PHOTO–ELECTRIC POTENTIALS FOR EXTREMELY SHORT WAVE–LENGTHS.

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THE following is a preliminary report of an investigation carried on in the Jefferson Physical Laboratory to determine the maximum photo-electric potential produced by light in the Schumann region of the spectrum as a function of the frequency.

Professor Millikan's work upon the voltage-frequency relationship in the case of the alkali metals has established the validity of the Einstein formula

$$V = \frac{h}{e}v - V_0$$

as a very close approximation ot the facts for these metals. The results of Kadesh and Hennings[1] using the same method upon other metals give a value of h differing from that of Millikan by an amount considerably greater than the percentage error given by the latter. It is therefore desirable to extend the range of frequencies available for photo-electric measurements upon the other metals.

Moreover, since the magnitude of photo-electric currents increases rapidly with decreasing wave-length, the Schumann region of the spectrum offers an attractive field for photo-electric investigations, while the photo-electric cell ought to prove a valuable aid in Schumann spectroscopy.

The results so far obtained may be summarized as follows:

1. A monochromatic illuminator for use in the region between λ 2300, and λ 1250 has been constructed and calibrated.

2. Voltage frequency measurements have been made upon a single metal, zinc, using light of wave-lengths between λ 1800 and λ 1250.

3. It has been shown that the slope of the voltage-frequency line is quite independent of the surface condition of the emitting metal, provided these conditions remain constant during the measurements.

4. A direct study of the effect of stray light of shorter wave-lengths has shown that it is a source of large error in voltage-frequency measurements.

[1] PHYSICAL REVIEW, Sept., 1916, p. 221.

5. The maximum potentials attained by plates of zinc, cadmium and copper illuminated by light of wave-length λ 1250 have been determined. These measurements, taken with those of other experimenters, for longer wave-lengths give values for the slope of the voltage-frequency line very close to h/e.

APPARATUS.

The monochromator is a modification of Professor Lyman's vacuum grating spectrometer. The essential point of difference lies in the fact that the grating is mounted so that it slides along the focal circle, thus focusing different portions of the spectrum upon the slot through which light shines onto the metal plate in the photo-electric cell. Fig. 1 shows
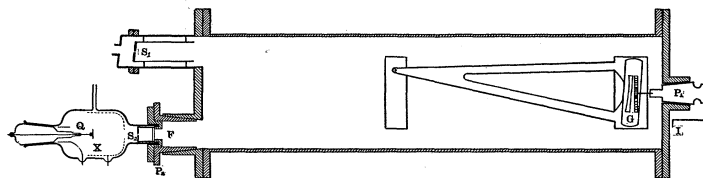

Fig. 1.

the general arrangement. The grating G is mounted upon a movable arm which is pivoted at the center of the focal circle. The slit S_1 and the slot S_2 are adjusted so as to lie upon the same circle. The grating is moved by means of a rack and pinion device. The rack is attached to the movable arm on which the grating is mounted. A small rod through the pinion is engaged by a slot in a sleeve at the end of the taper plug P_1. The grating is shifted from point to point on the focal circle by turning P_1. The position of the index I on a circular scale, attached to the outside of the face plate, determines the position of the grating upon the focal circle and hence the wave length that is incident upon the metal plate. The scale was calibrated by taking a series of photographs of the cadmium and aluminium spark spectra in the region between λ 2300, and λ 1854, and of the spectrum of the hydrogen discharge in the region from λ 1650 to λ 1280.

The photo-electric cell is cemented into the end of the conical plug P_2. The cell is separated from the spectroscope by means of the fluorite window F. The receiving Faraday cylinder is of the usual type made of oxidized copper gauze. The illuminated plate X is a strip of metal 6×25 mm., placed well inside the receiving cylinder. It is mounted on the end of a light metal rod, sealed with Khotinski cement into the ground glass stopper which closes the cell. A guard ring Q prevents charges leaking from the receiving cylinder to the illuminated plate.

