattered radiation projected from the block of carbon in directions at right angles to the primary x-ray beam. This horizontal primary beam of x-rays comes from the tube through a circular hole, A, in a vertical lead and brass disc, G, and strikes the block of carbon, B. The block is supported on a small metal disc, that can be turned about a vertical axis, which lies about 3 cm. in front of the circular hole, A. Part of the x-radiation scattered from the carbon block in a direction at right angles to the primary beam of x-rays passes through a cellophane window, C, into an air-tight chamber, D. It then passes through a very thin sheet of aluminum, D, into a metal box, E, containing a sharp metal point, usually of steel, but sometimes of platinum. The apparatus constitutes a "point counter" for counting photons that are absorbed in E. The writer first described this point-counter device in the *Comptes Rendus*, July 18, 1910. Since that date point counters have been greatly improved by Geiger and others. The point counter, the carbon block and its support are all attached to the lead disc, G, which can be rotated about an horizontal axis, parallel to the primary beam of x-rays. The disc is held in position by the fixed ring and support, H. A circular scale on the ring enables the direction of the scattered rays coming from the carbon and entering the point counter to be determined. In the experiments to be described, the scattered radiation in the two horizontal directions, left and right and in the vertical directions up and down, was investigated. It will be remembered that the stream of electrons hitting the mercury atoms and producing the x-rays traveled in a horizontal direction, so that, if the point counter is in the position represented in the figure, or on the diametrically opposite side of the circle, it registers scattered radiation in directions parallel to the direction of motion of the electrons, and, if it is in either of the vertical positions, it registers x-radiation projected in a direction perpendicular to that of the electron stream.

By means of the glass stop-cocks, I, we are able to fill the point-counter



A B C

FIGURE 3

chamber with any desired gas. In these particular experiments we have used Argon. Argon increases the number of photons caught and registered in the point-counter chamber about eight times. In order to detect the current of electricity that flows to the point, E, due to the absorption of a photon in the chamber, the point is connected metallically through F and a flexible wire cable, F, to a three-stage amplifying system.[3] This amplification suffices to operate both a loud speaker and an electric relay, the electric relay operating an ink syphon recorder. Both audible and ink records have been taken simultaneously of the number of photons absorbed in the chamber E. In order to make the point counter work, it is necessary to apply to it a voltage of several hundred volts. The voltage required is less, when Argon fills the chamber, than when air fills it. Point counters, that require 2200 volts in air to work properly, work in Argon at about 1200 volts.

The photographs A, B and C of figure 3 were produced by the primary beam of x-rays that came through the window, H, figure 1, of the x-ray tube, the window thus constituting a kind of pin hole in a pin-hole camera.

The films were enveloped in black paper, which cut off the rays of ordinary light. They were placed at a distance of 4.5 cm. from the window, *H*, and immediately back of the hole, *A*, (Fig. 2) in the vertical disc. They were held in position by the cross wires, the shadows of which appear in the photographs. In the case of figure 3*A*, the mercury heater was not running and the dark part of the photographic impression (the light part of the reproduction) came from the impacts of a few stray electrons against the solid parts of the anode in the tube. Owing to the fact that these parts were solid and not gaseous, the impression produced by the x-rays are relatively very intense. In the photograph of figure 3*A* appears a faint but definite horizontal streak. The streak represents the x-radiation that came from the electron stream as it passed through the mercury vapor that existed in the tube at room temperature. Figure 3*B* represents the radiation produced under the same conditions, except that here the mercury heater had been running for several hours and the track of the electrons through the mercury vapor is very strongly marked. This photograph illustrates the way in which one can assure one's self that the radiation passing through the circular hole, *A*, in figure 2, really comes from the impacts of the electrons against mercury vapor atoms and not against solid matter inside of the tube. The hole, *A*, lay directly behind the center of the square marked out in the photograph by the shadows of the crosswires. The diameter of the hole, *A*, was less than one-half of the length of a side of the square and, therefore, the hole lay entirely in the region of the radiation coming from the mercury vapor itself, and hence only this mercury vapor radiation struck the carbon block producing the observed scattered radiation. Figure 3*C* represents a photograph taken some hours later, at which time the pressure of the mercury vapor in the tube had risen slightly.

