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TEMPERATURE AND THE COMPTON EFFECT

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Abstract

The intensity of x-rays diffusely scattered by crystals should increase with the temperature according to Debye. It is to be expected that these scattered rays of Debye would be unmodified. Hence the ratio of modified to unmodified rays may decrease with the temperature. Debye's argument applies to powdered crystals and therefore to so-called amorphous substances. The effect of temperature on this ratio has therefore been examined. Using DeFoe's method an aluminum absorbing sheet was transferred from the primary to the scattered beam and the ratio of the two ionization currents found at temperatures of −140°C, 25°C and 565°C. Wave-lengths ranging from 0.32A to 0.62A were scattered by carbon at angles of 60°, 75° and 90°. Also x-rays were scattered from aluminum and copper at angles of 90° and 130°. In each case the difference between the ratios at the different temperatures was not greater than the probable error, implying that there is no effect of temperature on the ratio of modified to unmodified rays in the Compton effect.

1. Introduction

Debye[1], Waller,[2] and Waller and James[3] have shown that a decrease of the intensity of x-rays regularly reflected from crystals with increase of temperature is to be expected. This expectation has been realized in the experiments of Bragg,[4] Backhurst,[5] James and Firth[6] and others. Debye's theory further requires that the regular reflection from crystals should be accompanied by diffuse scattering at all angles and that the intensity of the diffusely scattered rays should increase with increase of temperature. This question of the increase of the intensity of the diffusely scattered x-rays was examined experimentally by Jauncey,[7] who found that the intensity varied much more slowly with the temperature than predicted by Debye's formula. Jauncey[8] also found that the diffusely scattered rays were softer than the

[1] P. Debye, Ann. d. Physik **43,** 49 (1914).
[2] I. Waller, Zeits. f. Physik **17,** 398 (1923).
[3] Waller and James, Proc. Roy. Soc. **A117,** 214 (1927).
[4] W. H. Bragg, Phil. Mag. **27,** 881 (1914).
[5] I. Backhurst, Proc. Roy. Soc. **A102,** 340 (1922).
[6] James and Firth, Proc. Roy. Soc. **A117,** 62 (1927).
[7] G. E. M. Jauncey, Phys. Rev. **20,** 421 (1922).
[8] G. E. M. Jauncey, Phys. Rev. **20,** 405 (1922).

primary rays and therefore probably consisted of both unmodified and modified rays. Since the intensity of the diffusely scattered rays varies more slowly with the temperature than predicted by Debye's theory, it might be supposed that these rays consist of two parts: one part whose intensity depends on the temperature according to Debye's formula and a second part whose intensity is either independent of the temperature or varies with the temperature in a different way from that required by Debye's formula. It is not unreasonable to suppose that the first part consists of unmodified rays, because this part is explained on the principles of the classical theory; and that the second part consists of modified rays. If this is so, the intensity of the unmodified rays should increase with temperature. Just how the intensity of the modified rays should vary with the temperature is uncertain. Since the modified rays are scattered mainly from the loosely bound electrons, and since it is possible that the number of these electrons is constant with the temperature or, at any rate, varies in a different way with the temperature from Debye's formula, the intensity of the modified rays should vary differently with the temperature than should the intensity of the unmodified rays. It is to be expected, therefore, that the ratio of the intensities of the modified and unmodified rays scattered at a given angle by a crystal will depend on the temperature of the crystal.

It is known that many solid substances such as aluminum consist of minute crystals and therefore act towards x-rays as powdered crystals. Collins[9] has shown that the intensities of the powdered crystal spectrum lines produced by a sheet of aluminum vary qualitatively with the temperature according to Debye's formula. Hence it would seem that the ratio of the intensities of the modified and unmodified scattered x-rays in the Compton effect should vary with the temperature. The present research was therefore undertaken, and we have examined the effect of varying the temperature from $-140°C$ to $565°C$ on this ratio for carbon, aluminum and copper as the scatterer.

