The Effect of Temperature on the Energy Distribution of Photoelectrons. II. Total Energies*

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An experimental test of DuBridge's theory of the total energy distribution of photoelectrons. Photoelectrons were released from an outgassed Mo filament placed at the center of a large collecting sphere connected to an FP-54 amplifier and current-voltage curves obtained for filament temperatures from 300 to 1000°K. The effect of temperature on the tail of these curves is quite pronounced, and when analyzed by DuBridge's method the curves show an excellent agreement with the theory. The derived energy distribution curves are also in general agreement with the theory and show, at room temperature, a most probable energy much closer to the maximum energy than obtained by other investigators. Further analysis of the theoretical curves has shown that fortunately they are of such a form that the temperature effect has probably not introduced appreciable errors in the determinations of h by the photoelectric method.

INTRODUCTION

IN the previous paper in this issue of the *Physical Review*, DuBridge and Hergenrother[1] have described an experimental test of the portion of DuBridge's theory[2] of energy distribution of photoelectrons relating to the energies perpendicular to the emitting surface. The present paper is a report of a test of the part having to do with the *total* energy of escape.

The ideal method for analyzing the distribution of total energies is to cause photoelectrons to be ejected from a small sphere placed at the center of a much larger collecting sphere, and to vary the retarding potential between the two. The photocurrent, I, to the collector when the retarding voltage is V is a measure of the number of electrons escaping with an initial energy greater than Ve. DuBridge derived the following approximate expression for the current-voltage curve for this case:

$$I = Ak^2T^2F(x, x_o), \quad (1)$$

where A is an undetermined constant, k the Boltzmann constant, T the absolute temperature of the emitting surface, and x and x_o are abbreviations for the expressions Ve/kT and V_me/kT, respectively, V_m being the maximum retarding potential at 0°K. $F(x, x_o)$ is a universal function (see Eqs. (31) and (32) of Paper I) for which numerical values can be computed once for all. The theoretical current-voltage curves given by this equation for three different temperatures are plotted in Fig. 1, together with the corresponding energy distribution curves obtained by differentiation.

For comparison with experimental results the following characteristics of these theoretical curves should be noted: (1) There is an appreciable "temperature tail" even at room temperature, and this becomes rapidly more pronounced as the temperature is raised. (2) The *relative* importance of the tail is greater for lower values of V_m, i.e., for incident frequencies close to the threshold. (3) The most probable energy of the photoelectrons is very close to the "maximum" energy, being equal to it at 0°K.

In deriving Eq. (1) approximations were introduced which are valid only (1) when the incident frequency is not too far from the threshold frequency of the emitting surface and (2) for values of V either greater than, or not much less than, V_m. The expression then simply represents the way in which the current-voltage curves approach the voltage axis. It is evident that there is a sharply defined *maximum* re-

* Presented in part at the Chicago meeting of the American Physical Society, June 19, 1933. See Phys. Rev. **44**, 316 (1933).

[1] L. A. DuBridge and R. C. Hergenrother, Phys. Rev. **44**, 861 (1933).

[2] L. A. DuBridge, Phys. Rev. **43**, 727 (1933). Hereafter referred to as Paper I.

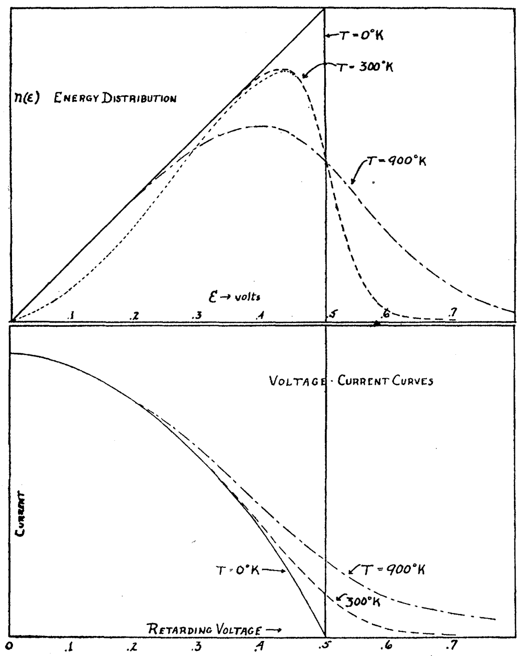

FIG. 1. Theoretical energy distribution and voltage-current curves for three temperatures.