In making a series of observations, it was customary to start the mercury heating circuit early in the morning and let it run for about five hours before beginning to take the readings. At that time, the thermal conditions, etc., had reached an approximately constant state. The electrical circuits of the high-tension battery were then closed and the Coolidge cathode put into operation and heated so as to give a current through the tube of a few milliamperes. The manganine wire potentiometer resistance was adjusted so as to give a current of 2.90 milliamperes through the portion of it parallel to the x-ray tube. The point counter was then placed vertically over the carbon block so as to record the effects of the scattered radiation in a direction perpendicular to the motion of the electrons. The number of photons absorbed in and recorded by the chamber during five minutes was then counted. Usually the counting took place not only orally by means of the loud speaker, but also by means of the ink syphon, recording on paper tape. The point counter was then moved to a horizontal position and the absorbed photons counted for another five minutes. The same procedure was then continued with the point counter vertically below the carbon block and, again, with the point counter in the other horizontal position. Thus records were obtained of the numbers of scattered photons absorbed in the chamber that came from the carbon in four directions, two vertically upward and downward (i.e., perpendicular to the direction of motion of the electrons in the tube) and two in horizontal directions to the right and left (in directions parallel to the stream of electrons). The same process was then repeated five or six times, proceeding each time all around the circle.

A somewhat detailed description of one complete set of readings (experiment No. 33, on May 24th), taken with the loud speaker, will now be given. Column 1, of table 1, contains the time at which the counting

TABLE 1

EXPERIMENT No. 33, MAY 24TH

TIME OF BEGINNING A SET OF FOUR COUNTS	NUMBER OF COUNTS BY LOUD SPEAKER IN FIVE MINUTES AT ANGLES INDICATED 0°	90°	180°	270°
1:40 P.M.	8	6	4	1
2:07 P.M.	115	41	109	36
2:32 P.M.	117	52	132	39
2:55 P.M.	95	43	92	33
3:18 P.M.	112	46	133	41
3:42 P.M.	111	43	141	52
Averages corrected for leaks	102	39	117	39

Degree of Polarization 0.474

began. Column 2 contains the number of photons recorded by the point counter during five minutes, when it lay vertically above the secondary radiator. Columns 3, 4 and 5 contain, respectively, similar counts of photons projected (*a*) in the direction of motion of the electrons, (*b*) vertically downward and (*c*) in the direction opposite to that of the motion of the electrons.

In this case, the heating current, started at 10:35 A.M., amounted to 1.05 amperes during the entire experiment. 3.55 milliamperes passed through the x-ray tube and 2.9 milliamperes passed through part of the potentiometer circuit in parallel with the tube. As the resistance of this parallel circuit amounted to 4,023,000 ohms, the voltage across the tube remained constant at 11,670 volts. This, as stated above, cannot produce any of the L series lines of the x-ray spectrum of mercury, for the generation of these L series lines requires at least 12,290 volts according to the well-known laws of x-ray production and, therefore, the x-rays contained general radiation only. The numbers in the first line represent the leak of the apparatus with the point counter in the four positions, respectively. They were obtained with a sheet of lead covering the opening A (Fig. 2), cutting off the primary x-rays. The following lines contain the numbers counted when this sheet of lead was removed and the primary beam passed through, striking the secondary radiator, B. Subtracting the former numbers from the latter, we get, on the average, the number of photons absorbed by the counting chamber in its various positions due to the secondary rays coming from the secondary radiator. The counts

