From Harnwell & Livingood "Experimental Atomic Physics"
McGraw-Hill (1933) pp 214-223

departs from a straight line at 0.8 volt applied accelerating potential; this point represents the true zero of potential between the filament and cylinder, indicating a retarding contact potential of 0.8 volt. With this and the value of the work function of the filament (obtained by an experiment with this tube such as yielded Fig. 6-6), the work function of the collecting cylinder can be computed through the use of Eq. (6-9).

6-8. Photoelectricity.—The discovery that a metallic surface, when illuminated by light of very short wave length, is able to emit electricity was made by Hertz in 1887,[1] during his fundamental researches in connection with an entirely different subject, namely, the resonance in electrical circuits. This discovery was investigated shortly afterward by Hallwachs[2] and by Elster and Geitel,[3] whose work established most of the fundamental phenomena of photoelectricity. As we have seen in an earlier chapter, Lenard and Thomson showed in 1898 that the ratio of the charge to the mass of the negatively charged particles emitted from a metal by the action of light had the same value as that for cathode rays. Hence the presumption that the particles were electrons was very strong, even at an early date. As the phenomena of photoelectricity are of such fundamental importance in physics, they have been the subject of careful investigation ever since their discovery. The enormous amount of experimental data which has accumulated and the modern interpretation have been presented by Hughes and DuBridge.[4]

The most important fundamental phenomena in connection with the ordinary surface photoelectric effect are the following:

1. If light of a given frequency is capable of liberating electrons from a surface, the electronic current is directly proportional to the intensity of the light.

2. For a given surface there is a longest wave length which can liberate electrons; light of longer wave length cannot free them, no matter how long it falls upon the surface or how great the intensity.

3. Light of wave length shorter than this critical value causes the emission of electrons, and the length of time which elapses between the illumination of the surface and the onset of the photoelectric current is not more than 3×10^{-9} sec.

4. The kinetic energy of the emitted electrons is directly proportional to the frequency of the light that frees them.

There are many other phenomena of great interest, such as the velocity distribution of the electrons, the effect of polarization and the angle of incidence of the light, the influence of the surface temperature and of applied electric fields, and the photoelectric behavior of thin films and composite surfaces. For a discussion of these points the reader is referred to Hughes and DuBridge.

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[1] HERTZ, *Ann. Physik*, **31**, 983 (1887).

[2] HALLWACHS, *Ann. Physik*, **33**, 301 (1888).

[3] ELSTER and GEITEL, series of papers in *Ann. Physik* (1889–1892).

[4] HUGHES and DUBRIDGE, "Photoelectric Phenomena," McGraw-Hill (1932).

These phenomena represent some of the most important corroborations of the conclusions reached in Chap. II as to the inadequacy of the classical electromagnetic theory of light. From the old viewpoint it can be shown that it would take hours for an atom to absorb enough energy from an advancing wave train of visible light of moderate intensity to supply the energy with which the photoelectron is actually ejected, and yet experiment shows that the emission occurs almost instantaneously. Furthermore, the electromagnetic theory is entirely unable to account for the fact that the energy of the electrons is independent of the intensity of the light but depends only on the frequency. These facts, however, find ready explanation on the quantum or photon conception of radiation developed in Chap. II. No mechanism is supposed to exist for the gradual accumulation of energy by an atom; if the energy of the incident photon is less than some critical value, say, $e\phi$, for the particular surface under consideration, no electron is emitted, and if the energy is absorbed at all it must result in increased thermal motion. On the other hand, the assumption is made that if the photon has enough or more than enough energy, it is absorbed as a whole by one of the semifree electrons which then escapes, using a quantity $e\phi$ of the photon's energy $h\nu$ in getting free of the surface, and carrying away the excess in the form of kinetic energy. This radical viewpoint of energy interchange was propounded by Einstein[1] in 1905 and is embodied in his fundamental equation

$$h\nu = \frac{mv^2}{2} + e\phi \tag{6-28}$$

where on the left we have the energy of the photon and on the right the kinetic energy of the emitted electron and the work done by it in getting over the potential barrier of the crystal. (We may here use the nonrelativistic expression for the kinetic energy, since the velocities are small.) It should be noted that since $e\phi$ represents the work done against the forces holding the electron to the crystal, there must be an equal reaction against the crystal itself, which is thus the third body necessary for the complete disappearance of the photon and the ejection of an electron, as we have seen earlier in this chapter. The quantity $e\phi$ is the difference between the height of the potential wall, in energy units, and the maximum energy of the electrons within the crystal at 0° Abs. and hence should be identical with the work function defined in Eq. (6-8), where we were describing the thermionic effect, *i.e.*, $e\phi = W_a - W$.

