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POLARIZATION OF THE CONTINUOUS X-RAYS FROM SINGLE ELECTRON IMPACTS[1]

By Balebail Dasannacharya
Ryerson Physical Laboratory
University of Chicago

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Abstract

Experiments are described on the polarization of continuous x-rays from targets of aluminum sheets varying in the thickness from 6 to 250×10^{-6} cm. The velocities of the exciting electrons corresponded to voltages from 27 to 57 kilovolts. It was found that the polarization increased exponentially with decreasing thicknesses, suggesting perhaps a nearly complete polarization for a thickness of about 6×10^{-6} cm. The polarization diminished with an increase in the velocity of the exciting electrons.

The theory of the polarization of continuous x-rays developed by Sugiura seems to be in conformity with the experimental results obtained in the experiments described below.

THE old problem of the radiation due to the stoppage of electrons, attacked by Stokes and J. J. Thomson immediately after Röntgen's discovery of the x-rays, was extended by Sommerfeld[2] by the methods of the classical theory. Recently Sommerfeld[3] extended his previous work by applying the mathematical methods of wave-mechanics to cases where the electrons were stopped in a single process (very thin anticathodes).

This new theory was well supported by the measurements of Kulenkampff[4] on the angular distribution of the radiation produced in an aluminum target of thickness 6.5×10^{-5} cm. The intensity in the forward direction of motion of electrons was from these experiments extrapolated to be zero. Duane[5] working with mercury vapour found that the intensities I_l in the forward direction and I_t at right angles were in the ratio of 1 to about 5.5. Defining the percent polarization as $(I_t-I_l/I_t+I_l)\times100$, this might be interpreted as a polarization of 70 percent. Sommerfeld consequently made a generalized assumption according to which only those electron beams emerging from the target with zero velocity should give rise to complete polarization, i.e., the radiation corresponding to the short wave-length limit of the continuous spectrum should be completely polarized.

[1] A short account was given at the Chicago meeting of the American Physical Society, Nov. 27, 1929. Phys. Rev. **35**, 129 (1930).
[2] A. Sommerfeld, Phys. Zeits. **10**, 969 (1909).
[3] A. Sommerfeld, Proc. Nat. Acad. Sci. **15**, 393 (1929).
[4] H. Kulenkampff Ann. d. Physik **87**, 597 (1928).
[5] W. Duane Proc. Nat. Acad. Sci. **14**, 450 (1928).

P. Kirkpatrick[6] calculated from his experiments with a thick tungsten anticathode a polarization of 11 percent for the short wave-length limit with a thick tungsten target. P. A. Ross[7] using a method of balanced double filters obtained nearly complete polarization at the short wave-length limit with a thick tungsten target. Wagner and Ott[8] reflected x-rays coming normal to the direction of the electron stream at the surface of a crystal and observed the intensity of the radiation thus reflected in directions along and at right angles to that of the electron beam. They found a maximum polarization of 47.5 for the short wave-length limit. Thus results so far recorded fail to show any general agreement.

It appeared therefore desirable to make some direct measurements on the polarization of continuous x-rays from thin targets, like aluminum foils of various thicknesses, with electrons accelerated by different potential drops.

Apparatus

An electron stream (see Fig. 1) from a hot spiral cathode fitted with a focussing cup passes through two openings A and B, both of which form a single element and are earthed. The distance between A and B is 5 cm. The

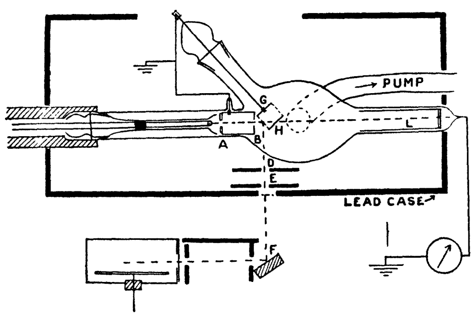

Fig. 1. Diagram of apparatus.

opening A is in the molybdenum disk facing the electron stream. B is in an iron sheet welded into the cylinder which carries the molybdenum. A centimeter behind B the electron beam meets the aluminum foils stretched across two rings G and H. The beam after passing through the aluminum passes without striking the sides of the lower ring H into a hollow cylinder L and through a miliammeter to the earth. Circular openings D and E in lead sheets are so placed and are of such a size as to prevent x-rays formed at B from falling on the graphite block F. The effectiveness of the shielding was tested by observing the effect on the readings of the electrometer when the aluminum foils between G and H were rotated away from the path of the electron beam. Further, when an aluminum foil is in the path of the electron beam, it easily gets punctured at the place where the beam meets the foil. The size of this puncture, about 4 mm in diameter, and the place where it occurs, gives good indication of the path of the beam in the foil system GH.

