ABSORPTION IN THE REGION OF SOFT X-RAYS

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ABSTRACT

Energy of soft x-rays from a tungsten-coated nickel target as a function of potential from 40 to 610 v—Soft x-rays from the target were allowed to fall on a solid solution consisting of $CaSO_4+2$ percent $MnSO_4$. The square of the time of duration of the thermoluminescence produced was assumed to be proportional to the total energy of the x-rays. The results indicate that in the range 40–610 v., the total energy varies approximately as the square of the potential applied to the tube.

Absorption of soft x-rays (40-610 v.) by thin celluloid films.—By interposing a thin celluloid film, about 25 mμ thick, between the target and the thermoluminescent substance, the transmission of the film was measured for various values of the applied potential from 40 to 610 volts. The transmission varied from 0.0 percent at 40 volts (minimum wave-length 310A) to 57 percent at 610 volts (minimum wave-length 20A). The results are in general agreement with the hypothesis that the absorption varies as the cube of the wave-length, that K absorption discontinuities in celluloid occur between 300 and 600 volts and that the x-rays cover a wide spectral region. A photographic method of investigating absorption is also described. The results are fairly consistent with those obtained otherwise but the method suffers from the fact that the photographic plate is not equally sensitive to energy of different wave-lengths.

Absorption of soft x-rays (300-600 v.) in air and H_2.—Computation based on previous measurements give for air values of $\mu/\rho=6.0, 6.25, 7.0, 7.6\times10^3$ at 600, 500, 400, and 300 volts respectively. These figures agree fairly well with those given by Holweck in O_2 and N_2. For H_2 the value of μ/ρ is calculated to be about 1.8×10^4 which is larger than the value given by Holweck and larger than is to be expected from the results for air.

THE absorption of various substances, but especially of thin celluloid films, for soft x-rays was measured by the author[1] in 1914 for the range 300 to 1300 volts, and was found to change little with the voltage. In all cases however, the radiation had to pass through one window-film in addition to the substance whose transmission was being measured, and this made the interpretation of the results doubtful. Later the absorption of films between 30 and 40 mμ thick was measured by an optical method,[2] using the vacuum spectrograph, and it was estimated that from 1700A down to 900A a thin celluloid film transmits from 50 to 20 percent, and below not much over 5 percent. The transmission was followed to about 450A and was thought to extend lower.

[1] Laird, Ann. d. Physik **46,** 105 (1915).
[2] Laird, Phys. Rev. **15,** 543 (1920).

Holweck[3] also measured the absorption of soft x-rays (10.8 to 1230 volts) by films 80 mμ thick using a method similar to the author's, i. e. one in which the radiation had to pass an absorbing window in addition to the film in question. He found the transmission in the Lyman-Millikan region approximately the same as that found by the author by the purely optical method, but his films were thicker. In the region of soft x-rays from 300 volts to 1200 volts he found likewise no substantial change in transmission, and likewise attributed this to the effect of the window. That with this filtering the absorption in this region follows approximately the law $I=I_0e^{-\mu d}$ is shown by the figures in Table I computed from the earlier data.

TABLE I

				Holweck
Thickness:	1.6	0.9	0.3	0.08
I/I_0:	0.17	0.4	0.7	0.92
$(1/d)\log(I_0/I)$:	0.48	0.44	0.52	0.45

On account of the usefulness of these films it was thought desirable to investigate the transmission by a method that would not involve the previous filtering of the radiation

