[4] Aston, *Proc. Roy. Soc.*, **115**, 487 (1927).
[5] Dirac, *Ibid.*, **109**, 206 (1925).
[6] Millikan and Cameron, *Phys. Rev.*, June, 1928.
[7] Bowen, *Astrophys. Jour.*, **57**, 1 (1928).

THE GENERAL X-RADIATION FROM MERCURY VAPOR

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A recently published note[1] described experiments on the general or continuous spectrum radiation coming from the impacts of electrons against mercury vapor atoms. The electrons fell through a constant difference of potential produced by the high tension storage battery and, therefore, had substantially the same velocities when they struck the atoms. The radiation projected from the impacts at right angles to the stream of electrons did not appear to be homogeneous. After it had come through the thin glass window of the apparatus, 57.5% of it passed through a sheet of aluminum about $^1/_{10}$ of a millimeter thick. If the radiation had had the wave-length of the short wave-length limit of the spectrum corresponding to the voltage on the tube, 62% would have passed through the sheet of aluminum.

The object of the researches described in this note has been to investigate the radiation proceeding in the direction of motion of the electron stream, as well as at right angles to it, and, also, to compare the penetration of both rays with the penetration of the radiation that would come from the impacts of the electrons according to certain theories.

Figure 1 represents a horizontal cross-section of the apparatus employed. The electrons from a hot wire cathode, *C*, pass through an opening into the interior of an anode, consisting of two brass tubes, *A* and *B*, joined together by four curved wires, represented by dotted lines in the figures. The high tension storage battery produced a difference of potential of 11,780 volts, which was determined by measuring the current passing through a manganine wire resistance of 3,019,000 ohms in parallel with the tube. The stream of mercury vapor came up through the vertical tube, *D*, from an electrically heated furnace. It then passed across and down through the vertical tube, *E*. The apparatus was exhausted through the vertical tube, *F*, which communicated with a mercury diffusion pump, not shown in the figure. Although all parts of the apparatus contained at least a small amount of mercury vapor, most of the impacts of electrons against the mercury atoms occurred in the region,

E. Radiation coming from these impacts at right angles to the line of flight of the electrons could be examined after it came through the window, G. The radiation coming from the impacts in the direction of motion of the electrons could be examined through the window, H. In order to prevent the electrons, themselves, from hitting the window, a strong magnetic field, produced by an electro-magnet not shown in the figure, was applied in the region, B. Each beam of rays was examined, both by its photographic and by its ionizing effects. To obtain pin-hole camera photographs of the source of radiation, a sheet of lead with a small hole in it, K, was mounted in front of each window in turn. In order properly to direct the radiation coming from the mercury vapor atoms only into the ionization chamber, I, thumb screws were attached to the lead sheet by which the pin-hole, K, could be moved accurately

