THE VALUE OF *h* DETERMINED PHOTO-ELECTRICALLY FROM THE ORDINARY METALS.

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INTRODUCTION.

AMONG the various theories of the photo-electric effect none has inspired a more active interest among physicists than that of Einstein.[1] It has been recognized that the equation

$$Ve = \frac{R}{N}\beta\nu - P \tag{1}$$

if true, is of extreme importance. The various implications of this equation have been frequently investigated, but with no resulting unanimity of opinion as to the truth of any one of them. It is the purpose of this paper to present the results of observations made on a few of the common metals, and to draw attention to the bearing of those results on certain of the implications of the theory.

EXPERIMENTAL ARRANGEMENT, AND OBSERVATIONS.

The experimental arrangement and procedure were in the main the same as in the work reported in the preceding paper. In addition to the observations there recorded others which form the basis of the present paper were made on magnesium and aluminum. These were chosen for special study because they are sensitive to a greater range of available frequencies than are the less electropositive metals.

Owing to the presence in the beam transmitted by the spectrometer of a small amount of diffused light of all the frequencies given by the mercury-in-quartz lamp, various absorbing screens were interposed to cut out that of wave-length shorter than the spectral line desired. The effect of the more perfect monochromatism obtained in this way was to cause the potential-photo-current curves to plunge more sharply into the potential axis. The same effect was shown in a recent paper by Millikan.[2] The trailing off of the curves in the absence of absorbing screens was much less marked in these experiments, however, than in his.

In the case of magnesium five different spectral lines were used, in that of aluminum four. The latter metal, while photo-sensitive to λ3652,

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[1] Einstein, Ann. der Physik, 17, p. 145, 1905.

[2] Millikan, PHYS. REV., N.S., 7, p. 18, 1916.

gave currents so small that no accurate determinations of V for this line could be made.

A representative set of potential-photo-current curves for each of these metals is shown in Fig. 1. The points at which the curves cut the voltage
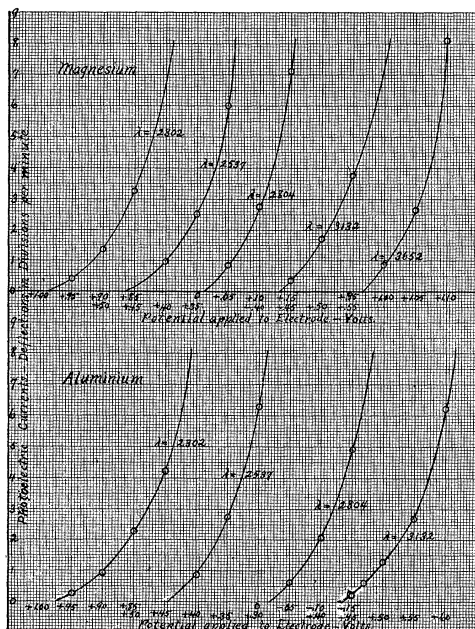

Fig. 1.

axis are taken as the apparent maximum energies of emission, measured in volts, of electrons freed by the several wave lengths. In Fig. 2, frequencies of exciting light are plotted as abscissæ; maximum emission energies in volts as ordinates. Within the errors of experiment the curve in each case is a straight line. The slopes give values for the coefficient of v, in the above equation, of 6.45×10^{-27} and 6.41×10^{-27} for magnesium and aluminum respectively.

From the curves of Fig. 1, assuming that the points there located are correct, it would appear that there is an uncertainty of perhaps $\pm$ .02 volt in the determination of the maximum energies of emission for wavelengths, λ 2302 and λ 2537, and a somewhat smaller one for the others. The close agreement among the values of V obtained from different sets of data leads us to believe that the actual errors are in no case greater than this. Perhaps a better idea of their magnitude may be got from Table I. Under the numbers indicating the wave lengths are given the

values of V, obtained as above described, from different sets of obser-
vations.

TABLE I.

