THE ENERGY OF PHOTO-ELECTRONS FROM SODIUM AND POTASSIUM AS A FUNCTION OF THE FREQUENCY OF THE INCIDENT LIGHT

By W. H. Kadesch.

THE energy of photo-electrons as a function of the frequency of the incident light has been studied in numerous researches, but with little concordance of results. Ladenburg,[1] who was the first to investigate the subject, concluded that the emission velocity varies directly as the frequency. Joffé[2] showed, however, that Ladenburg's observations were in quite as good agreement with the view that not the velocity of electrons, but their energy, varies as the frequency. Kunz[3] at first found a linear relation between energy and wave length. Later observations led him to develop a theory according to which the velocity varies as the frequency. Wright[4] found a maximum in the energy curve which was taken as a confirmation of the view that the photo-electric effect is a resonance phenomenon. The same conclusion had been reached by Lenard[5] and by Ladenburg and Markau.[6] Hughes[7] found a linear relation between energy and frequency, as did also Richardson and Compton.[8] Cornelius[9] obtained results which were taken to support the theory of Kunz. Compton,[10] however, showed that according to Cornelius's data the energy is more nearly proportional to the cube of the frequency than to the square.

This total lack of agreement in experimental results, and the bearing of photo-electric phenomena on the unitary theories of radiation, render it important that further work be done. It was with the hope of eliminating some of the difficulties and errors that have beset investigators in this field that the present research was undertaken.

[1] E. Ladenburg, Verh. d. D. Phys. Gesell., 9, p. 504, 1907.

[2] A. Joffé, Ann. der Physik, 24, p. 939, 1907.

[3] Jakob Kunz, Phys. Rev., 29, p. 212, 1909, and 33, p. 208, 1911.

[4] J. R. Wright, Phys. Rev., 33, p. 43, 1911.

[5] Lenard, Ann. der Physik, 8, p. 149, 1902.

[6] Ladenburg and Markau, Verh. d. D. Phys. Gesell., 10, p. 562, 1908.

[7] A. L. Hughes, Phil. Trans. (A), 212, p. 205, 1912.

[8] Richardson and Compton, Phil. Mag., 24, p. 575, 1912.

[9] David W. Cornelius, Phys. Rev. (2), 1, p. 16, 1913.

[10] Karl T. Compton, Phys. Rev. (2), 5, p. 382, 1913.

The chief sources of uncertainty in photo-electric work have been the following: (1) The illuminated surfaces have usually been of metals sensitive to only a short range of frequencies. (2) Surface conditions have not been controlled, so that there was no assurance of uniformity throughout a set of observations. (3) There has been in some cases much trouble with reflected light. In order, so far as possible, to obviate these difficulties, the following precautions were taken. (1) Surfaces of the strongly electro-positive metals, sodium and potassium, were illuminated, these being sensitive to long waves as well as short. (2) A device was employed for exposing a fresh surface very readily, and as often as desired.

Apparatus.—The photo-electric cell was of the form shown in Fig. 1.

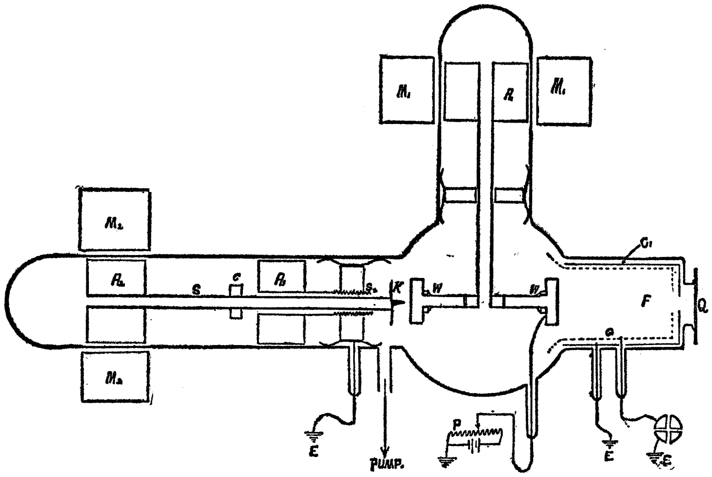

Fig. 1.

W is a brass wheel about 8 cm. in diameter, which could be rotated by means of the electro-magnet M_1, acting on the armature A_1. To the periphery of this wheel, which was insulated from the shaft by means of amber, the electrodes were attached. These were cylindrical in form, 2 cm. in diam. and initially about 8 mm. deep. They were made by pouring the molten metal in an atmosphere of dry CO_2 into a mould whose removable brass bottom was designed to hold the metal firmly, and make metallic contact with it. This base was then screwed into the wheel *W*. *K* is an auger-like knife rotated by means of the electro-magnet M_2 and armature A_2. This knife could also be slid along the tube in the direction of *W*, but the point to which it could be carried was limited by a third armature A_3, and a collar *C*, fixed to the shaft *S*. This armature was connected with the framework by a fine screw S_2, and so, by means of M_2, could itself be advanced or withdrawn. This arrangement made it possible to take off a slice as thin as desired from the electrode, and turn the fresh surface in the direction of F, in position to receive the illumination.