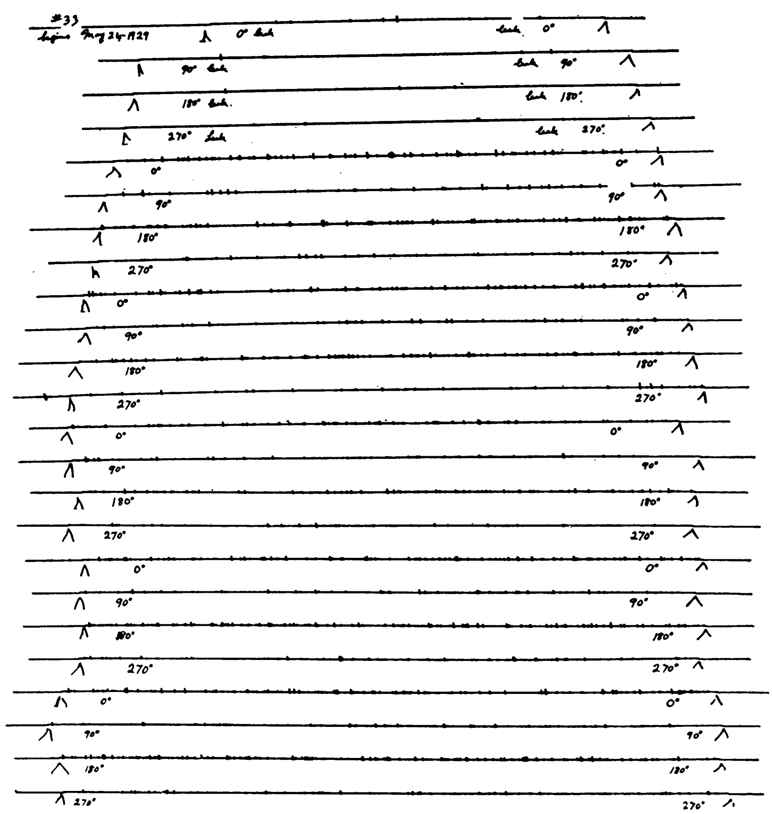


FIGURE 4

show conclusively that the numbers are nearly three times as great in the two directions up and down (perpendicular to the line of motion of electrons) as in the two directions forward and backward (parallel to the motion of electrons). In other words, the primary radiation is polarized to a considerable extent, since it produces more intense scattered radiation in directions perpendicular to the line of flight of the electrons than in directions parallel to it. The average numbers of photons absorbed in five minutes are $n_1 = 109.7$ in directions perpendicular to the electron stream and $n_2 = 39.1$ in directions parallel to the stream.

There are various ways in which the degree of polarization, p, of a beam of rays may be estimated and stated. For the present, we shall take the difference between the maximum number, n_1, of photons absorbed in a given time and the minimum number, n_2, divided by the sum of the two, namely, $p = \frac{n_1 - n_2}{n_1 + n_2}$. In this instance, the degree of polarization is $p = 0.474$.

Figure 4 contains a photograph of the record obtained with the ink syphon recording apparatus for exactly the same set of photon beams (Experiment 33). The ink syphon recorded the photons, while the observer counted the total number of the sound impulses coming from the loud speaker with a mechanical counter. All counts represent five-minute intervals. Those marked 0° and 180° record photons projected from the secondary radiator up and down, respectively (i.e., perpendicular to the electron stream); and those marked 90° and 270° record photons traveling in directions parallel to the electron stream. The first four records correspond to the leak of the instrument. Among the others, those marked 0° and 180° show a far greater number of photons absorbed than those marked 90° and 270°, indicating the same kind of polarization of the primary beam as the loud speaker indicated. The total numbers of absorbed photons recorded by the ink syphon were always less than those recorded at the same time by ear, showing that this particular syphon recorder was less sensitive than the loud speaker. The degree of polarization, however, was substantially the same in almost all cases. In this particular experiment, the degree of polarization determined by the ink syphon was 0.468, as compared with 0.474 determined by the loud speaker.