The latter is connected to a pair of quadrants of the electrometer. Both cell and spectroscope are exhausted by a Trimount Rotary Oil pump. The higher vacuum needed in the photo-electric cells is secured by means of charcoal and liquid air.

Source of Light.

Considerable time has been spent in attempts to secure a suitable and convenient source of light. What is desired is a source, with a few strong lines well distributed in the region between λ 2300 and λ 1250, that shall be steady and require little attention. Such a combination of qualities has not yet been found in any one source. The metallic vapor arcs of zinc, calcium and cadmium enclosed in quartz have been tried. These spectra possess the requisite lines in this region, but so far it has not been possible to secure working conditions giving the necessary steadiness and reliability. Metallic arcs are difficult to start without heating. Moreover for continuous operation the pressure must be very low. Otherwise the metal soon oxidizes and the arc becomes unsteady. Without a fluorite window between the arc and the spectroscope a very slight leak in the latter soon produces this result. If a fluorite window is inserted, it shortly becomes covered with a film of the metallic vapor even when the arc is 15 cm. from the window and the space between is cooled by a water jacket around the lamp.

On the whole, the hydrogen discharge, while far from ideal, has proven the most satisfactory of the sources tried. It is objectionable in that, with a wide slit, its spectrum becomes practically continuous. Moreover when pure there is little or no radiation of wave-length longer than λ 1650. However, with a trace of air in the spectroscope, carbon bands appear in the region between λ 1650 and λ 2000, so that under these conditions a fairly wide range of frequencies is available. The discharge tube made of quartz was of the usual internal capillary type used by Lyman. It was designed with a view to securing the largest possible current.

The spectrometer case itself served as one electrode. The other electrode was attached to a taper plug of "invar" carefully ground into the quartz tube. The tube was water-jacketed and would carry a current of .2 ampere for 50 seconds without serious heating.

Experimental Conditions.

Large photo-electric currents are desirable in determining maximum potentials. Although with the present form of apparatus only a small fraction of the energy of the source falls on the photo-electric plate, yet the effectiveness of these extremely short wave-lengths is so great that

fairly large currents were obtained. Thus for λ 1600, the most intense region of the hydrogen spectrum, with a slit .03 cm. wide a saturation current giving 10 mm. deflection per second was obtained. For λ 1250, currents one third to one half as great were produced under the same conditions. One millimeter deflection corresponded to .5 millivolt. For the most part electrical conditions were so steady that 1 mm. deflection in 50 seconds could be detected with certainty.

The "back current" due to light reflected from the illuminated plate to the walls of the cell was small. Generally such a current could not be detected at all even under a retarding potential one and a half volts greater than that required to produce zero current. In no case did it amount to more than .5 per cent. of the saturation current. This is probably to be explained by the low reflecting power of the emitting metals for light of short wave-lengths. Hulbert[1] has found that zinc and cadmium have small reflection coefficients in the extreme ultra-violet.

The error due to stray light from the grating, of wave-lengths shorter than that for which the illuminator was set, was found to be large. It will be discussed in a later section.

Surface Conditions and the Voltage-Frequency Relation.

No provision was made in these experiments for preparing surfaces in vacuo. Therefore, it is essential to know how the voltage-frequency relation depends upon the condition of the metal surface. The work of previous investigators seems to show that the only effect of changing surface conditions is a shift of the voltage-frequency line parallel to itself, without affecting its slope. For example Hughes[2] found that exposing a cadmium surface that had been distilled in vacuo, to the action of dry oxygen at a pressure of 14 cm. for 15 minutes, decreased the maximum potentials for all wave-length by the same amount.[3] Millikan[2] also observed that the slope of the voltage-frequency line obtained with a sodium surface originally scraped in vacuo and then exposed to a pressure of .01 mm. agreed very closely with that obtained when the surface was scraped in the highest attainable vacuum and kept under this pressure while measurements were being made. To further test this point experiments were made using a zinc plate with widely different surface conditions. Table I. is typical of the results.