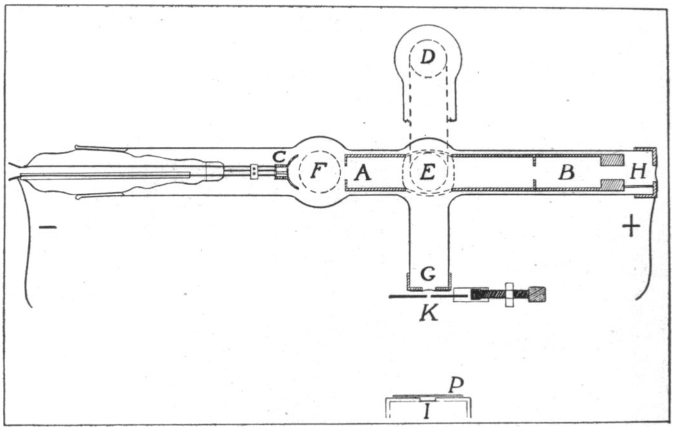
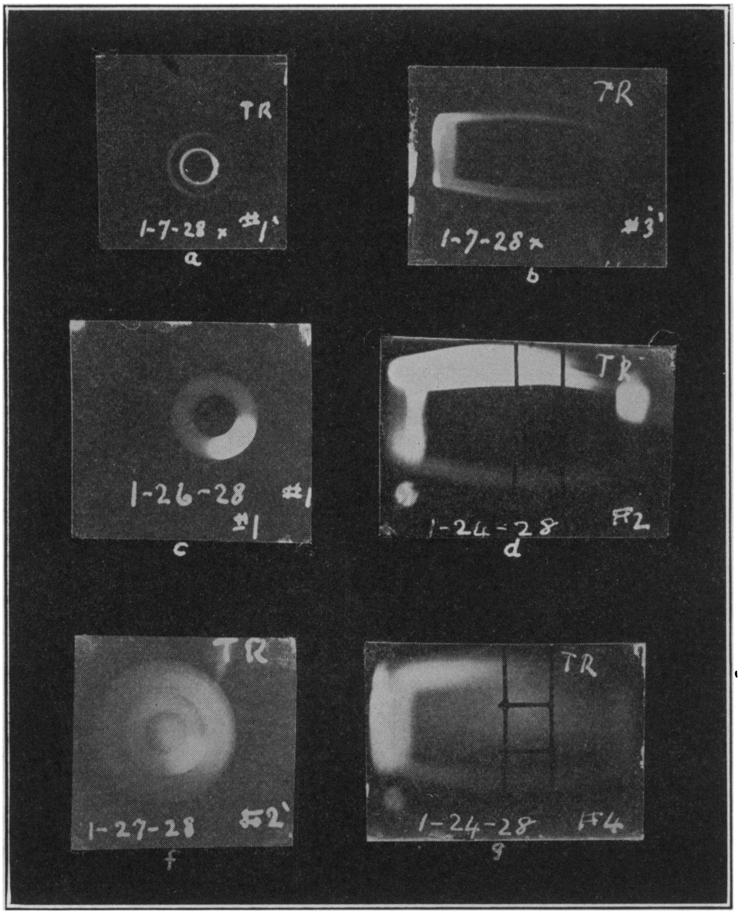


FIGURE 1

in the horizontal and also in the vertical direction. The photographic film, P, wrapped in black paper, was placed over the window into the ionization chamber, I.

Figure 2 contains copies of several pin-hole camera photographs of the radiation coming through the window, G; and also that coming through the window, H, after the tube had been turned around so that the window, H, lay in front of the pin-hole. Photographs, a and b, were taken with a very small pin-hole and without the mercury vapor passing through the tube. Photograph a represents the source of the radiation passing through the window, H. The two circles correspond to the edges of the two circular holes, A and B (Figure 1), in the anode. The radiation from these edges was produced by a few stray electrons traveling outside of the main beam of electrons, which passed almost wholly through the opening, A. Only at one point did the main beam of electrons hit the edge of A as indicated by the dark spot on one side of the inner circle. Photograph b represents the source of the radiation passing through the window, G. The curved horizontal lines correspond to the wires which connected the portion A to the portion B of the anode. The vertical lines correspond to the edges of the tube, A, and of the tube, B. The radiation producing these photographic impressions came from a few



stray electrons (reflected or secondary) that struck the metal parts of the anode. Photographs, c and d, were taken with a very much larger pin-hole (about 2 mm. in diameter). In these experiments, also, no mercury vapor passed through the tube. Photograph d illustrates the method by which the radiation entering the ionization chamber could be limited to that coming from a particular part, only, of the source of rays. The black lines across the photograph are the shadows of wires placed directly in front of the photograph, P, on the side toward the tube. The window into the ionization chamber lay directly behind the center of the square formed by the wires. By shifting the position of the pin-hole, K, the radiation from any part of the source of rays could be directed into the ionization chamber. It is important to note that photographs a and c do not show an appreciable effect of radiation inside of the smaller circles. These portions of the photographs correspond to the direct line of flight of the electrons through the tube. The only solid material on this line, inside the tube, was the cathode itself.