The Faraday cylinder consisted of a fine-meshed copper gauze, blackened by oxidation, and a brass cylinder outside the gauze, concentric with it, and insulated from it by means of ebonite rings. Terminals were led out separately from the brass cylinder, the gauze, the wheel W, and the mechanism of the tube. Those from the mechanism and brass cylinder were put to earth, that from the gauze to an electrometer of sensitiveness about 150 scale divisions per volt, while that from the wheel was connected with a potentiometer arrangement by which any potential desired could be given the electrode.

Extraneous light was excluded by surrounding the tube with a light tight box of sheet iron, painted inside with optical black. This box was also earthed, and helped to eliminate electro-magnetic disturbances, and static effects.

The source of light was a spark between iron terminals. These were joined to the secondary of a large induction coil designed to operate with alternating current. The disturbances attending its use in this way, however,[1] made it necessary to energize the coil with storage cells. Leyden jars were placed in parallel with the spark to increase its instantaneous intensity. The light was passed through a quartz spectrometer, previously calibrated by means of the lines of the mercury arc. During the photo-electric observations the slit width was about 1 mm. for both collimator and telescope. The spark terminals were carried by a clamp fixed to the collimator. In passing from one wave length to another the telescope was allowed to remain in position, only the collimator being moved. The lenses not being achromatic, it was necessary to change the lengths of spectrometer tubes for each new frequency. The lengths required were determined in advance by allowing the light of each mercury line, after traversing the system, to fall upon a screen of uranium sulphate, a satisfactory adjustment being indicated by the sharpness of the focus on the screen. The tube length required at 2,002 A.U. was 22.5 cm., at 3,906 A.U. 28.5 cm. During the process just described the collimator slit was made as narrow as possible while that of the telescope was removed. During the determination of the spectrometer setting corresponding to the various wave-lengths both were in place and narrow.

The whole optical arrangement including induction coil, storage cells,

---

[1] Millikan, Phys. Rev. (2), 1, p. 73, 1913; Pohl and Pringsheim, Ber. d. D. Phys. Gesell., 10, p. 974, 1912.

Leyden jars, and spectrometer, was placed inside a large box, made of sheet iron 2 mm. thick. This was necessary in order to eliminate completely the electro-magnetic disturbances referred to above.

The photo-electric cell was evacuated through a tube about 3 cm. in diameter by means of a Gaede molecular pump. This was kept running throughout every set of observations. A McLeod gauge reading to .000001 mm. of mercury showed no indication. No attempt, however, was made to test for the residual vapors of mercury or of stopcock grease.

Observations.—In determining the energy of the electrons emitted under the influence of any wave-length two methods were employed. In the first, distribution of velocity curves were run in the usual way by plotting as abscissæ the potentials applied to the electrode, and as ordinates the electrometer deflections due to a given period of illumination. The point where this curve met the axis of potentials was taken as a measure of the energy of the swiftest electrons. In the second method a potential was applied to the electrode just sufficient to prevent a deflection of the electrometer. The agreement between the results given by the two methods was very close.

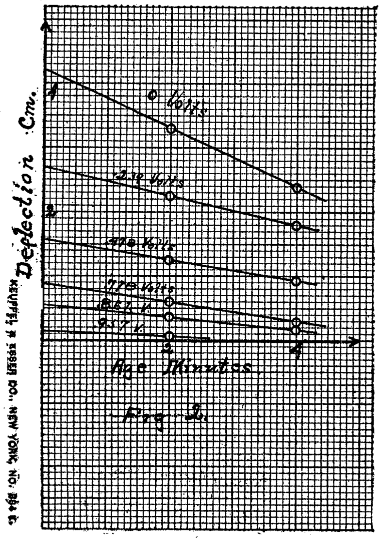

Fig. 2.

