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The Polarization of General X-Radiation from Thick Targets

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The method applied in this experiment is that of 90° scattering combined with the balanced filter method. Bands of the x-ray spectrum between the *K*-absorption limits of molybdenum and columbium, of palladium and rhodium and of tungsten and tantalum, from targets of tungsten, copper and aluminum have been tested for polarization, using potentials from about 20 kilovolts to 100 kilovolts. Besides the confirmation of the previous experimental results[1] about the relation between polarization and voltage and the relation between polarization and wave-length, two other points have been demonstrated more quantitatively. First, while the maximum experimental value of polarization was not over 60 percent, the polarization at the quantum voltage of the band by extrapolation is nearly complete for all targets and all wave-length bands. Second, the polarization of x-rays of a given wave-length from targets of lower atomic number is higher than that from targets of higher atomic number, except near the quantum voltage where they approach 100 percent.

INTRODUCTION

THE experiments on x-ray polarization date back to 1896,[2] one year after the discovery of x-rays. The first systematic study was made by Barkla[3] in 1905, following which Haga,[4] Herweg,[5] Bassler,[6] Vegard[7] and Ham[8] worked on the problem. These investigations all showed definite polarization in continuous x-ray spectra. Later Kirkpatrick[9] found that the polarization increased approximately linearly with decrease of wave-length for x-rays emitted at constant voltage but even at the short wave-length limit, the polarization was still far from complete. These results partially confirmed the classical electromagnetic pulse theory.[10] From the standpoint of radiation quanta, Bubb[11] predicted partial polarization of x-rays of all wave-lengths but a greater polarization for rays of shorter wave-length. Sommerfeld[12] by the application of wave mechanics, at first obtained the general conclusion that at the short wave-length limit there should be complete polarization, but later concluded that at this limit, the polarization should not always be complete but should vary for spectra produced at different voltages.[13] According to the theory of Sugiura[14] the polarization cannot be complete, even at the quantum

[1] P. A. Ross, J. O. S. A. and R. S. I. **16**, 375 (1928). H. Kulenkampf, Phys. Zeits. **30**, 513 (1929).
[2] J. W. Gifford, Nature **54**, 172 (1896).
[3] C. G. Barkla, Phil. Trans. Roy. Soc. **A204**, 467 (1905); Proc. Roy. Soc. **A77**, 247 (1906).
[4] H. Haga, Ann. d. Physik **23**, 439 (1907).
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[12] A. Sommerfeld, J. Frank. Inst. **208**, 571 (1929); Proc. Nat. Acad. Sci. **15**, 393 (1929).
[13] A. Sommerfeld, Ann. d. Physik **403**, 257 (1931).
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limit, the possible maximum polarization being about 85 percent.

Unfortunately experimental results in recent years have also shown great variation. Ross[1] found that the polarization of a fixed wave-length from a thick target increased as voltage decreased. The curve of polarization against voltage indicated complete polarization at the short wave-length limit. Kulenkampf[15] obtained a similar relation with a thin aluminum target. Wagner and Ott[16] found no indication of high polarization toward the quantum voltage of a band, the maximum polarization obtainable being below 50 percent. Also no variation of polarization with atomic number could be demonstrated. Duane[17] using a mercury vapor target and Dasanachyra[18] using thin aluminum, both obtained maximum average polarizations less than 50 percent for different wave-lengths.

The lack of good agreement either between theory and experiment or between the results of different experiments necessitates the present research which, following the preliminary experiment of Ross with several modifications, investigates the state of polarization of different spectral bands and of the radiation from different target materials. It also investigates the relation between polarization and the exciting voltage and the question of the completeness of polarization at the short wave-length limit.

Apparatus and Procedure

The general arrangement of apparatus for this research is shown in Fig. 1. A glass x-ray tube, together with its pumping system was mounted on a frame fastened to a stand which was free to rotate about a vertical axis and which could be moved in both longitudinal and transverse directions. When the frame was loosened, the tube also could be adjusted in these two directions with respect to the stand. The cathode could be adjusted horizontally and vertically without breaking the vacuum of the tube in the manner described by Webster.[19] The target

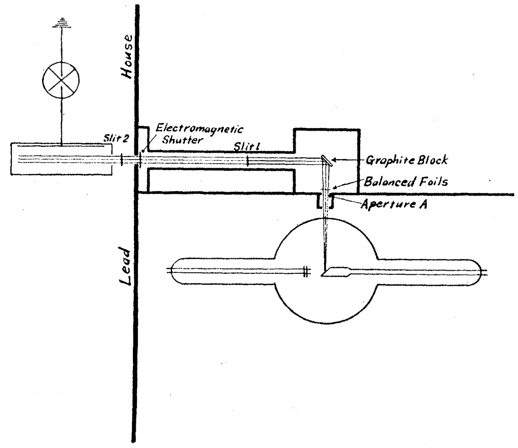

Fig. 1. General arrangement of apparatus for the study of polarization.

surface was inclined 45° to the cathode-ray stream. The focal spot of the target was set accurately on the axis of rotation with the aid of x-ray pinhole photography.