TABLE 2

SUMMARY OF ALL DATA

NUMBER OF EXPERIMENT	DATE	HEATING CURRENT AMPERES	TUBE CURRENT MILLIAMP.	LOUD SPEAKER COUNTED IN 5 MINUTES	LOUD SPEAKER DEGREES OF POLARIZATION	SYPHON RECORDER DEGREES OF POLARIZATION
28	May 14	1.00 a.c.	3.4	94.4	0.482	0.382
30	May 20	0.93 a.c.	3.4	87.7	0.568	0.639
31	May 21	0.93 a.c.	3.4	75.1	0.507	0.494
33	May 24	1.05 d.c.	3.5	109.7	0.475	0.468
35	May 28	1.05 d.c.	3.5	154.0	0.478	0.495
36	May 31	1.05 d.c.	3.5	159.0	0.524	0.510
37	June 3	1.05 d.c.	3.3	183.5	0.472	0.351
38	June 5	0.75 d.c.	3.5	28.0	0.513	0.511
39	June 6	0.75 d.c.	3.5	35.3	0.587	0.581
40	June 7	0.75 d.c.	3.5	41.5	0.558	0.546
44	June 14	1.05 d.c.	6.2	205.0	0.428	...
46	June 18	0.80 d.c.	6.4	98.5	0.427	0.446

Table 2 contains a summary of all the data obtained after the preliminary runs made to adjust the apparatus, etc. Column 1 contains the number of the experiment. Where a number is omitted, it means that an experiment was begun, but, for some reason (interruption of one or more of the currents, for instance), was broken off before completion. Column 2 contains the date; column 3, the current in amperes heating the mercury; column 4, the current in milliamperes through the tube; column 5, the average number of photons counted by the loud speaker in vertical directions during five minutes and column 6, the degree of polarization as defined above and as determined by the loud speaker. Column 7 contains the degree of polarization in the various experiments as determined by the ink syphon recorder.

It will be noticed that in all but two of the experiments the degrees of polarization determined by the loud speaker and the syphon recorder, respectively, agree with each other reasonably well, although, as stated above, the total number of photons counted by the loud speaker always exceeds the number counted by the syphon recorder. The average of the numbers representing the degree of polarization is 0.501 as determined by the loud speaker and 0.492 as determined by the syphon recorder. There seems to be no doubt that the radiation coming from the single atoms struck by electrons is very considerably polarized, but that it is not completely polarized.

The largest of the numbers representing the degree of polarization, as determined by the loud speaker, is 0.587, and the smallest is 0.427. The variation among the degree of polarization numbers, therefore, appears to be quite large. This variation is partly inherent in the method of counting, as the numbers of photons recorded in the point-counting chamber are in themselves variable. Some of the variation in the numbers representing the degree of polarization, however, is due to slight variations in the apparatus itself, such as slight differences in the amount of mercury vaporized per second, etc.

According to the Compton effect, part of the radiation scattered from the carbon block consists of modified and part of unmodified x-rays. The interesting question now arises, namely, whether both kinds of rays give the same indication as to the state of polarization of the primary beam. To obtain data bearing on this point, experiments were performed with chemical elements other than carbon as the scatterer; for the ratio of the intensity of the modified rays to that of the unmodified rays becomes much smaller for chemical elements of high atomic weight. However, in the experiments for chemical elements of high atomic weight, the number of photons registered in five minutes became so small that many more counts will have to be made before reliable conclusions can be drawn from them.