Photographs f and g represent the sources of the radiation coming through the windows, H and G, respectively, when the stream of mercury vapor passed through the tube as well as the stream of electrons. Each photograph shows radiation coming from the impacts of electrons against the mercury in addition to that coming from the solid parts of the anode. In photograph f the effect of the mercury radiation lies inside of the inner circle corresponding to the edge of the circular opening, A. The mercury radiation effect appears to be separated from that of the edge by a circular line of less intensity. This line is probably due to the fact that the cathode (a fine focus Coolidge cathode) produced a conical beam of converging electrons and, therefore, its greatest effect lay near the axis of the cone. The radiation producing the outer circle in photograph f came from the edges of the opening, B, in figure 1. The circle is much more strongly marked than in photograph c. It can be seen on the film of c itself, but may not appear in the reproduction. Photograph g represents the effect of the radiation coming at right angles to the stream of electrons through the window, G. In addition to the radiation from the rods and cylinders of the anodes, that from the mercury vapor appears in the center as a sort of elongated cloud. The electron stream passed from right to left and produced its most intense mercury radiation near the center, where the electrons struck the main stream of mercury atoms flowing downward. The cross wires in front of the film cast shadows across this cloud and, as the opening into the ionization chamber lay behind the center of the square, only the radiation from the mercury vapor entered the ionization chamber when the pin-hole, K, was in the position it occupied during the taking of the photograph.

The intensity and penetrating power of the mercury radiation projected in the direction of motion of the electrons and also perpendicular to it have been measured by means of the ionizing effects produced inside of the ionization chamber. These experiments have been made in order to determine whether or not the beams of rays are homogeneous, and, also, to compare the penetration with that to be expected according to certain theoretical distributions of energy in the spectrum of radiation due to the impacts of electrons of given velocity. The material used to determine the penetration of the rays was a sheet of aluminum about 0.1 mm. This test sheet weighed 0.02773 gram per square centimeter. In order to obtain as accurate a comparison between the observed and theoretical penetrations as possible, one must use very thin windows. The windows, *G* and *H*, in the tube and the window, *I*, in the ionization chamber were of very thin mica. The amounts of radiation of different wave-lengths coming through these three windows were measured by means of an x-ray spectrometer.

To determine the penetration of the radiation through the sheet of aluminum a number of measurements of the ionization current due to the radiation from the mercury vapor with and without the test sheet of aluminum in the path of the rays were made. The test sheet was placed close to the pin-hole, *K*, so that a negligible amount of the scattered radiation from it entered the ionization chamber.

In order to investigate the general or continuous spectrum radiation alone, without the line spectrum, it was necessary to apply to the tube a difference of potential insufficient to produce the line spectrum. It requires a difference of potential of 12,250 volts to produce the L series lines of longest wave-lengths. Consequently, a difference of potential less than that has been used, namely: 11,780 volts. The short wave-length limit of an x-ray spectrum corresponding to this voltage is 1.05 Ångström.

Measurements of the penetration of the radiation through the test sheet of aluminum showed that 40% of the mercury radiation coming through the window, *G*, passed through the aluminum sheet and 38.8% of the radiation coming through the window, *H*, passed through the aluminum sheet. In order to find out whether or not the radiation is homogeneous, additional sheets of aluminum were placed in front of the windows and then the percentage of radiation passing through the test sheet was measured. The measurements showed for the mercury radiation coming through the window, *G*, that after this radiation had gone through one sheet of aluminum (weighing 0.02773 gr. per sq. cm.), 47.5% passed through the test sheet, and, after the radiation had gone through an additional sheet of aluminum (weighing 0.02717 gr. per sq. cm.), 51.3% passed through the test sheet. Similar measurements for the radiation coming through the window, *H*, showed that 46.1% of the radiation that had gone through the first sheet of aluminum passed through the test sheet, and that 50.7% of the radiation that had gone through the two sheets of aluminum passed through the test sheet. All these percentages have been corrected for the natural leak of the ionization chamber and for any small ionization currents that it detected when the mercury heater was not running. It appears, therefore, that the mercury radiation both in the direction of the electron stream and perpendicular to it becomes more and more penetrating as it passes through successive layers of aluminum. In other words, neither beam of rays is homogeneous.