The primary radiation passed vertically through an aperture A and was scattered by an analyzing graphite block inclined at 45° to the vertical. In the case of the tungsten target the aperture A was circular, with a diameter of 0.5 cm, but in order to get sufficiently intense scattered beams from the copper and aluminum targets while preserving 90° scattering, a rectangular aperture of 0.5 cm wide and 4 cm long in a direction normal to the plane of scattering was used. The maximum deviation from 90° scattering was less than $\pm 0.5°$. A lead collimating system between the tube and the aperture A prevented x-rays from the target stem from striking the scattering block. A pair of balanced foils was mounted on a carrier above the aperture so that either foil might be slid into position by means of a pulley system controlled from outside of the lead house indicated in Fig. 1. Besides the slit window on the lead house, the two other horizontal slits shown in Fig. 1 were placed in the path of the secondary rays. As the slit aperture on the lead wall was horizontal, the electromagnetic shutter had to open and close vertically so as to insure uniformity of exposure for ionization. This shutter, equipped with suitable counterweights, was operated by impulses from a standard laboratory clock through a selector clock which automatically counted the

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TABLE I. *Polarization of Pd-Rh band from W-target.*

			$I_\perp$ 0°			$I_\perp$ 180°				$I_{\parallel}$ 90°			$I_{\parallel}$ 270°				
kv	m.a.	sec.	Pd	Rh	diff.	Pd	Rh	diff.	Mean diff.	Pd	Rh	diff.	Pd	Rh	diff.	Mean diff.	Percent P
23.7	12	60	512.2	494.8	17.4	515.0	497.0	18.0	17.7	368.2	362.6	5.6	364.6	357.4	5.2	5.4	53.3
24.0	12	60	556.6	519.4	37.2	561.0	525.0	36.0	36.6	417.5	403.3	14.2	415.8	401.2	14.6	14.4	43.5
24.5	12	60	626.4	561.5	64.9	632.0	566.4	65.6	65.3	490.0	455.8	34.2	486.6	453.4	33.2	33.7	32.0
25.0	12	60	664.2	581.0	83.2	667.4	585.6	81.8	82.5	521.4	473.7	47.7	519.3	471.0	48.3	48.0	26.4
25.5	12	50	661.3	578.8	82.5	666.9	584.8	82.1	82.3	532.0	478.9	53.1	531.0	478.5	52.5	52.8	21.8
26.0	12	40	590.3	512.6	77.7	596.3	516.2	80.1	78.9	470.0	415.9	54.1	467.6	412.9	54.7	54.4	18.4
27.0	12	36	610.9	520.8	90.1	617.3	529.2	88.1	89.1	518.6	451.9	66.7	510.8	443.5	67.3	67.0	14.2
28.0	12	30	572.2	478.4	93.8	577.2	483.2	94.0	93.9	468.8	394.8	74.0	460.8	386.0	74.8	74.4	11.6
30.0	11	30	682.3	571.0	111.3	689.3	574.4	114.9	113.1	581.2	485.7	95.5	574.8	479.1	95.7	95.6	8.36
32.0	9	30	711.0	592.8	118.2	718.9	598.6	120.3	119.3	619.0	514.8	104.2	614.8	510.2	104.6	104.4	6.67
35.0	9	20	635.5	529.4	106.1	639.2	531.8	107.4	106.8	559.0	461.5	97.5	558.4	459.7	98.7	98.1	4.24
40.0	7	16	627.9	533.4	94.5	633.9	540.0	93.9	94.2	560.4	469.9	90.5	555.8	466.1	89.7	90.1	2.22
45.0	5	16	659.4	577.0	82.4	665.4	580.4	85.0	83.7	595.8	513.8	82.0	591.2	510.4	80.8	81.4	1.39

proper time of exposure and made the opening and closing switch contacts. In order to eliminate scattering by air as much as possible, the scatterer, the slit system and the shutter were screened by lead tubes and boxes.

Since the high voltage d.c. source has been described elsewhere,[20] it should be sufficient to say that it was a 500 cycle, kenotron rectified, full-wave high voltage outfit producing potentials up to 100 kv with a ripple of only about 4 volts at 10 m.a. The voltage was measured by the electrostatic voltmeter described by Clark.[21] It was calibrated by comparison with the voltage drop across a 6 megohm resistance.