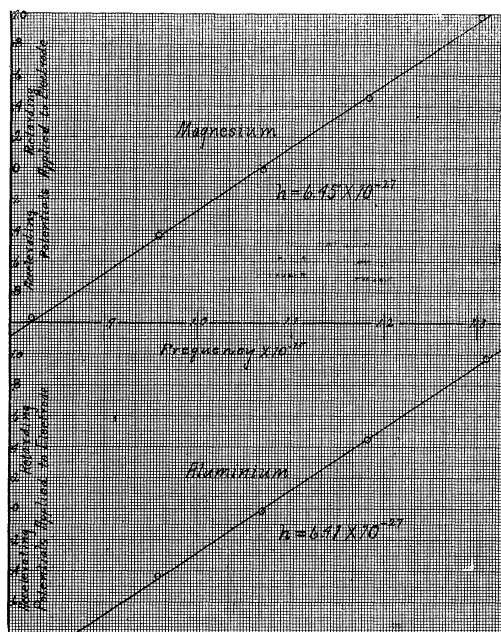|	2302	2537	2804	3132	3652
Mg.	.97 volt	.45 volt	—.035 volt	—.43 volt	—.96 volt
	.99 "	.46 "	+.02 "	—.43 "	—.97 "
			—.01 "		
Al.	.97 "	.44 "	—.02 "	—.42 "	......
	.98 "	.45 "	—.02 "	—.44 "	......
	.97 "	.44 "	—.01 "	—.43 "	......
	.97 "	.445 "	+.02 "	—.45 "	......

Fig. 2.

Since the experimental points do not fall accurately on a straight line,
there is also a probability of error in determining the slope of the fre-
quency-potential curve.   That this need not be large is shown by the
sort of agreement found among the slopes of the curves plotted for dif-
ferent sets of observations and by different observers.   In columns 3
and 4 of Table II. are given the h's calculated from the slopes obtained
by two different observers who had been asked to locate each line as
accurately as possible, giving all the points equal weight, but had not
been told what the V's and v's represent.   Only three sets were plotted
for Al by observer A.

TABLE II.

Metal.	Set.	Observer A.	Observer B.
Mg	1	6.31×10^{-27}	6.30×10^{-27}
"	2	6.42×10^{-27}	6.38×10^{-27}
"	Average	6.37×10^{-27}	6.34×10^{-27}
Al	1	6.50×10^{-27}	6.52×10^{-27}
"	2	6.44×10^{-27}	6.52×10^{-27}
"	3	6.38×10^{-27}	6.38×10^{-27}
"	4	....	6.38×10^{-27}
"	Average	6.44×10^{-27}	6.45×10^{-27}

DISCUSSION OF RESULTS.

The first of the assumptions of Einstein's theory is that photo-electrons emitted from a given surface under the influence of light of a given frequency have a definite maximum emission velocity. The existence of such maximum is indicated by nearly all of the photo-electric work yet done.[1] In some cases the errors due to reflected light, imperfect monochromatism, smallness of photo-currents, and perhaps other causes, such as reflected electrons and electrostatic leaks, have been very considerable. But the experiments in which these factors have been most nearly eliminated are the ones that speak most decisively for a maximum emission velocity. In contradiction with this, Ramsauer[2] concludes from his experiments that the emission velocities are grouped about a most probable value, according to some exponential law. The large and uncertain correction to be applied for the effects of " Falsches Licht," however, render the evidence on this point wholly unconvincing.

It will be seen by reference to Fig. 1 that the present experiments also indicate the existence of maximum emission velocities. All the curves approach the voltage axis quite definitely at finite angles.

It is now agreed among those who admit the existence of maximum energies of emission that these are proportional to the frequency in the exciting beam. There is no such unanimity of opinion, however, as to the way in which the slope of the energy-frequency curve varies, if at all, with the nature of the illuminated surface. According to Einstein's theory this should be the same for all.

[1] Lenard, Ann. der Physik, 8, p. 149, 1902. Millikan and Winchester, Phil. Mag., 14, p. 201, 1907. Ladenburg, Verh. d. D. Phys. Gesell., 9, p. 504, 1907. Ladenburg and Markau, Verh. d. D. Phys. Gesell., 10 p. 562, 1908. Kunz, PHYS. REV., 29, p. 212, 1909. Cornelius, PHYS. REV., N.S., 1, p. 16, 1913. Hughes, Phil. Trans. Roy. Soc., A, 212, p. 205, 1913. Richardson and Compton, Phil. Mag., 24, p. 575, 1912. Page, Amer. Jour. Sci., 36, p. 501, 1913. Kadesch, PHYS. REV., N. S., 3, p. 367, 1914. Millikan, PHYS. REV., N.S., 4, p. 73, 1914; 6, p. 55, 1915.