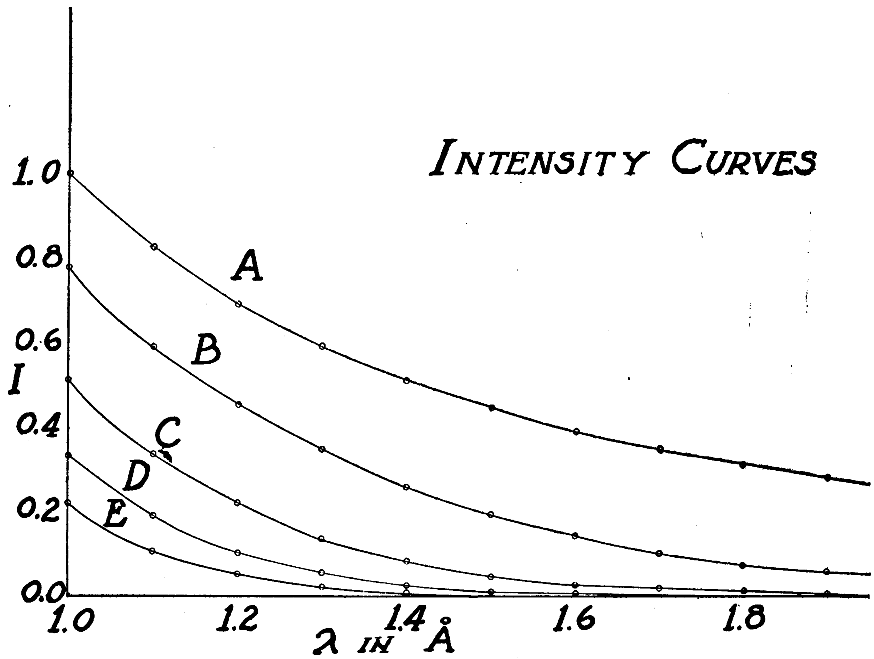
The mercury radiation through the window, *H*, appeared to be slightly more penetrating than that through the window, *G*. This, however, is due to the fact that the mica in window, *H*, was somewhat thinner than that in window, *G*, as will be seen later.

If the radiation has been homogeneous and had had a wave-length equal to that of the short wave-length limit of the spectrum, 1.05 Ångström, 61.3% of it would have passed through the test sheet of aluminum. This percentage has been determined by measuring the absorption of monochromatic radiation produced by reflection from a calcite crystal in an x-ray spectrometer. It appears, therefore, that the wave-lengths of the inhomogeneous beams of rays are on the average somewhat longer than that of the short wave-length limit of the x-ray spectrum. They are not very much longer, however, for the absorption of aluminum increases as the cube of the wave-length.

The intensity of the mercury radiation coming through the window, *H*, appeared to be five or six times as great as that coming through the window, *G*. It would be difficult to estimate accurately how much of this difference may be due to the fact that the beams came from different thicknesses of mercury vapor. We may conclude, however, that the intensities per mercury atom in the direction of motion of the electron and perpendicular to it are of the same order of magnitude. Further experiments on this point are in progress.

Some interesting conclusions have been drawn by D. L. Webster[2] and his students from their experiments on the general x-radiation coming from solid targets. One of these conclusions is that the radiation from an indefinitely thin target should have a maximum of intensity at the short wave-length limit and that this intensity should decrease beyond the limit, toward longer wave-lengths, approximately as the inverse square of the wave-length. Kramers[3] came to the conclusion that it would decrease almost exactly as the inverse square of the wave-length in his theory of the radiation that should be emitted by an electron approaching an atomic nucleus. He based his theory on classical ideas and Bohr's correspondence principle, assuming arbitrarily that the radiation would be cut off at the short wave-length limit given by the quantum equation.

In order to calculate the theoretical amount of radiation that should pass through the test sheet of aluminum, if the distribution in the spectrum follows the above inverse square law, it is necessary to determine accurately the absorption of x-rays of different wave-lengths by the mica windows and the sheets of aluminum. This has been done as described in the previous note by measuring the absorption of a few monochromatic rays, produced in an x-ray spectrometer, and then calculating the percentages of radiant energy passing through the various sheets of material by means of the accurately known law of variation of their absorptions with the wave-length. This spectrometric method of measuring the penetration of the rays through the windows and sheets of aluminum gives more accurate results than the measurements of their masses per square centimeter, for it automatically corrects for small impurities. The curves in figure 3 give the results of these measurements and calculations for the end window, H. The abscissas represent the wave-lengths and the ordinates, the intensities expressed on an arbitrary scale. Corrections have been made in these curves for the absorption of the radia-