[6] P. Kirkpatrick, Phys. Rev. **22**, 226 (1923).
[7] P. A. Ross, J. Opt. Soc. Am. **16**, 375 and 433; Phys. Rev. **28**, 425 (1926).
[8] E. Wagner and P. Ott, Ann. d. Physik **85**, 425 (1928).

Pinhole photographs were also made for further confirmation. The openings in the diaphragms in front of the ionization chamber on a Bragg spectrograph were one square centimeter.

In order to avoid charge developing on the inside walls of the x-ray tube, and deflecting the electron beam, the inside surface from A to the end of the tube at L was platinized with platinum paint. Before the paint was heated it was nearly completely removed from that part of the wall through which the x-rays passed to the graphite F, in order to prevent any filtering action of the x-rays by the platinum layer.

The ionization current was measured in a Compton electrometer worked at a deflection of the reflected spot of about 30,000 mm per volt, with the scale at a distance of 2 meters from the mirror. The current from a transformer was rectified through a kenetron before being admitted into the x-ray tube.

Experimental Results

The intensities I_l and I_t of the x-ray beam emerging from the graphite along the direction of the electron beam and at right angles to the same were

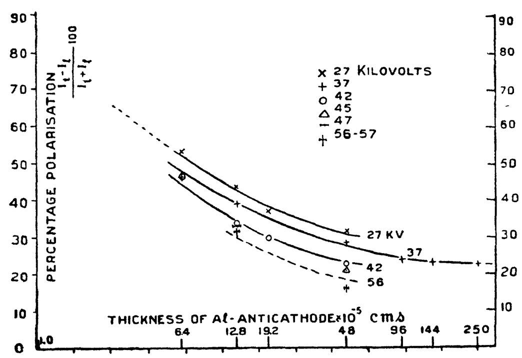

Fig. 2.

measured. Correction due to stray radiation when there was no aluminum foil in the path of the electron beam at C was found negligible. The thickness of the aluminum foils or plates varied from 6.4 to 250×10^{-5} cm. For the thinnest aluminum foil my obligations are due to Dr. Kulenkampff. These foils were stretched between the rings G and H, fastened with a paint made of fine aluminum powder and a little varnish dried over hot air.

The experiments of June 23rd (see Table I) showed that the polarization increased with the diminution of thickness as well as by a diminution of the accelerating voltage of the electrons. The value for 57 KV seems rather too low and that for 45 KV rather too high. The effect of voltage and thickness seems however to be unmistakable. The experiments of October 18 were carried out with one of the thinnest foils used previously, nearly 48.0×10^{-5} cm, and three others. The effects of voltage and thickness (see Fig. 2) are here more clearly marked.

A rough extrapolation for smaller thicknesses indicates that complete polarization may result for a thickness of about 6×10^{-6} cm. This thickness

TABLE I.

Date	Accelerating potential in kilovolts.	Thickness of the aluminum plates, in 10^{-6} cm	Percentage polarization $(I_t-I_l)/(I_t+I_l)\times 100$
June 23, 1929	37 ...	250 ...	... 22.2
		144 ...	... 22.3
		96 ...	... 23.7
		48 ...	... 28.5
	45 ...	48 ...	... 26.3
	57 ...	48 ...	... 16.3 (?)
Oct. 18, 1929	27 ...	48 ...	... 31.5
		19.2 ...	... 37.1
		12.8 ...	... 43.5
		6.4 ...	... 53.0
	37 ...	12.8 ..	... 39.0
		6.4 ...	... 46.2
	42 ...	48.0 ...	... 22.5
		19.2 ...	... 29.8
		12.8 ...	... 33.8
		6.4 . .	... 46.7
	56 ...	12.8 . .	... 31.5
	47 ...	12.8 . .	... 33.0