It was found that the strength of the photo-electric current fell off very rapidly with increasing age of surface. To determine whether this was due to illumination, or to changes taking place independently of the illumination, observations on the current were made under two conditions. In the one the same surface was illuminated for 30 seconds at intervals of two or three minutes. Curves with ages of surface as abscissæ and the corresponding electrometer deflections as ordinates were then drawn. These were convex toward the axes of coördinates. In the second case a fresh surface was exposed each time, but at different age. The age current curves obtained by this method were straight lines, with negative slope. From this is seen that both age and illumination affect the surface in such a way as to cut down the current. It was thought that an improvement in the method might be made by observing the electrometer deflections as in method two, extending the curve backward to the line of zero age, and taking this point of intersection as the measure of the current from a clean metallic surface. This however was found to be unnecessary, since the slope of these curves became smaller and smaller, approaching zero as the potential applied approached that required to prevent the escape of electrons. This is clearly shown in Fig. 2. In this case only two points on each curve were determined. The method of observation finally adopted was to cut a fresh surface for each potential applied to the electrode, to allow this surface to attain an age of two minutes (about the length of time required to close the box containing the photo-electric cell, and otherwise prepare to make an observation) and then illuminate. The applied potentials were then plotted as abscissæ and the corresponding electrometer deflections as ordinates. Only a small section of the curve was determined in each case, since only the point at which it met the voltage axis was required.

The observations made on sodium by illuminating with four different wave-lengths are graphically shown in Fig. 3. Plotting frequencies as abscissæ, and the corresponding maximum potentials determined as above, as ordinates, the curve in Fig. 4 is obtained. Observations made in the same way on potassium give the points marked by circles in Fig. 5.

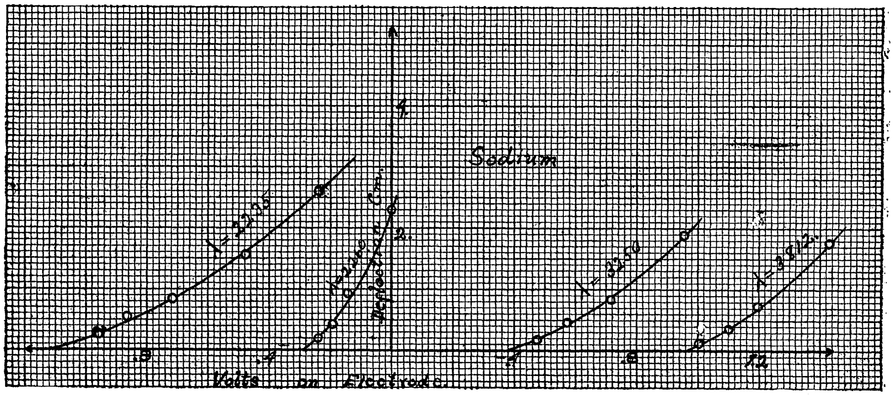

Fig. 3.

In the second method of observation also, namely, that in which a potential was applied to the electrode just sufficient to prevent the escape of electrons, fresh surfaces were frequently cut, especially when the balancing potential was approached. This was done to insure greater accuracy, merely by providing a surface as sensitive as possible to the light. This method was employed only for potassium. The points thus determined are indicated by dots in Fig. 5.

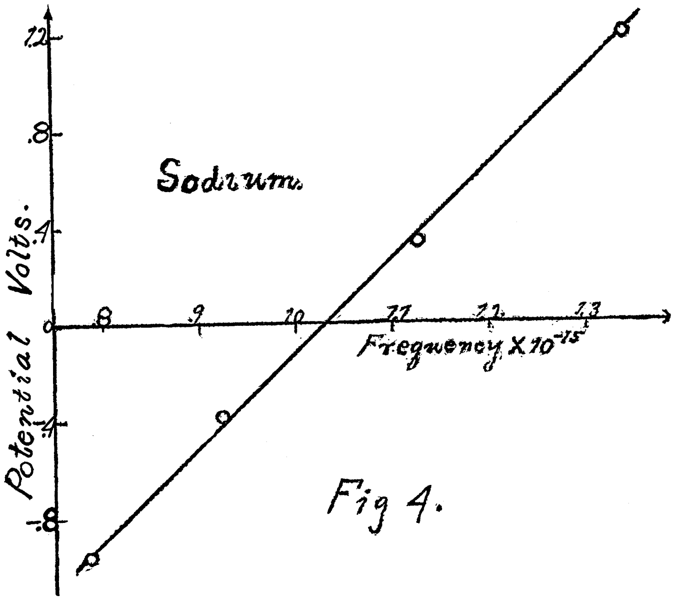

Fig. 4.

Discussion of Results.—The results of the investigation are seen to be in agreement with those of Hughes[1] and of Richardson and Compton.[2] They may be expressed by an equation of the form

$$V = Kn - V_0,$$

in which V is the difference in potential in volts between the electrode and the adjacent parts of the tube, just sufficient to prevent a deflection of the electrometer, n is the frequency of the incident light, and K and V_0 constants.