2. Apparatus and Experimental Method

The source of voltage consisted of two motor-generator sets. The first set comprised a 3 phase, 60 cycle, 220 volt induction motor, which was driven by the local power supply, and a 110 volt d.c. generator with a voltage regulator connected to the field coils. This steady d.c. voltage was then applied to the d.c. motor of the second motor-generator set, the a.c. generator of which supplied very constant 110 volt, single phase current to the primary coil of the x-ray transformer. The high voltage applied to the x-ray tube was rectified by means of a kenotron. With this arrangement it was found that the rate of radiation from the x-ray tube remained remarkably constant.

The method of obtaining the ratio of the modified to the unmodified intensities was similar to that used by De Foe[10] with the exception that a direct deflection instead of a balance method was used. Referring to Fig. 1, the x-rays entered the heating, or cooling, chamber C through a thin mica window. The x-rays were then scattered by a block of the scattering sub-

[9] E. H. Collins, Phys. Rev. **24**, 152 (1924).

stance placed in the position AA or BB. The scattered rays passed out through a second mica window in the chamber C and thence to the ionization chamber D. The method consists of placing a certain thickness of aluminum absorber at P and noting the ionization current I_P, and then transferring this absorber to Q and noting the ionization current I_Q. If the scattered rays contain any modified rays, I_Q will be less than I_P and the ratio I_P/I_Q will be greater than unity. The value of I_P/I_Q then gives a measure of the percentage of the total scattered radiation which is modified. Knowing I_P/I_Q, the thickness transferred, the wave-length, and the angle of scattering, De Foe calculated this percentage by means of a formula developed by Jauncey and De Foe.[11] However, this formula is based on the assumption that the modified rays are all of the same wave-length whereas it has been pointed out by Jauncey[12] that the modified line has a width. Also, more recently, it has been

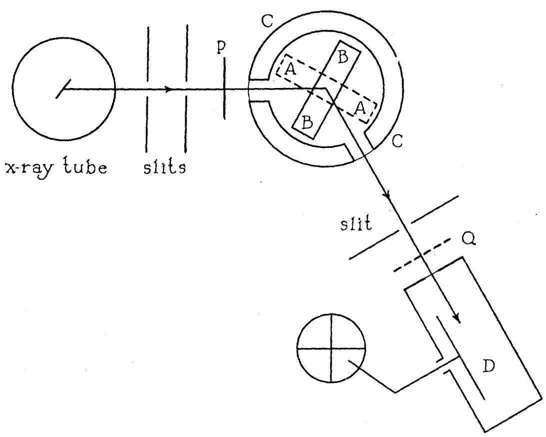

Fig. 1. Diagram of apparatus.

shown by Du Mond[13] and Davis and Purks[14] that the modified line has a structure. The formula of Jauncey and De Foe is therefore only an approximation and in this paper we shall content ourselves with finding the values of I_P/I_Q for given angles of scattering and given wave-lengths for three different temperatures of the scatterer and comparing the values for the different temperatures.

The heating chamber, or furnace consisted of an iron cup packed in asbestos. Imbedded in the asbestos was a heating coil of iron wire. The temperature inside the furnace was measured by placing a thermocouple just behind the scattering block. The furnace was heated for 60 minutes before readings were taken of the scattered x-rays. The temperature attained was 565°C.

The cooling chamber, or refrigerator, consisted of a copper cylinder of 2 in. diameter and 5.5 in. height. A cavity of 1.5 in. depth and 1.25 in. diameter

[10] O. K. DeFoe, Phys. Rev. **27,** 675 (1926).
[11] Jauncey and DeFoe, Phil. Mag. **1,** 714 (1926).
[12] G. E. M. Jauncey, Phys. Rev. **25,** 314 (1925).
[13] J. W. DuMond, Phys. Rev. **33,** 643 (1929).
[14] Davis and Purks, Phys. Rev. **33,** 1089 (1929).

was drilled in the top end of the cylinder. Windows at angles of 0°, 60° and 90° were drilled in the sides of the cup and a copper stopper screwed down a distance of 0.375 in. into the cup. The lower end of the copper cylinder dipped into liquid air which was contained in a Dewar flask. The upper part of the cylinder except for the windows was covered with felt. In order to prevent the deposition of frost on the mica windows, each mica window, which was on the outside of the felt, was surrounded by an iron wire which could be heated by means of an electric current. The temperature inside the cavity was determined by means of a thermocouple while the lower end of the cylinder was in the liquid air and the wires around the windows were being heated and was found to be -140°C.