tarding potential (stopping potential) only at 0°K while for all higher temperatures the curves should approach the axis asymptotically. Making further approximations which are valid for V nearly equal to V_m, and taking logarithms, Eq. (1) may be written in the form

$$\log (I/xT^2) = B + f(x - x_o), \tag{2}$$

where $f(x-x_o)$ is another universal function. Its numerical values are tabulated for reference in Table I. Eq. (2) is most useful for graphical analysis of experimental curves.

Experimental Method

The experimental tube, shown in Fig. 2, was designed to approximate as closely as possible

TABLE I. *Values of the distribution function f.*

(x_o-x)	$f(x-x_o)$	(x_o-x)	$f(x-x_o)$
32	4.983	−1	2.524
24	4.624	−2	2.117
16	4.331	−3	1.697
8	3.960	−4	1.264
4	3.631	−5	0.830
2	3.346	−6	0.394
0	2.851		

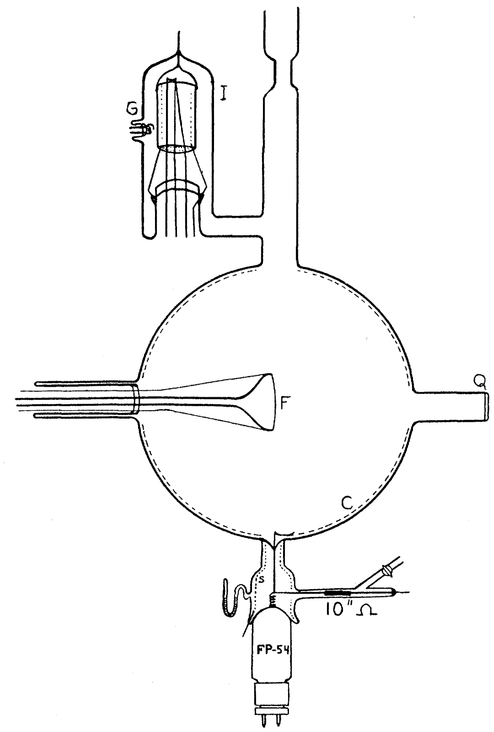

FIG. 2. Experimental tube. *F*, filament. *C*, Pt collecting film. *Q*, quartz-to-Pyrex seal. *I*, ionization gauge. *G*, Mg getter. *S*, compensating shield.

the ideal concentric-sphere arrangement. Photoelectrons were ejected from a strip of molybdenum foil (40×2.3×.01 mm) mounted at the center of a Pyrex sphere, 15 cm in diameter, on the inside surface of which a semi-transparent layer of platinum (or gold) had been evaporated to serve as the collecting electrode. The lead to this electrode was brought out through a seal at the bottom of the sphere and connected directly to the grid of an FP-54 Pliotron, mounted as shown. The auxiliary chamber containing the grid lead and the high resistance (10^{11} ohms) was evacuated. The amplifying circuit was of the type recently described by DuBridge and Brown.[3] Readings were taken by the null method, the galvanometer deflection being brought to zero by applying a potential to compensate for the drop across the high resistance. The variable potential between the Mo filament and the collector was applied by a calibrated potential divider.

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[3] L. A. DuBridge and H. Brown, Rev. Sci. Inst. **4**, 532 (1933).

The tube and ionization gauge were attached to the usual type of high-vacuum system and given an extended outgassing treatment, after which the Mo filament was heated at temperatures between 1900 and 2100°K until its photoelectric threshold had reached its steady state.[4] Final readings were taken with pressures of the order of 10^{-8} mm Hg.

The incident light from a quartz mercury arc was resolved by a van Cittert quartz double monochromatic illuminator which effectively eliminates frequencies other than that which the instrument is set to isolate. The temperature of the filament was determined from its resistance, the results at the higher temperatures being checked with an optical pyrometer.