Surface I. had been scraped with a steel tool, and immediately placed in the photo-electric cell. The cell was exhausted in 15 minutes to .001 mm. and the pressure still further reduced by charcoal and liquid

[1] Astrophysical Journal, 42, No. 3, p. 205.

[2] Phil. Trans. A., Vol. 212, pp. 205–226.

[3] Phys. Rev., March, 1916, p. 375.

TABLE I.

Surface.	Max. Volt. λ1280.	Max. Volt. λ1600.	δV.
I................	5.44	4.32	1.12
II...............	4.64	3.51	1.13
III..............	4.92	3.79	1.13

air. Surface II. had been in the cell for four days at a pressure of .002 mm. and later exposed to the air for 15 minutes. Surface III. had been treated similarly to surface I., but had stood in the cell at low pressure for twenty-four hours. Other experiments in which the variation in the maximum voltage for a given frequency was not so great as those given, showed practically the same difference for the two wave-lengths, so that it seems certain that the change in maximum voltage for a given change in frequency is independent of the surface conditions of the metal, provided these conditions remain constant during the measurements.

SCATTERED LIGHT OF SHORT WAVE-LENGTH.

Millikan[1] has pointed out that the effect of stray light from the optical system giving the monochromatic illumination is in general to decrease the slope of the voltage-frequency curve, by raising the apparent potential due to the lower frequencies. The present attempt to determine the voltage frequency relation in the Schumann region of the spectrum bears out Millikan's suggestion in a somewhat striking manner. The results without color screens briefly stated are these. For wave-lengths λ 1800, λ 1600 and λ 1250 the voltage frequency curve was very accurately a straight line, with a slope however only a little more than one half as great as that called for by the Einstein formula. Table II. gives

TABLE II.

Wave-length.	Frequency.	Applied Voltage.	Max. Potential.
1800..............	1.66×10^{15}	3.82	4.88
1600..............	1.87×10^{15}	4.32	5.38
1250..............	2.40×10^{15}	5.44	6.50

the values obtained using a scraped surface of zinc. Other determinations with different surfaces gave virtually the same result so far as the slope of the line is concerned. The contact potential difference of 1.06 volts, between the zinc and the receiving cylinder was determined by measuring the positive potential applied to the latter that was necessary to produce the saturation current. These results are plotted (⊙) in

[1] PHYSICAL REV., March, 1916, p. 355.

Fig. 2. The results of Richardson and Compton for a similarly treated zinc surface are shown on the same graph. The slope of the line through the author's points in the Schumann region gives a value for h of 3.6×10^{-27}. That the potential measured for the two longer wave-lengths is larger than that corresponding to the maximum energy of

+, Richardson and Compton's values ⎫
⊙, Author's values   ⎬ for zinc.
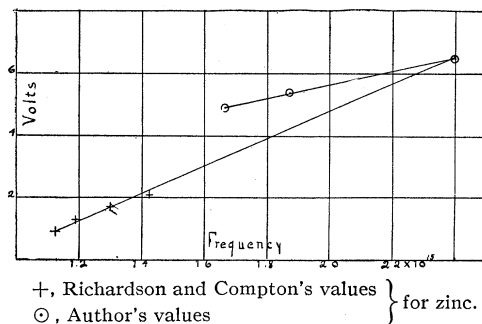   ⎭

Fig. 2.

electron emission due to these wave-lengths was shown by the following experiment:

With the spectroscope so tight that the leak was less than .02 mm. in twenty-four hours, pure hydrogen was admitted. As has been stated, there are no lines in the Schumann region of the hydrogen spectrum of wave-length longer than about λ 1670. Examined spectroscopically the discharge showed no trace of carbon bands. Yet with the monochromator set for λ 1800, a photo-electric leak almost one tenth as great as that due to λ 1600 was observed. Applying retarding potentials, a voltage current curve was taken. This was found to coincide very closely with the curve due to λ 1600, the nearest and by far the most intense portion of the hydrogen spectrum, and to reach the axis of zero current at very nearly the same value of the retarding potential. In other words, one had the effect due to stray light alone, which in this case was found to be the same as the effect due to the strongest lines in the source of shorter wave-length than that for which the monochromator was set. It appears therefore that without color filters, the maximum potential determined is that at which this stray light effect becomes less than can be detected by the electrometer used and that with a sufficiently sensitive electrometer the voltage frequency line thus determined would be parallel to the frequency axis, at a voltage given by the shortest wave-length that is transmitted by the optical system employed. In the present experiment the trace of air in the spectroscope necessary to produce the radiation at λ 1800 served as a screen to reduce in a