The large ionization chamber was filled with methyl bromide at a pressure of 51 cm Hg. Ionization currents were read by means of a modified Compton electrometer at a sensitivity of 6000 scale divisions per volt. The linearity of the scale was checked by potentiometer measurements. Natural ionization was compensated for by a radioactive leak.

Polarization data were obtained by alternating the balanced foils in the path of the primary x-rays when the tube was set in a position with the cathode rays perpendicular to the scattering plane. The mean of a set of readings for each foil was computed and the difference of the two means for both foils calculated. The tube was then turned 180°. The readings were repeated and the mean of each set of readings and the difference of the two means were again calculated. The average of the two differences was then taken as the measure of the component of primary radiation of the spectrum band between the two K-absorption limits of the balanced foils with electric vector parallel to the cathode rays. Similar measurements were then made of the component of the same band with electric vector perpendicular to the cathode rays.

DATA AND CALCULATIONS

The polarization was calculated by the formula

$$P=(I_\perp-I_{\parallel})/(I_\perp+I_{\parallel}),$$

in which $I_\perp$ is the electrometer deflection observed with the cathode rays perpendicular to the scattering plane and $I_{\parallel}$ is the deflection with the cathode rays parallel to the scattering plane. For illustration, values of polarization and of intensities $I_\perp$ and $I_{\parallel}$ for the tungsten target at various voltages and for the palladium-rhodium spectrum band are given in Table I.

In this table, each datum is the average value of at least five readings. In data of other targets, ten readings were usually taken. The 0°, 180°, etc., are some arbitrary marks on the graduated circle of the stand of the x-ray tube, indicating the position of the tube.

Due to the low intensity of the radiation from the aluminum target, the Pd-Rh and Mo-Cb spectrum bands which have low corresponding quantum voltages could not be tested. Instead the W-Ta band was used. In experiments on this band, voltages higher than 100 kv were not tried in order to avoid the danger of puncturing the glass of the tube.

Fig. 2 and Fig. 3 show the graphs of polarization against voltage. Pairs of dotted lines show

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[21] H. Clark, Rev. Sci. Inst. **1**, 615 (1930).

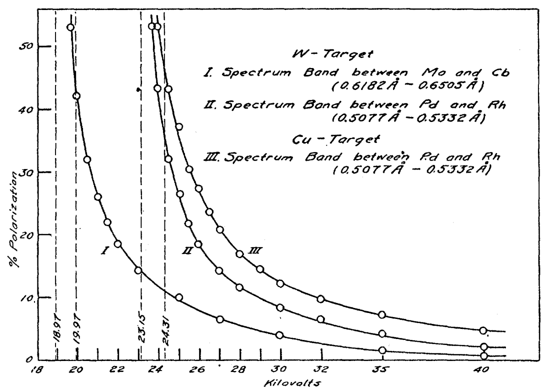

FIG. 2. Polarization of general x-radiation as a function of voltage.

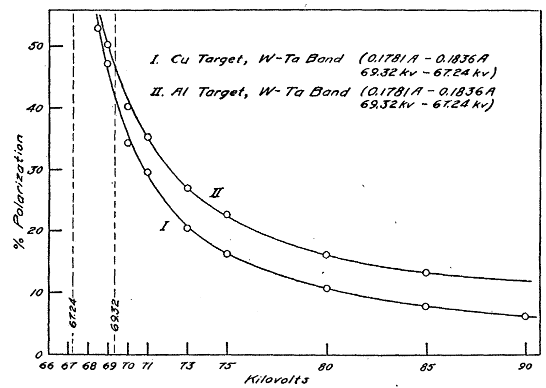

FIG. 3. Polarization of general x-radiation as a function of voltage.

the region of voltage corresponding to the wave-length of the two sides of each band. In Fig. 4 the graphs show the values of polarization for different targets and different spectrum bands against V/V_q, where V is the tube voltage and V_q is the quantum voltage of the band. In this way all the curves are shown on the same scale. By the quantum voltage of each band we here mean the quantum voltage of the edge of the band on the long wave-length side.

The largest experimental values of polarization are not over 60 percent. Since the actual functional form of these curves (Fig. 4) is unknown, the exact extrapolation to the quantum voltage of the band is not possible. Such extrapolation is facilitated however by the fact that the graph of $1/P$ against V' is nearly linear. The most probable representative line for this graph can be determined by the application of least square formulas[22] and the most probable value of polarization corresponding to the quantum voltage of the band in question and the probable error of the same can be computed from the value of y at $x=0$. The results of these calculations are given in Table II.