According to the theory of Einstein[3] the relation between energy and frequency should be represented by the equation

$$Ve = \frac{R}{N}\beta n - P,$$

in which e is the elementary electrical charge, $R\beta/N$ is Planck's constant equal to 6.55×10^{-27}, and P a constant representing the loss of energy suffered by an electron in escaping from the metal.

The observations on sodium gave a value for K equal to 3.87×10^{-15}, those on potassium 3.83×10^{-15}.

Writing the equation in the form given by Einstein, and substituting

---

[1] Loc. cit.

[2] Loc. cit.

[3] Einstein, Ann. der Physik, 20, p. 199, 1905.

for *e*, 4.772×10^{-10}, the slope for sodium becomes 6.16×10^{-27}, that for potassium 6.09×10^{-27}.

Errors.—In addition to the usual errors due to "personal equation" which in the end would be expected to annul one another, the observations are subject to several others of a systematic sort, depending upon conditions unavoidable in the experiment. First among these may be mentioned electrostatic leaks. In the first method of observation these would have the effect of causing the distribution of velocity curves to approach the axis of potentials at a more acute angle thus rendering the points of contact more uncertain. The tendency would be to assume a positive potential somewhat smaller than the true. This error would be greatest for wave-lengths giving weakest currents. From Fig. 3 these are seen to be the longest and the shortest waves. This would tend to bend the frequency-potential curve in such a way as to make it concave downward. However, since the leak for a deflection of 500 scale divisions never exceed and seldom reached 3 divisions per minute, becoming rapidly smaller with diminishing deflection, the effect on the shape of the curve, as well as on its slope, is negligible.

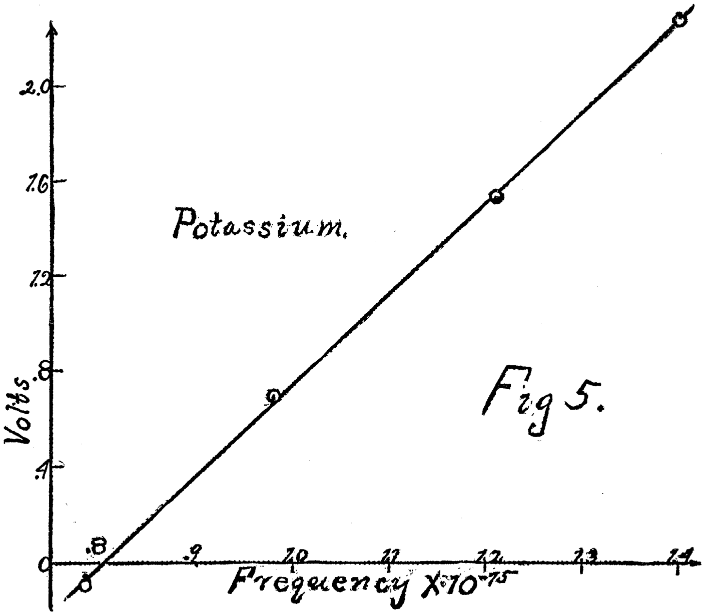

Fig. 5.

The electrostatic capacity of the electrometer and receiving gauze would also introduce an error. This will best be seen by considering the second method of determining electronic energies. Even though the electrical arrangement was fairly sensitive, many electrons would have to pass before an observable deflection would take place. The observed potential, then, is somewhat smaller than the true. Here again the error would be greatest for wave-lengths giving smallest current, and the effect on the frequency potential curve would be the same in character as that due to electrostatic leak, and also very small.

A third error would arise from the effect of reflected light. A ray incident on the receiving gauze would, if of sufficiently high frequency, there release electrons. These would travel to the electrode, and so offset the effect of an equal number passing to the gauze. The observed positive potential would then be smaller than that required to prevent the escape of electrons. Since the surface of the gauze was of copper oxide, not sensitive to long waves, this error would affect only the potentials for the higher frequencies. The curve would therefore have a slope somewhat smaller than the true. Charging the electrode to a high negative potential, however, and illuminating with these waves, gave a negative deflection never exceeding a few hundredths of one per cent. of its positive saturation value. The error due to this cause, then, must also have been small. The total observational error would not account for a difference as large as that between the slopes of the experimental curves and that of Einstein's formula.

In conclusion the writer wishes to acknowledge his obligation to Mr. Fred Pearson and Dr. Harvey B. Lemon for repeated assistance in the course of the investigation, to Mr. Albert E. Hennings, from whom ideas on the mechanism of the tube were freely borrowed, to Mr. Julius Pearson, who constructed the tube and to whose skill and ingenuity its successful operation was largely due, and especially to Professor Millikan, at whose suggestion the research was undertaken, and under whose direction and constant inspiration it was brought to a conclusion.

U. S. NAVAL ACADEMY,
January 12, 1914.