In order to take photoelectric measurements with the filament hot, it was necessary to heat the filament intermittently, the photocurrents being measured while no heating current was flowing through it. The circuit used is shown in Fig. 3. A Thyratron FG-67 was used to cut out

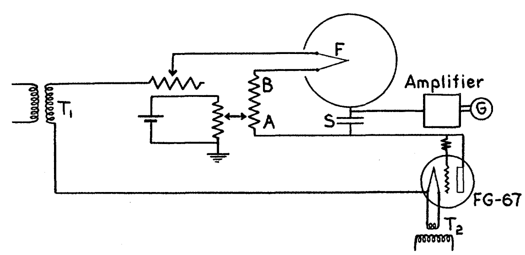

FIG. 3. Circuit for intermittent filament heating.

half of each cycle of a 60-cycle source which was isolated from the main line by a 110–110 volt transformer, T_1. The current, flowing from filament to plate every half cycle gives rise to an intermittent current through the Mo filament. The potential of the filament with respect to ground at any instant is equal to the sum of the voltage applied by the potential divider and the voltage drop across AB, the latter being zero for zero heating current. Hence, during the time the heating current is flowing, there is a large retarding potential which keeps electrons from escaping, while when no current is flowing the emitter is at the potential applied to A.

Because of the capacitance of the experimental tube a charge is induced on the platinum surface by the filament voltage. This is compensated by an equal and opposite charge induced on the control grid lead of the FP-54 tube by means of the compensating shield, S. (See also Fig. 2.)

RESULTS

Current-voltage curves

In order to work with as large a photocurrent as possible the present investigation was restricted to the wave-lengths 2482A, 2536A, and 2654A, the three lines in the Hg arc spectrum which gave the largest emission. For the shorter wave-lengths there was a slight reverse current from the Pt collector for which a correction was made in the manner described by Lukirsky and Prilezaev.[5]

In Fig. 4 are shown the current-voltage curves at room temperature for the three wave-lengths, the curves being brought to the same saturation point. The retarding potential has been corrected for contact potential difference between emitter and collector. The dotted lines indicate the type of curve one would expect at 0°K. Similar curves for the emitting surface at 1000°K are shown in Fig. 5. The tails are much greater at the higher temperature, and even for the small range of frequencies used here, the relative increase in the tail as one approaches the long wave-length limit is quite noticeable.

Fig. 6, curve I, gives an indication of the relative unimportance of the tail at room temperature for wave-lengths far from the threshold. This curve was taken at a stage during the outgassing when the specimen was in its most sensitive state, the threshold being at about 3600A. Even here the asymptotic approach to the voltage axis is quite apparent, as can be seen from curve II which is an enlargement of the part of curve I to the right of the arrow. The voltages given in the abscissa are not corrected for contact potential.

The current-voltage curves shown in Fig. 7 indicate how the size of the tail varies with the temperature for a given wave-length. Only the tails are shown here, the curves having been

[4] L. A. DuBridge and W. W. Roehr, Phys. Rev. **42**, 52 (1932).

[5] P. Lukirsky and S. Prilezaev, Zeits. f. Physik **49**, 236 (1928).

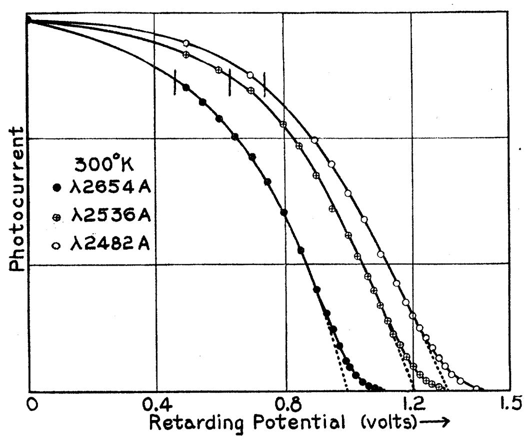

FIG. 4. Current-voltage curves for room temperature.