There are difficulties in using the photoelectric method without a window, as seen by the discrepancies in the results of different investigators who have used this method, hence a thermoluminescent method was chosen which seemed likely to give at least a general orientation on the problem. The apparatus is suggested by Fig. 1. A tungsten coil, as used in 100-watt, 110-volt lamps furnished by the General Electric Company, served as cathode and gave ample electron current at from 0.62 to 0.64 amp. heating current. The voltage was furnished by small storage cells and wireless B batteries, and was measured from the negative end of the filament by a Weston voltmeter. The potential drop across the filament was from 8 to 10 volts. The anti-cathode was of nickel, v-shaped. It was placed about 2 mm from the filament cathode and hence was soon covered with a layer of tungsten. To produce the vacuum a diffusion pump, with carbon dioxide cooling, following a Gaede mercury pump with phosphorous pentoxide drying was used. The pressure on the Gaede pump side was from .0008 to .00001 mm Hg as measured while the filament current was on. A channelled metal piece D, with a magnet MM was used to prevent any stray corpuscular radiation from reaching the thermoluminescent substance T. The latter was a solid solution of $CaSO_4+2$ percent $MnSO_4$, well heated, spread on resistance ribbon wire bent to form a plate. It could be

[3] Holweck, Ann. d. physique **17**, 5 (1922).

heated and the thermoluminescence observed *in situ*. This substance was not at all sensitive to the light from the tungsten filament. Exposures up to six hours with the filament lighted gave no effect. In one experiment when a leak suddenly developed during a run, it was noticed that after the short-time luminescence ceased, there persisted a faint luminescence of long duration. This effect was reproduced later when at the end of an experiment air was admitted as a test. The effect was

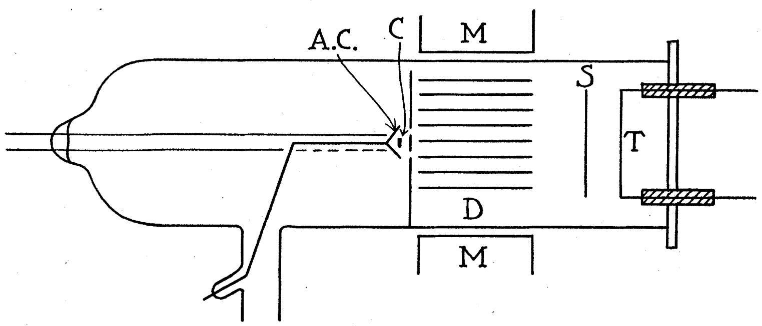

Fig. 1. Diagram of apparatus.

therefore ascribed to a change in the thermoluminescent substance caused by the presence of air or a trace of moisture. In investigations on Entladungsstrahlen it has previously been observed that luminescence may be caused by ordinary light in this same detector when it was insufficiently heated before using.

In front of the thermoluminescent substance was a screen S, with two groups of three openings (see Fig. 2). In the one group 4 and 6 were open while 5 was covered with thin celluloid. In the other, 1 and

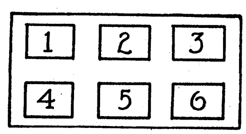

Fig. 2. Diagram of screen.

3 were covered with celluloid and 2 with fluorite. It may be said at once that only once, with 630 volts on the tube, I thought possibly I saw a faint flash of light under the fluorite. After a six-hour exposure at 40 volts there was no visible fluorescence under the fluorite.

It has been estimated in connection with earlier experiments[4] that the square of the time during which the thermoluminescence is visible

[4] Laird, Phys. Rev. **30,** 293 (1910).

is roughly proportional to the total quantity of radiation received, and the results given by C. A. Pierce[5] make this plausible. It is not supposed that this holds exactly, as the times would depend on the threshold of vision, but comparison of the duration of visibility for exposures of different lengths at the same voltage showed that the radiation received is more nearly proportional to the square than to the first power of the time, and this square has been used in computations of transmission.