measure the intensity of the stray light of shorter wave-lengths, thus giving a slope greater than zero and less than that due to the lines for which the monochromator was set.

It has not as yet been possible to undertake the task of finding specimens of quartz and colored fluorite to serve as color filters and of accurately determining the limits of their transparency. It has seemed worth while, however, to report this positive result concerning the effect of stray light, in view of the fact that this source of error must exist in all experiments in which color filters are not used.

Maximum Potential for λ 1250.

The foregoing does not apply to the values obtained for the shortest wave-length used since the fluorite window between the cell and the spectroscope cuts out all wave-lengths shorter than λ 1250, the limit of transparency of fluorite. The maximum potential produced when the monochromator is set for this wave-length is therefore a measure of the kinetic energy of the fastest electrons liberated. Since this voltage is large compared with those produced by ordinary ultra-violet light, the percentage error in its determination is correspondingly small. The large range of frequencies between this and the long wave-length limit of most metals is sufficient to afford a good test of the validity of the Einstein formula. Careful determinations of the maximum potential acquired by zinc, cadmium and copper plates were made. In each case the contact potential difference was measured simultaneously by determining the positive potential applied to the receiving electrode necessary to produce saturation of the photo-electric current. The values are given in Table III.

Table III.

Metal.	App. Potential.	Contact Potential.	Max. Potential.	Mean.
Zinc.............	5.44	1.25	6.69	
"	5.70	1.17	6.87	6.70
"	5.16	1.35	6.51	
"	5.21	1.60	6.81	
"	5.00	1.63	6.63	
Cadmium........	5.35	1.25	6.60	
"	5.25	1.28	6.53	6.57
Copper..........	6.05	.63	6.68	6.68
"	6.22	.47	6.69	

The two determinations for copper were made using the same surface, with an interval of about five hours between. Each of the other cases represents a fresh metallic surface. It is to be said that experimental

conditions were much more satisfactory when the measurements upon the cadmium and copper were made than when the earlier work with zinc was done. To make sure that surface conditions had not altered materially between taking the maximum and the contact potentials, the experimental procedure was as follows: First increasing accelerating potentials were applied and the upper part of the voltage current curve was taken to determine the applied voltage that just gave the saturation current. Immediately afterward retarding potentials were applied and the lower end of the current-voltage curve was taken to determine the applied potential just necessary to produce zero current. The saturation voltage was then again determined and the mean of the two values was assumed to be the contact potential difference between the emitting
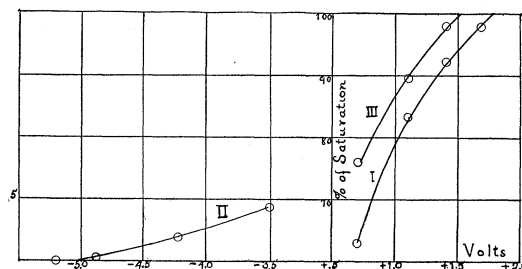

Fig. 3.

and receiving electrodes at the time the maximum potential was determined. The curves in Fig. 3 illustrate the method. They were taken in the order given. The shift of contact potential, *.2* volt in the case illustrated was rather larger than usually occurred during a single set of measurements. The time between taking curves I. and III. was about two and a half hours.

The contact potential differences measured in this way with the metal surfaces in vacuo are in good agreement with values given by direct measurement. Thus the mean value for this difference between zinc and the walls of the copper oxide cylinder is 1.4. For copper against copper oxide, the mean C.P.D. is .55 volt. For zinc against copper we have .85 as compared with .84 volt determined directly by Hallwachs for fresh surfaces in air.