happens to be about the same as that (4×10^{-6} cm) for which the electron keeps its initial direction of motion, as calculated from theories of the diffusion of electrons through matter[9] for an average accelerating potential of 34 KV. According to the diffusion theory, however, the length of path along which the electron keeps its initial direction should increase with increase in speed, which would mean greater polarization for greater electron speeds. Since this is contrary to the results of the present experiments, it would appear that the approximate agreement between the length of the undeviated path and the thickness for complete polarization is probably fortuitous.

According to Sugiura,[10] who has recently developed a theory of the production of continuous x-rays somewhat on the lines followed by Sommerfeld, one should expect that the polarization at right angles to the direction of motion of the electron beam even for vanishing thickness of the target to be incomplete. The polarization should be greater for rays corresponding to electrons of smaller speed, a result which is in keeping with the findings of our present experiment.

It is interesting to note that Kulenkampff[11] has recorded a value of 45 percent for the polarization with electron beams of 36 KV presumably for the thickness of aluminum the same as the least one in our present experiment.

[9] Handb. d. Exptl. Physik, Kathodenstrahlen by Lenard and Becker pages 333, 379. Akad. Verl. Buchh., Leipzig, 1927.

[10] Sugiura Sci. Papers I. P. C. R. **11**, 251–290 (1929).

[11] H. Kulenkampff, Phys. Zeits. **30**, 513 (1929).

Our value for the same is 47.5, within errors of experiment the same as the value obtained by Kulenkampff.

Duane[12] did not find any great difference between the polarizations with jets of mercury vapour as anticathode, the density of the vapour being varied from one to four. On an average the polarization decreased from 51.4 to 48.6, a result not contradicting our own findings, though Duane is inclined to believe that the difference perhaps is not very much greater than the experimental errors. Secondly, it may be that in Duane's experiment we are nearly at the maximum of polarization; or it may also be that in the case of mercury the change of polarization with thickness is small. Thirdly, a comparison of Duane's value (taking it to be nearly the maximum for mercury) with our own for Al extrapolated to smaller thicknesses than actually used, would lead us to suppose that an increase in the atomic number of the anticathode would result in a decrease in the polarization.

This last result as well as results of Duane just referred to would be hard to reconcile with the almost perfect polarization obtained by Ross[13] with his double filter method, and using thick tungsten as anticathode. Perhaps the balancing of Ross's filters, which may have been perfect, or the error in the same inappreciable, when the differences are large, would cease to be so when the difference to be obtained is about of the order of the inaccuracy. As against Ross,[7] Wagner and Ott[8] using platinum as anticathode could get only 47.5 as the polarization for the short wave-length limit.

A Rough Picture of the Production of Polarization in Continuous X-Rays

The polarization may depend on the following:

(1). Initial direction of the impinging electron.

(2). Its final direction, and probably also on,

(3). The atomic number of the material of the anticathode, and

(4). Electron configuration round the nucleus.

If the energy of the impinging electron is completely utilized in the production of the continuous x-ray, as would be the case for radiation at the short wave-length limit of the spectrum, and consequently (2) is negligible and if (3) and (4) should happen to be negligible too, the polarization may be complete. On the other hand, as we come to frequencies smaller than the limiting one, we may think of them as being produced by electrons leaving the atom with appreciable speeds in directions which however are arbitrary. Consequently (2) becomes increasingly appreciable so that the electric vector would deviate progressively from the initial direction. If we are to account for more complete polarization for smaller velocities, we have to assume that the probability is greater that an electron of a smaller speed would emerge from the atmosphere of an atom with comparatively greater loss of energy.

I wish to thank Professor A. H. Compton for suggesting the problem, for his continued encouragement and for his kindness in permitting me to work in his laboratory as a visiting foreign guest of the University.

[12] W. Duane, Proc. Nat. Acad. Sci. **15**, 805 (1929).

[13] P. A. Ross, J. Opt. Soc. Am. **16**, 375 and 433. Phys. Rev. **28**, 425 (1926)