The procedure was to expose the thermoluminescent substance for a given time to the radiation from the anti-cathode with a given potential difference on the tube and then, with metronome and stopwatch, to measure the time that the luminosity under the holes and under the celluloid lasts. From this the transmission was computed. In observing the thermoluminescence I had the help, on a number of occasions, of Mr. Smyth, curator of the department. We found good agreement in our observations. The results are given in Table II and are, in general, averages of several trials. Two exposures at 40 volts were made, each lasting six hours, the thermoluminescence with no screen lasted 11 sec. but no luminosity was seen under the celluloid. It was thought that a 5 percent transmission should have been visible, but as it would be faint it might have been missed. It is not intended to attach importance to

TABLE II

Transmission of soft x-rays through a celluloid film

Volts on tube	Transmission through thin celluloid	Minimum wave-length	Volts on tube	Transmission through thin celluloid	Minimum wave-length
40	0.00	310A	310	.24	40A
60	.06	206	360	.32	34
75	.06	164	390	.54	32
115	.09	107	480	.46	26
220	.13	56	540	.44	23
270	.11	46	610	.57	20
295	.21	42			

the slightly higher values of transmission given at 220 volts and at 390 volts. In the first case one of four observations was decidedly larger than the others, and in the second only one observation was made. The potential as given is measured to the center of the filament. The last column contains the corresponding minimum wave-length computed in the usual way.

A computation was made of the theoretical absorption of celluloid, assuming it composed of two parts pyroxylin and one part camphor by weight, and also assuming that each atom absorbs independently of the others. The formula

$$\tau a/\rho = .0106(n+.02n_L)N^4\lambda^3$$

was used to compute the coefficient of absorption for the different substances present, where n is zero until the wave-length is reached at which K absorption begins, and then equals two, and n_L is the number of L-electrons per atom. One may suppose that for wave-lengths greater than 50A the absorption for carbon, nitrogen and oxygen is of type L only, and that K absorption has begun for carbon at 40A, for nitrogen at 30A, and for oxygen at 25A. The result of this computation is shown in Table III for a film 100 mμ thick. To find from these figures the effect to be expected in a given experiment, one needs to know the distribution of energy in the spectrum for a given voltage, and

TABLE III

Calculated transmission of a celluloid film, 100 mμ thick

λ in A:	15	20	25	30	35	40	50	60	90	120	150
Transmission:	.90	.78	.61	.71	.64	.51	.79	.67	.26	.04	.002

the variation in sensitiveness of the detector for different wave-lengths. Graphs were made of the Kuhlenkampf equation in the form,

$$E_\lambda = [A(1/\lambda_0 - 1/\lambda) + B]/\lambda^2$$

and then the computed transmission factors were used to draw curves representing the approximate distribution of energy after passing the film. Radiation of wave-length longer than 120A was neglected and uniform energy sensitiveness of the thermoluminescent detector was assumed. The ratio of the areas under the curves then gives the transmission. At 1230 volts this was computed to be 62 percent, at 615 volts 56 percent, a relatively small change, and at 246 volts the transmission would be less than 25 percent, but through a second film would be 50 percent of what had passed the first. It is seen that theoretically, because of (a) the rapidly diminishing factor, λ^3, in the absorption coefficient, combined with the introduction between 40A and 20A of the various K terms, and (b) the integration of the effect over a considerable spectrum range, the result is to produce an absorption of soft x-rays which does not vary greatly in the range considered. It is also seen that theoretically, for voltages above 300, the effect of a celluloid window would be to cut off wave-lengths greater than 90A almost completely, but to transmit the whole range of shorter wave-lengths in the general radiation. Films made from the same solution as used in this work measured 25 mμ in equivalent thickness. When one compares computation and experiment one sees therefore that while the theoretical result is in general agreement in the sense of predicting, for the transmission of general radiation at low voltages, small values, which gradually increase as the voltage increases and then remain approximately constant over a certain range, that the actual absorption is greater than predicted. From Table I one may see that for agreement with the earlier experiments these films should transmit 95 percent of a filtered radiation at 600 volts. While the luminescence at 600 volts is quite strong the total duration under the film is appreciably less than under the free opening, the difference being greater than the figure 95 percent would imply. Any corpuscular rays mixed with the radiation would have the effect of diminishing the apparent transmission, but tests made with the metal carrying the thermoluminescent substance insulated and at positive and at negative potentials showed no difference, hence it is certain that a corpuscular radiation was not involved. This difference between the present and earlier results has been however already explained, at least in part, by the fact that the filtered radiation of the earlier experiments had already lost the easily absorbed part. That the computation describes the phenomenon as nearly as it does is interesting because one could not expect an atomic formula to hold exactly in this region. Holweck[3] made the statement (l. c. p. 37) that a film which transmits 92 percent before the carbon K discontinuity transmits only 9 percent of a radiation of slightly shorter wave-length. He thus accounted for the uniform transmission from 300 volts on by assuming that beyond this potential the window-film transmitted only the same longer wave-lengths. This is evidently not in accord with the facts.