Separate experiments were made with the furnace and with the refrigerator. In each case a set of readings was taken at room temperature (about 25°C), a second set at 565°C or -140°C according as the furnace or the refrigerator was used and a third set at room temperature again. The time between two successive sets was about an hour so as to give the scatterer time to come to a steady temperature. Each set of readings consisted of 8 readings of the ionization current with the aluminum absorber at P and 8 readings with the absorber at Q (see Fig. 1), the readings in the two positions being alternated. Since it is the ratio I_P/I_Q which is important and not the absolute values of I_P and I_Q it is seen that the only thing which can cause a difference in the ratio if the wave-length and angle of scattering are kept constant is the temperature. It was found to be unnecessary to correct for a leak because when the scatterer was removed from the furnace or refrigerator the ionization current was negligible.

In order to keep any characteristic radiation from entering the ionization chamber the thickness of the aluminum window of this chamber was 0.045 cm. The wave-length of the x-rays was determined as follows: The thickness of aluminum which was transferred from P to Q was placed at P and the ionization current measured. Additional thickness of aluminum was placed at P until the ionization current was reduced to half value. From this additional thickness the average absorption coefficient was found and the average wave-length determined from Compton's tables.[15]

3. Experimental Results

The experimental results are shown in Table I. Average wave-lengths are shown in the third column and the thickness of aluminum transferred from the P position to the Q position of Fig. 1 is shown in the fifth column. In the sixth, seventh and eighth columns are shown the values of I_P/I_Q for the temperatures of -140°C, 25°C and 565°C respectively. In the fourth column are shown the fractions of the respective beams of x-rays which consist of modified rays. These values are calculated by Jauncey and De Foe's formula[11] from the mean of the two or three values of I_P/I_Q. As pointed out previously, however, the formula is only approximately correct. These values are given so as to give some idea of the proportion of modified rays. In some cases our values of the proportion agree with the values given in De Foe's paper while in others there is considerable disagreement. We believe, however, that, due

[15] A. H. Compton, X-Rays and Electrons, p. 184.

TABLE I. *Values of I_P/I_Q at different temperatures.*

Substance	Scattering angle	λ A	Proportion modified rays	d cm	I_P/I_Q −140°C	I_P/I_Q 25°C	I_P/I_Q 565°C
Carbon (graphite)	60°	0.35	0.86	0.334	1.050	1.052	1.049
		.42	.77	.334	—	1.070	1.073
		.48	.74	.334	1.091	1.092	—
		.58	.63	.083	1.027	1.023	1.022
	75°	.46	.72	.334	—	1.121	1.119
		.58	.71	.166	—	1.086	1.084
		.62	.64	.083		1.044	1.048
	90°	.49	.83	.334	1.197	1.200	1.195
		.52	.77	.334	1.222	1.218	—
		.58	.76	.334	1.065	1.064	—
		.58	.76	.166	—	1.128	1.129
		.62	.76	.166	—	1.157	1.159
Aluminum	90°	.32	.58	.334	1.057	1.058	1.056
		.36	.55	.334	1.067	1.066	—
		.41	.52	.334	1.082	1.080	1.083
	130°	.37	.73	.334	—	1.159	1.157
		.45	.63	.334	—	1.198	1.202
		.50	.62	.083	—	1.069	1.064
Copper	90°	.33	.64	.334	1.072	1.066	1.064
		.36	.57	.334	1.070	1.070	1.066
		.42	.54	.334	1.095	1.093	1.097
	130°	.30	.64	.334	—	1.110	1.104
		.41	.60	.334	—	1.147	1.144

to our steady source of voltage, our values are more reliable than De Foe's values. It is necessary that the proportion be less than unity. We have obtained several values of I_P/I_Q for the case where all of the rays were of the modified type. No change of I_P/I_Q with change of temperature was observed. These values, however, are not recorded because no change of I_P/I_Q should be expected.