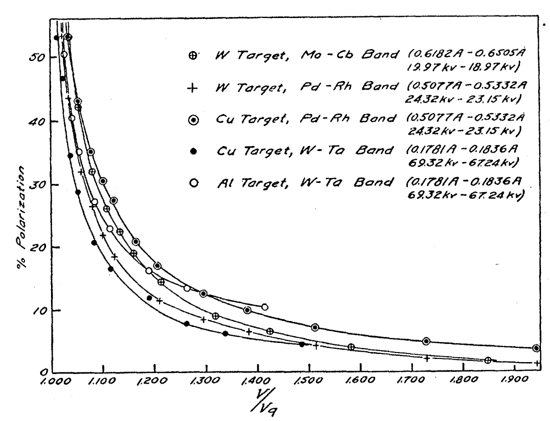

FIG. 4. Polarization of general x-radiation as a function of v/vq.

TABLE II. *Polarization at short wave-length limit by least squares extrapolation.*

Target	Spectrum band	Percent Polarization
Tungsten	Molybdenum and columbium	96.24 ± 4.76
Tungsten	Palladium and rhodium	100.95 ± 6.66
Copper	Palladium and rhodium	94.63 ± 3.41
Copper	Tungsten and tantalum	98.36 ± 3.18
Aluminum	Tungsten and tantalum	97.51 ± 2.33

If one assumes that the value of polarization at the short wave-length limit should be the same for all targets, one can calculate the weighted mean of polarization and its probable error to be 97.165 ± 0.529 percent by assigning a weight proportional to the inverse of the square of the probable error to each value of polarization shown in the above table.

Fig. 5 shows the graph of $1/P'$ against V'. The points are calculated values while straight lines are least square reductions. It is to be noted that a few points near the high voltage end (not shown in the graphs) of the tungsten and copper curves have been rejected in the calculation by least squares, because they do not fall on a straight line very closely. On the whole the

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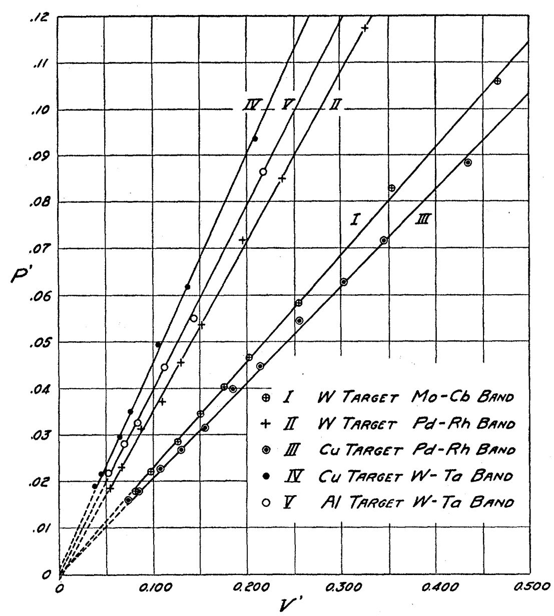

FIG. 5. Graphs for the extrapolation of polarization to the short wave-length limit. *Note:* The ordinates in this figure are $1/P'$ not P' as shown on the axis.

points in each graph lie fairly well on a straight line showing no consistent indication of curvature. One may therefore place considerable confidence in the method used and the value of polarization deduced.

DISCUSSION AND CONCLUSION

All the curves in Fig. 2 and Fig. 3 indicate clearly that polarization increases as voltage decreases and increases very rapidly as the quantum voltage of the band is approached. This agrees with both classical and recent theories and also agrees with Ross', Kulenkampf's and Dasanachyra's experimental results.

From the comparison of the curves I and II in Fig. 2 it can be seen that in the continuous spectrum of the same target (tungsten) at a constant voltage, for instance 27 kv, the polarization of the Pd-Rh band is higher than that of Mo-Cb band. That is, in any one continuous spectrum, the polarization of the band of shorter wave-length is higher than that of longer wave-length. This has been predicted by classical and recent theories and has been shown by previous experiments using the method of filtering out the longer wave-length.

In Fig. 2 curves II and III show polarization for the same Pd-Rh band from targets of tungsten and copper, respectively. It is evident that with the same voltage, polarization is always higher for copper than for tungsten. Also in Fig. 3 the two curves for W-Ta band from copper and aluminum targets indicate that with the same voltage, the polarization for aluminum is higher than that for copper. From these results, one may therefore conclude that the polarization of x-rays from elements of lower atomic number is higher than the polarization of x-rays from elements of higher atomic number. This result is in fact required by the wave-mechanical theory developed by Sommerfeld although it does not check with the experimental work of Wagner and Ott.

The result shown in Table II gives some evidence that at the short wave-length limit, the polarization of x-rays is nearly complete for all targets and all wave-length bands. This confirms the results of Ross and Kulenkampf in a more quantitative way.

In conclusion, the writer wishes to express his gratitude to Professor P. A. Ross under whose direction this work was carried out; to Professor P. Kirkpatrick for his frequent and valuable advice and to Professor D. L. Webster for his helpful suggestions.