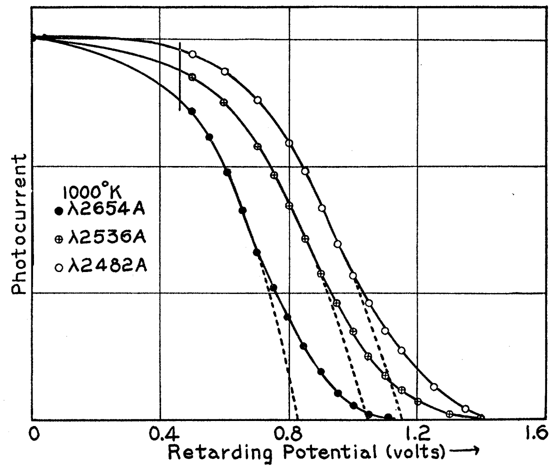

FIG. 5. Current-voltage curves for 1000°K.

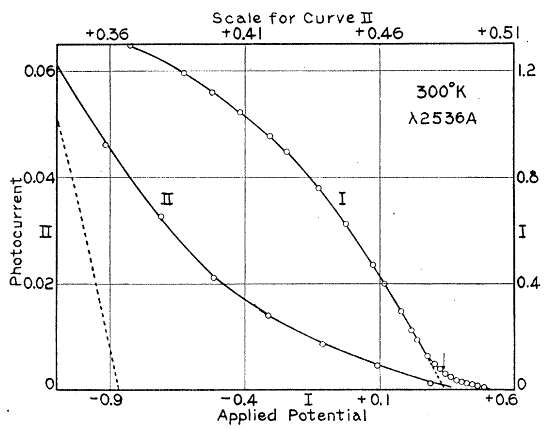

FIG. 6. I. Current-voltage curve for frequency far from threshold. II. Enlargement of tail of Curve I showing asymptotic approach.

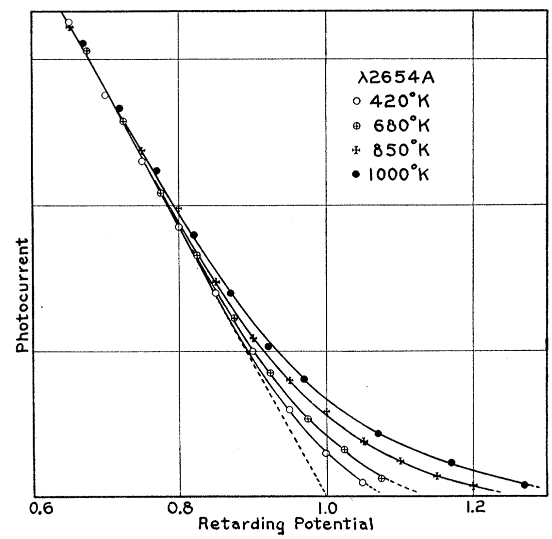

FIG. 7. Effect of temperature on tail of current-voltage curves.

superimposed in the region of saturation current. The 2654 line, being fairly close to the threshold, shows a rather large temperature variation. At 1000°K the value of the maximum energy obtained by extrapolation would be more than 0.3 volt beyond the theoretical absolute zero intercept of 1.0 volt.

Theoretical analysis

In order to analyze the experimental current-voltage curves DuBridge[2] developed a graphical method similar to that used by Fowler in determining photoelectric thresholds. The theoretical expression for the tails of the current-voltage curves is given in Eq. (2). Plotting $f(x-x_o)$ as a function of (x_o-x) gives the theoretical curves shown in Figs. 8, 9 and 10. If experimental results are then plotted in the form $\log (I/xT^2)$ against x, a curve of the same form as the theoretical one is obtained. A horizontal and vertical shift are required to make the two coincide, the horizontal shift being equal to $x_o = V_m e/kT$, thus determining the maximum energy at absolute zero. In Figs. 8 and 9 the data of Figs. 4 and 5 are plotted in this manner, the shifts being indicated on the graphs. All points to the right of the vertical lines in the current-voltage curves (Figs. 4 and 5) fit the

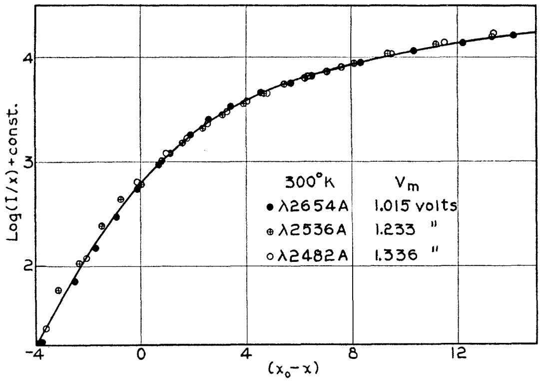

FIG. 8. Theoretical analysis of room temperature curves.