4. Discussion

If the values in the last three columns of Table I are examined it will be seen that these values change very little with the temperature. Such changes as are shown are mostly within the probable error which was found to be about 0.004. If the values of I_P/I_Q for carbon are examined it will be seen that, comparing the values in the sixth with those in the seventh column and also the values in the seventh with those in the eighth column of Table I, there are seven small increases and eight small decreases with increase of temperature. For aluminum there are three increases and five decreases with increase of temperature. Hence it may be concluded that there is no change in the ratio of modified and unmodified scattering for a temperature range of −140°C to 565°C.

In the case of copper, there may be a slight decrease of I_P/I_Q with rise of temperature as there is only one increase, one no change and six decreases with rise of temperature. Even in the case of copper, however, the differences are about the size of the probable error and so there may be no effect due to temperature. At the temperature of 565° the copper becomes coated with a scale of oxide and this may explain the preponderance of decreases because at the cold temperatures the scattering is done by copper whereas at the high temperature the scattering is partially done by copper oxide. It may, therefore, be safely concluded that the copper shows no change in the ratio of modified to unmodified scattering for the above temperature range.

The characteristic temperatures[16] for carbon (graphite), aluminum and copper as calculated from their densities and compressibilities are 1600°K, 396°K, and 309°K respectively. According to Debye,[1] the intensity of the x-rays diffusely scattered by a crystal is proportional to $(1-e^{-M})$ where M is a function of the temperature of the crystal, the characteristic temperature of the crystal and other quantities. If zero-point energy is assumed the function M is different from the case where no zero-point energy is assumed. The values of $1-e^{-M}$ have been calculated and are shown in Table II.

TABLE II. *Diffuse scattering from crystals.*

Substance	Scattering angle	Wave-length	$1-e^{-M}$					
			No zero-point energy			Zero-point energy		
		A	−140°C	25°C	565°C	−140°C	25°C	565°C
Carbon (graphite)	60°	0.32	0.017	0.079	0.375	0.323	0.362	0.564
		.58	.005	.025	.131	.113	.131	.221
	75°	.46	.012	.057	.236	.244	.274	.375
		.62	.006	.032	.173	.131	.156	.281
	90°	.48	.014	.069	.343	.274	.323	.523
		.62	.009	.043	.221	.189	.213	.356
Aluminum	90°	.32	.573	.939	1.000	.883	.983	1.000
		.41	.405	.817	.997	.727	.918	.998
	130°	.37	.632	.966	1.000	.928	.993	1.000
		.50	.435	.849	.998	.763	.936	1.000
Copper	90°	.32	.498	.866	1.000	.753	.939	1.000
		.43	.316	.686	.980	.537	.788	.986
	130°	.30	.725	.980	1.000	.925	.995	1.000
		.41	.498	.871	1.000	.753	.935	1.000

It is the opinion of the authors that the unmodified x-rays should be made up at least partially of the diffuse crystal scattering as predicted by Debye. If this is the case then the values of $(1-e^{-M})$ show that there should be a large variation in this diffuse crystal scattering with the temperature when there is no zero-point energy and a smaller but still considerable variation when there is zero-point energy. We should, therefore, expect to find a considerable variation of the ratio of the intensities of the modified and unmodified rays in the temperature range of our experiments. Our experiments, however, show no detectable variation and we are led to conclude that the diffuse scattering from crystals does not obey the formula developed by Debye.

[16] See P. Debye, Ann. d. Physik **43,** 49 (1914) and L. B. Loeb, Kinetic Theory of Gases, p. 385.