A comparison of the total energy in the radiation at different voltages for the same electron current, as estimated by the thermoluminescence produced, suffers both from the difficulty of estimating quantitatively the thermoluminescence, and the uncertainty as to whether the same proportion of the total radiation is being utilized at different voltages when on account of diaphragms the whole surface of the anticathode does not act as source. In a general way the results would agree with the hypothesis that the energy increases with the square of the voltage, but there is a big scattering of points. The effect of a one-minute exposure at 15 m.a. electron current at 600 volts is about the same as for a five-minute exposure at 300 volts, and is estimated to be more than twice as great as for a six-hour exposure with 4 m.a. current at 40 volts.

As another means of investigating this region of radiation it was thought desirable to try a photographic method. This introduced the

[5] E. L. Nichols and E. Merritt, Studies in Luminescence, p. 91.

difficulty of eliminating effects from direct or reflected filament light, and necessitated the use of a Wehnelt cathode which could be used at a dull red temperature. With this cathode, even when the McLeod gauge between the tube and diffusion pump registered no pressure, one could with rested eye in a dark room usually detect some luminosity in the tube, perhaps on the walls of the glass. The arrangement as finally used was as indicated in Fig. 3, in which *G* is a grid in an opening in a piece of mica, *AC* is the plate serving as source of radiation, *S* is a long tubular slit, *A* is a shelf on which absorbing screens may be placed, *P* is the photographic plate which may be moved along by a ground glass joint. A horseshoe magnet was used to deflect sidewise any corpuscular rays passing down the slit. There were three openings in the screen *A*,

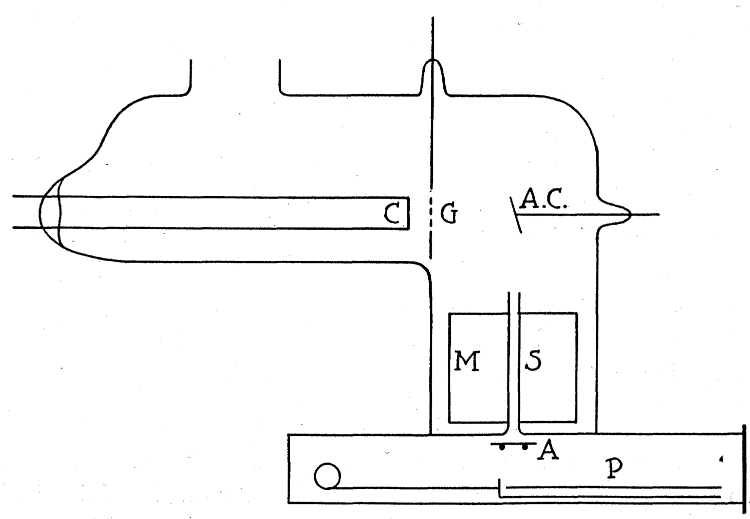

Fig. 3. Arrangement of apparatus for the photographic method.

one was covered with thin quartz, and one with a celluloid film. With this arrangement there was no photographic effect due to the hot filament, but when the potential was applied to the tube slight effects showing the presence of a small amount of ultra-violet light were found at various times under the quartz.