tion by the air through which it passed between the tube and the ionization chamber. The upper curve, A, shows the theoretical distribution of energy in the spectrum according to the inverse square of the wave-length law, starting with a short wave-length limit of 1 Å. Curve B represents the distribution of energy in the spectrum after the radiation has passed through the mica in the window, H, of the tube, through the air from the tube to the ionization chamber and through its mica window, I. Curve C represents the theoretical distribution of energy in the spectrum after this radiation has passed through the test sheet of aluminum in addition to the mica and air. The area under the curves give the total intensity of the radiation in the respective cases. The area under curve, C, from $\lambda = 1.05$ on divided by the corresponding area under curve, B, represents therefore the fraction of the radiation that, theoretically, should pass through the test sheet of aluminum. The ratio of these areas shows that for the radiation coming through window, H, 38.2% should pass through the test sheet of aluminum. This theoretical percentage should be compared with the observed percentage 38.8%. Curves D and E have been drawn to represent the radiation that should come through the aluminum when the additional sheets are placed in the path of the rays. Corrections have been made for the slight differences of the masses per square centimeter of these sheets. Similar curves have been drawn for the radiation coming through the side window, G. All the curves were drawn on a large scale extending out to long wave-lengths and the areas under them determined with considerable precision. The numerical results of the calculations, as well as of the experimental measurements appear in table 1.

TABLE 1

PERCENTAGE THROUGH TEST SHEET

NUMBER OF SHEETS	SIDE RADIATION OBSERVED	SIDE RADIATION CALCULATED	END RADIATION OBSERVED	END RADIATION CALCULATED
0	40.0%	38.4%	38.8%	38.2%
1	47.5	46.4	46.1	46.2
2	51.3	50.2	50.7	50.0

The first column contains the number of sheets of aluminum placed near the windows. The second and third columns contain the observed and theoretical percentages of the radiation passing through the test sheet of aluminum for the radiation projected at right angles to the stream of electrons. The fourth and fifth columns contain the same percentages for the radiation projected in the direction of motion of the electrons. It appears that the percentages calculated from the inverse square of the wave-length law agree very well with the observed values. The air corrections mentioned above have been made in the calculated values of the percentages as recorded in the table. The corrections were applied during the latter part of April. Previous to that the calculated values always came out several per cent smaller than the observed values. The radiation appeared to be actually somewhat more penetrating than would be expected according to the inverse square of the wave-length law. It had not been thought possible that the passage of the radiation through thicknesses of air ranging from 12 cm. to 22 cm. could so filter out the longer rays as to account for these differences. It was thought that the differences might be due to some excess radiation at or close to the short wave-length limit. The air corrections, however, brought the theoretical percentages so close to the experimental values that their differences may reasonably be regarded as due to experimental errors. Small corrections such as those for the fact that a few of the electrons must have had velocities slightly less than the maximum and for the fact that not quite all of the radiation may have been absorbed in the ionization chamber (which contained methyliodide) would tend to decrease the calculated percentages and increase the amounts by which they fall below the observed values. The calculated and observed values, however, agree so well that we may conclude that, if there is any excess radiation at or close to the short wavelength limit, its intensity must be quite small.

After the experiments reported in the previous note (loc. cit.) had been finished, the tube was purposely broken and the absorption of the glass window determined for homogeneous rays in the x-ray spectrometer. Calculations similar to those described above show that in the earlier experiments, 56% of the radiation coming through the glass window theoretically should have passed through the test sheet of aluminum, whereas, as previously reported, 57.5% passed through it. The results of the earlier experiments, therefore, indicate that the theoretical penetration of the radiation is approximately that observed.

An attempt to obtain a spectrum of the mercury radiation is being made by means of a small spectrometer inside the tube.

[1] William Duane, "The Character of the General Radiation," *Proc. Nat. Acad. Sci.*, September, **1927**, p. 662.

[2] *Phys. Rev.*, March, **1923**, p. 323.

[3] *Phil. Mag.*, November, **1923**, p. 836.

ON THE QUANTITY OF ELECTRICITY DISCHARGED IN A LIGHTNING STROKE

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The experimental field work of Norinder[1] on the extent of the electric fields of thunderclouds and magnitudes of these fields makes it possible to calculate approximately, or at least determine the order of magnitude of, the quantity of electricity involved in a lightning stroke.

If a gradient F is maintained over a level surface (the earth's surface) of area A, the quantity of electricity stored on the area is given by

$$Q = AF/4\pi. \quad (1)$$

Norinder has established experimentally that the extent of the field of a thundercloud is of the order of magnitude of one circular kilometer and from the work of Peek[2] we may conclude that the maximum gradient