[2] Ramsauer, Am. der Physik, 45, p. 1121, 1914.

Hughes[1] concluded from observations on ten different elements, that among those having the same valency the slope increases regularly with diminishing atomic volume. With change of valency he found an abrupt change of slope. The values of the coefficient of ν in equation (1) calculated from his tabulated values of k, range from 5.04×10^{-27} to 6.03×10^{-27}.

Richardson and Compton[2] obtained slopes which group themselves more or less closely about two definite values. For Pt, Sn, Zn, Al, Mg and Na this was about 5.4×10^{-27}; for Cu and Bi it was about two thirds as great. One of the authors[3] obtained 6.16×10^{-27} and 6.09×10^{-27} for Na and K respectively, while Millikan,[4] for Na and Li obtained 6.561×10^{-27} and 6.585×10^{-27}. In the present experiment the values found for Mg and Al are 6.45×10^{-27} and 6.41×10^{-27} respectively. A glance at Figs. 2 and 3 of the preceding article will show that the slopes for all the other metals there studied agree within the errors of experiment with those for Mg and Al.

It is not claimed that the accuracy with which the slopes of the energy-frequency curves were determined in the present experiments is as great as in those of Millikan. The range of available frequencies was only half as great as in the case of Na. Moreover, the photo-currents were much smaller. It is thought, however, that the accuracy obtained is great enough to warrant the belief that the slopes are the same for all the metals tested. These, within the errors of experiment, are equal to Planck's h. It seems probable that other metals, whatever their nature, would yield the same result. This fact that h may be determined from the energy-frequency curve for any one of a large number of metals, of course, leaves no foundation for the conclusion reached by Sutton[5] that the product of the atomic heat of a metal by its photo-electric constant, is the same for all metals.

In comparing his values of k with h/e Hughes observes that there is no reason on the quantum theory for expecting that the slope of the frequency-potential curve should be equal to the quotient of these two universal constants. He suggests that the sharing of the energy between the electron and the parent molecule may depend on the nature of the element. It would seem, however, that the departures from this value should be accounted for in another way. It will be seen from the forms of the photo-cell employed that in his experiments the effects of reflected

[1] Hughes, *loc. cit.*
[2] *Loc. cit.*
[3] *Loc. cit.*
[4] *Loc. cit.*
[5] Sutton, Phil. Mag., 29, p. 734, 1915.

light must have been considerable. These would in every case be such
as to diminish the potential to which the illuminated surface would
charge up, but this effect would be greatest for the highest frequencies.
The observed slope would then be smaller than it should be, by an
amount which might easily be as great as the observed departure from h/e.

In the experiments of Richardson and Compton the departure of the
observed slope from that predicted by Einstein's theory cannot be fully
accounted for in this way. In addition to whatever errors were intro-
duced by the back leakage due to reflected light, there would seem to
have been others, due to diffused light of higher frequency than that of
the spectral line desired. Both Hughes and Millikan found that the
Hilger monochromators used in their experiments threw in a considerable
amount of such light. Both of these observers interposed absorbing
screens to cut out that of shorter wave length. No mention is made in
the paper of Richardson & Compton who also used a Hilger instrument,
of the use of such screens. If diffused light was present, it would have
had the effect of causing the illuminated surface to charge up to a po-
tential higher than that corresponding to the spectral line employed.
This effect would have been greatest for the longest waves, so that the
result in this case would also have been a diminished slope.

From the above considerations, and in view of the results of the
present work and of that of Millikan, we are led to believe that when all
the varied sources of error in photo-electric experiments are eliminated,
or reduced to a minimum, it will be found that the slope of the frequency-
potential curve is independent of the nature of the illuminated surface,
and yields a value of h agreeing with that required by Einstein's equation.

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