In these experiments liquid air was used on the mercury trap, and after the tube was exhausted, it was run for from one and a half to three hours before the definite exposures were made. The pumps were kept going continuously. Several exposures were made on one plate. The effect of different times of exposure with the same voltage, and of different voltages was thus tested. It was at once apparent that the photographic effect did not increase with voltage so rapidly as the thermoluminescence or ionization does. To give the same darkening the product of electron current and time of exposure was more nearly inversely as the voltage than as its square, or was varied even more slowly than this. The interpretation of absorption records is hence difficult, since if the energy in the longer wave-lengths is more effective in producing a photographic effect than the same quantity of energy in the shorter wave-lengths, then the transmission through a film which transmits the shorter wave-lengths relatively better will appear less than by a method which more nearly measures the total energy of the radiation.

The darkening of the plate was measured by a thermocouple densitometer. Estimates of the transmission were made both by comparing the time of exposure, with film interposed, and that exposure without the film which gave most nearly the same darkening, and by comparing the density with and without film from a simultaneous exposure. These gave at 600 and 845 volts a transmission between 40 and 50 percent, and at 265 volts between 30 and 40 percent. In some experiments two absorbing films of different thickness were used, and as expected the ratio of transmission through thick to that through thin was greater than the above. These experiments served then to confirm in a general way the results obtained by other methods. It may be added that a five-minute exposure with 0.4 m.a. plate current at 600 volts gave a good photographic effect.

Absorption in Gases

In 1920, data were given[6] from which could be computed the coefficient of absorption of air in the region from 600 to 300 volts, by giving ionization currents produced at different air pressures in an ionization chamber. The source of error was the difficulty in maintaining a constant electron current. There is an error in the published table, the electrometer deflections at 2 mm pressure and at 7.5 mm pressure being for 2 and 1.5 min. respectively instead of for 1 min. as stated. These gave for μ/ρ the values 6, 6.25, 7, 7.6×10^3 at 600, 500, 400 and 300 volts respectively. Another set of values not taken with this in view, and probably not as accurate because of greater inconstancy in the source of radiation, gave at 600 volts 5.4×10^3. These values are quite close to those given by Holweck, viz. log μ/ρ for nitrogen 3.68 and for oxygen somewhat larger. Holweck examined the absorption for nitrogen over a wide region, and found it substantially constant between 300 and 1200 volts. He ex-

[6] Laird and Barton, Phys. Rev. **15**, 303 (1920).

plained this also as the effect of the transmission of an approximately unchanged wave-length by the celluloid window. Considerations similar to those employed for celluloid show that also here, with just one discontinuity to be expected in the region, there is still but slight change in the integrated absorption phenomena, if one assumes a distribution of energy such as was computed previously for the radiation after passing a window. The average value of μ/ρ as so computed for the case of 600 volts is however 1.2×10^4, corresponding to a much larger absorption than that found, instead of smaller as in the case of the celluloid. One may question whether the absorption is strictly atomic.

Some earlier experiments[7] were also made with hydrogen, and while not made for this purpose serve to indicate that while μ in cm^{-1} for hydrogen is smaller than for air, μ/ρ would be larger, 1.8×10^4, contrary to the result given by Holweck and to the usual theory. Assuming his value for μ at a pressure of 3 mm in the ionization vessel used, one should have only about 2 percent of the maximum ionization, and the large difference between this and the result found by the author is not easy to explain. Perhaps reflection from the walls play a larger part than is thought. I hope to try this by a slightly different method.

The work on developing and using the photographic method for these experiments and those on reflection reported earlier, was done at the Sloane Physical Laboratory, Yale University. It is a pleasure to thank Professor Zeleny and Professor Swann for their great kindness in placing the facilities of the laboratory at my disposal.

Mount Holyoke College,
August 7, 1926.

[7] l. c. pp. 301, 302.