In order to use the results here obtained in connection with the longer wave-length determinations of previous observers one must take account of the contact potential difference between the emitting and receiving electrodes in these earlier experiments. Hughes in his work neglected this point entirely so that before using his values they must be corrected for the contact potential difference between the emitting metal and the

soot-blackened surface of the surrounding walls. One may get an approximate value for this correction as follows: Hallwachs[1] gives as the contact potential difference between zinc and lamp black 1.1 volts. For cadmium and lamp black this value would be .94. Hughes (l. c.) found that exposing his vacuum prepared surface of cadmium to the action of dry oxygen at a pressure of 160 mm. for 15 minutes lowered the maximum voltages for all wave-lengths by the same amount, .25 volt. Hence to compare Hughes's values with those for a surface prepared in air .25 volt must be subtracted. In Table IV. Hughes's values for cadmium corrected by adding .69 volt, *i. e.*, (.94 − .25) are given together with the value here obtained for λ 1250.

TABLE IV.

Wave-length.	Frequency.	Corrected Potential.	
2537.............	1.18×10^{15}	1.52	Hughes
2357.............	1.33 × "	2.05	"
1849.............	1.62 × "	3.13	"
1250.............	2.40 × "	6.57	Author

These are plotted in Fig. 4. The straight line through the extreme points gives a value of h, equal to 6.58×10^{-27}.

In the case of zinc, the mean value of the maximum potential for λ 2537 obtained by Hughes is computed to be .70 volt. Making the
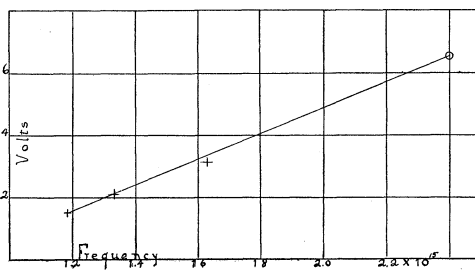
+, Hughes' values.   ⊙, Author's value.

Fig. 4.

correction for contact potential and for the effect of air as in the case of cadmium, we have the potential which measures the maximum energy of electrons liberated by this wave-length

$$V = .70 + 1.1 - .25 = 1.55 \text{ volts.}$$

This with the maximum potential for λ 1250 gives

$$h = 6.71 \times 10^{-27}.$$

[1] Handbuch der Radiologie, Band III., p. 349.

The slope of the line in Fig. 2 in which Richardson and Compton's values are used, gives for the value of h, 7.23×10^{-27}.

It is scarcely possible to draw any conclusion from the data for the copper surface, since there are no very satisfactory figures for copper in the longer wave-length region. Richardson and Compton found that copper and bismuth gave unusually low values for the slope of the voltage frequency line. On the other hand, Hughes found that the slope of the bismuth line was very nearly the same as that for cadmium, while Kadesh and Hennings report that for a given frequency all of the metals examined by them including copper acquire practically the same maximum potential when emitting electrons to the same receiving electrode. The experiment with copper was tried only in view of Richardson and Compton's results, to ascertain whether the small slope of the voltage frequency line as determined by them for this metal showed itself in a correspondingly low voltage when the higher frequency was used. The results indicate that there is no reason for supposing that copper differs in any considerable degree from the other metals in the voltage frequency relation of the photo-electric effect.

Taken as a whole the values of the photo-electric potentials for λ 1250, when compared with the results of other investigators, while not affording any very accurate determination of the Planck constant, nevertheless give very good reason to believe that h/e is the slope of the voltage frequency line for zinc and cadmium. It is of course highly desirable that the measurements for both extremities of the available frequency range be made in a single set of experiments with proper precaution to eliminate the known large source of error due to stray light. The necessary changes in the present apparatus are being made for this purpose.

I acknowledge, with great pleasure, my obligation to Prof. Lyman, both for suggesting this research, and for his keen interest in its progress and constant help with the troublesome details of vacuum spectroscopy.