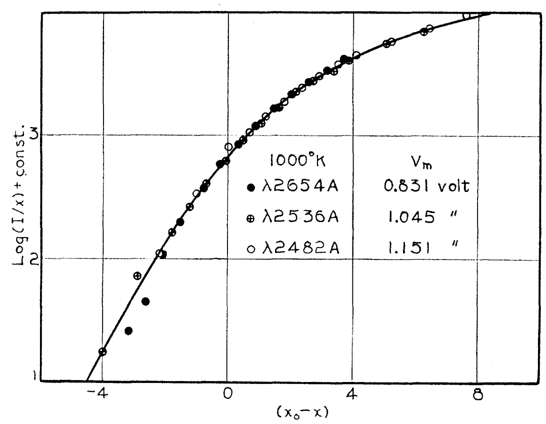

FIG. 9. Theoretical analysis of 1000°K curves.

theoretical curve quite well, while at lower energies there is an expected deviation because the theory does not take into account a variation of the transmission coefficient. When V_m is plotted against ν the points fall accurately on a straight line whose slope is within 1 percent of the accepted value of h/e.

Fig. 10 is an analysis of the results of Fig. 7. Since all observations were made for a single wave-length, the horizontal shifts should be such as to give the same value of V_m for all temperatures, which is true within the limits of experimental error. As before, this voltage shift V_m is indicated by the intercept of the dotted line with the voltage axis in the original curves.

Energy distribution

Differentiation of the current-voltage curves of Figs. 4 and 5 yields the energy distribution curves shown in Figs. 11 and 12. In order to facilitate comparison the curves in each set have been reduced to a common level at the most probable value. The arrows indicate the maximum energy at 0°K as determined by the shifts. It is to be noted that at room temperature the most probable energy is quite close to the maximum measurable energy while at 1000°K it shifts to relatively lower values. Previous experiments on the total energy distribution have shown a most probable energy of from 40 to 50 percent of the apparent maximum. The values obtained here are of the order of 75 percent. This is probably because previous experiments were carried out with surfaces not thoroughly outgassed.[6]

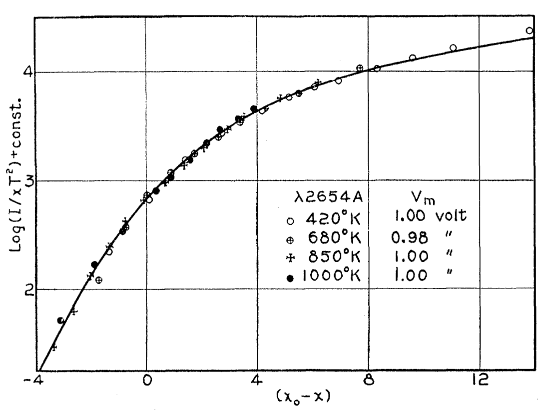

FIG. 10. Theoretical analysis of curves shown in Fig. 7.

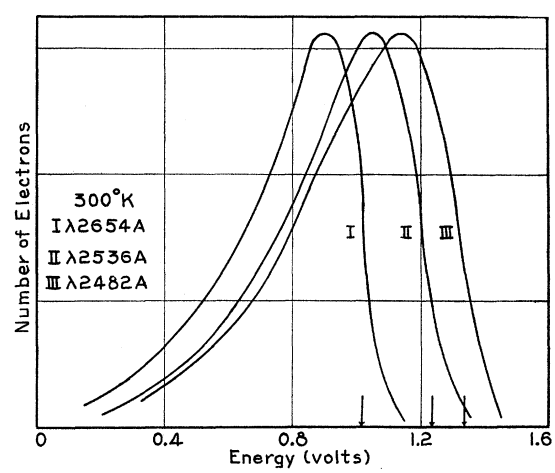

FIG. 11. Energy distribution of photoelectrons at room temperature.