There is one source of error which would make the degree of polarization appear to be too small. When the electrons pass through the stream of mercury atoms, a certain number of them will be deflected and have their velocities reduced in magnitude and these will strike other mercury atoms producing radiation corresponding to the slower velocities. Whether or not the error coming from this source is large enough to be perceptible can be determined, if we change the number of mercury atoms per cubic centimeter in the gas stream. If this number is twice as great, there will be twice as many electrons deflected and each deflected electron will have twice the chance of striking another mercury atom. The number of photons, therefore, produced by the electrons that have been slowed down will increase as the square of the density of the mercury atoms, whereas the number of photons produced by the impacts of full-speed electrons will increase as the first power of the density. We would expect, therefore, that the degree of polarization would depend upon the density of the mercury vapor. In some of the experiments recorded in table 2, the numbers of photons registered are several times as large as those registered in other experiments, due to the fact that the current heating the mercury was larger in some experiments than in others. If we compare experiments 33, 35, 36, 37 and 44 with experiments 38, 39, 40 and 46, we see that the numbers of photons recorded per minute in the first set of experiments average more than four times as large as in the second set. Hence, the density of the mercury vapor, on the average, must have been about four times as great in the first set as in the second. On calculating the degrees of polarization in the two cases, however, we find that the average degree of polarization for the denser experiments is 0.486, whereas, for the less dense experiments, the degree of polarization is 0.514. These figures differ from each other by less than six per cent, and it is doubtful whether the errors of experiment would not account for the difference, especially when we take into consideration the fact that the observer may miss some of the photons when they follow each other in rapid succession. We can, therefore, only conclude that if the change in density produces a change in the calculated degree of polarization at all, the change cannot be very great.

The number of counts made in the various experiments recorded in table 2 were not always the same. Hence, the various degrees of polarization recorded must carry with them different weights, when we calculate the average degree of polarization given by the data. A weighted mean value for the degree of polarization may be obtained by taking the total number of photons recorded in all experiments for each of the several positions of the point counter. These numbers are:

0°	90°	180°	270°
5351	1815	5696	1900

The total numbers give 0.497 as the weighted mean value of the degree of polarization, assuming it to be sensibly the same for all of the experiments under the various conditions of tube current, density of mercury vapor, etc.

The degree of polarization adopted in this note has been defined by means of the numbers of photons registered by the point counter in different positions and not by means of the amount of energy radiated in different directions. If the radiations had been homogeneous, this would have made no difference. As mentioned above we have found that the radiation from the mercury atoms is not homogeneous. Therefore, the degree of polarization determined by the ratios of the numbers of photons registered is a kind of average degree of polarization for x-rays of different wave-lengths or for photons of different energy contents. We would expect the radiation from the mercury atoms to have the characteristics found by Ross[4] in his interesting experiments on the x-rays coming from a solid target. We would expect, namely, that the rays from the mercury atoms would become more and more completely polarized as we approach their short wave-length limit. In terms of the photon theory, this characteristic may be expressed by saying that the photons of greatest energy content would have the vectors in them (whatever the vectors are) all pointing in the same direction, whereas, for those photons in which the entire energy of the electrons are not taken over by the photons, the vectors may point in somewhat different directions.

According to the classical and other theories of the production of x-radiation, the radiation should be polarized in the plane containing the direction of motion of the electrons by which it was produced. In this respect the experiments on mercury vapor radiation substantiate the conclusions of the theory in part only. Radiation from the mercury vapor appears to be polarized in the proper direction, but only partially polarized. In a recent note to the Academy[4] Sommerfeld has generalized his interesting theory of the production of x-rays so as to include the possibility of their being only partially polarized and also the possibility of the projection of radiation in the direction of motion of the electrons.

When we regard the polarization of radiation from the point of view of the photon theory, many interesting problems present themselves—problems connected with the question of what we really mean by polarization and how the degree of polarization for non-homogeneous rays should be defined. If the degree of polarization is determined by the amounts of secondary radiation radiated in different directions, it may be that we shall have to regard the degree of polarization as a kind of probability problem.

It gives me great pleasure to thank my assistant, Mr. Lanza, for the care that he has shown in setting up various of the above described experiments and for the patience with which he has made the very tedious counts.

[1] Duane, William, these PROCEEDINGS, **13**, 662(1927); **14**, 450(1928).

[2] Webster, D. L., *Phys. Rev.*, March, 1923, p. 325; Kramers, *Phil. Mag.*, November, 1923, p. 836.

[3] Designed by Mr. Hewlett of the General Electric Co.

[4] *J. Opt. Soc.*, **16**, 375, June, 1928.

[5] PROC. NAT. ACAD. SCI., **15**, 393 (May, 1929).