[6] The results of Ives, Olpin and Johnsrud (Phys. Rev. **32**, 57 (1928)) however seem to be in fair accord with the theory.

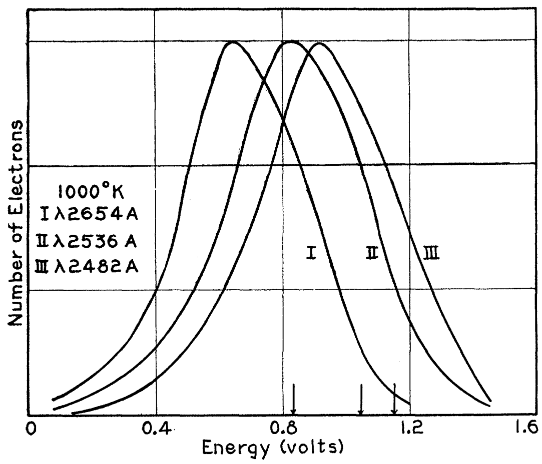

FIG. 12. Energy distribution of photoelectrons at 1000°K.

Fig. 13 shows the energy distribution curves for the 2654A line at the temperatures indicated, which are in good agreement with the theoretical prediction of Fig. 1. At higher temperatures the most probable energy shifts steadily to lower values. The dotted line is the distribution to be expected at 0°K and the region R is presumably accounted for by the fact that the transmission coefficient becomes less than unity in this region.

While the results presented are in excellent agreement with the theory, it is nevertheless desirable to extend the investigation, and work on the problem is being continued to see whether the method can be developed to give a more accurate determination of h.

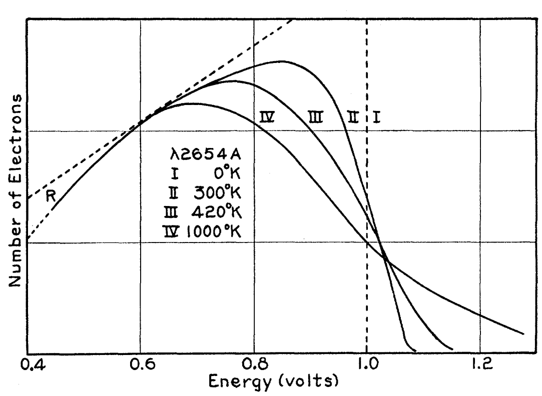

FIG. 13. Effect of temperature on energy distribution curves.

CONCLUSION

It is evident in Figs. 8, 9 and 10 that the experimental points fit the theoretical curve well within the limits of experimental error. From this we conclude that DuBridge's theory predicts quite accurately the form of the photoelectric energy distribution curves in the vicinity of the maximum energy. This result has a double significance. In the first place it means that we have further direct evidence that the electrons in a metal obey the Fermi statistics and that in escaping as photoelectrons this distribution is not appreciably affected by collision phenomena.

In the second place, as DuBridge has pointed out, it means that it is now necessary to examine more critically the previous experiments which have sought to evaluate Planck's constant by the photoelectric method. It is obvious that the ordinary extrapolation methods of determining V_m do not in general yield the value of V_m at 0°K, which according to the theory is the only one for which Einstein's equation would be expected to hold accurately. A study of the theoretical curves however reveals the surprising and fortunate fact that if a definite extrapolation method is adopted and followed consistently, it will yield apparent values of V_m which are all greater than the absolute zero values by almost exactly the same amount, provided only that the individual values of V_m are greater than about 1 volt. This would still yield the correct value of h. In other words, there is reason to believe that in the more accurate determinations of h by the photoelectric method (since they have satisfied the above conditions) the errors due to the temperature effect are not greater than the ordinary errors of extrapolation.[7]

In conclusion, the author takes this opportunity to express his gratitude to Professor L. A. DuBridge who proposed this problem, and whose suggestions were an invaluable aid throughout the investigation.

[7] This statement apparently applies also to the work of Lukirsky and Prilezaev, contrary to the tentative opinion expressed as to their work in Paper I, p. 741.