The above equation is in accord with the experimental observation that the energy of the freed electron is proportional to the frequency

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[1] EINSTEIN, *Ann. Physik*, **17**, 132 (1905); **20**, 199 (1906).

of the radiation. An increase of photoelectric current with an increase of light intensity follows from the picture of greater intensity being due to an increased density of incident photons, assuming a constant value for the probability of absorption of a photon by an electron. (The efficiency of emission, or the number of electrons freed per incident photon, is generally very low; it varies with the surface and with the frequency. The highest photoelectric yield yet recorded is about one electron for every ten photons, but it may be as low as only one electron per million photons.) The Einstein equation may be tested by observing the "stopping potential" V_0, between the emitting surface and a collecting electrode, against which the electrons are just not able to advance. This means that the kinetic energy at emission is equal to eV_0, so we may write

$$eV_0 = \frac{mv^2}{2} = h\nu - e\phi \tag{6-29}$$

It is apparent that if the frequency of the light is reduced the kinetic energy becomes less, reaching zero at the threshold frequency ν_0, so that

$$h\nu_0 = e\phi \tag{6-30}$$

A critical frequency ν_0 (or a critical wave length $\lambda_0 = c/\nu_0$) is thus predicted; lower frequencies should not cause any photoelectric emission at all. This is in agreement with the experimental facts. A plot of the stopping potentials for different frequencies against the latter should give a straight line of slope h/e, according to Eq. (6-29); the intersection with the voltage axis yields the value of ϕ, while the intercept on the ν-axis gives the threshold frequency ν_0. Studies of the photoelectric stopping potentials thus afford an extremely reliable method of determining Planck's constant h, if the electronic charge is assumed to be known. The most accurate values obtained by this method are given below.

Millikan,[1] 1916	$h = 6.57 \times 10^{-27}$ erg. sec.
Lukirsky and Prilezaev,[2] 1928	6.543
Olpin,[3] 1930	6.541

The estimated errors in the last two values are about 0.1 per cent. These values are in excellent agreement with those obtained from the black-body radiation laws and from other types of experiment to be mentioned later.

If we have a tube suitably designed for measuring photoelectric currents from an illuminated surface against a retarding potential, the types of current-voltage curves that are obtained are similar to those in

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[1] Millikan, *Phys. Rev.*, **7**, 355, (1916).
[2] Lukirsky, and Prilezaev, *Zeits. Physik*, **49**, 236 (1928).
[3] Olpin, *Phys. Rev.*, **36**, 251 (1930).

Fig. 6-11. As the retarding voltage is decreased a photoelectric current sets in quite suddenly, the voltage at which this occurs depending on the wave length of the light used. As the retarding potential is further reduced, the current rises rapidly and reaches a saturation value which is attained at approximately the same voltage for all wave lengths. As the space charge is negligible for such small currents, it follows that at this potential all the electrons liberated by the surface at all wave lengths less than the critical value are able to reach the collecting plate. Hence this represents the true zero of potential difference between the electrode surfaces, and the variation between this and the apparent potential V_m, as read by a potentiometer, is the contact potential between the surfaces. In Fig. 6-11 the critical voltage is taken as that at which the curves first show a tendency to saturation; reflection of electrons at the collecting plate prevents the break from being ideally sharp. All the electron currents have been proportionally reduced to the same value at this point, since the absolute values of the currents are of little significance, as they depend on the intrinsic brilliancy of each color in the exciting mercury arc and on the transparency of the glass bulb of the cell for the different wave lengths. If the observed values of the stopping potentials, at which the currents first begin, are plotted against the frequency of the light,

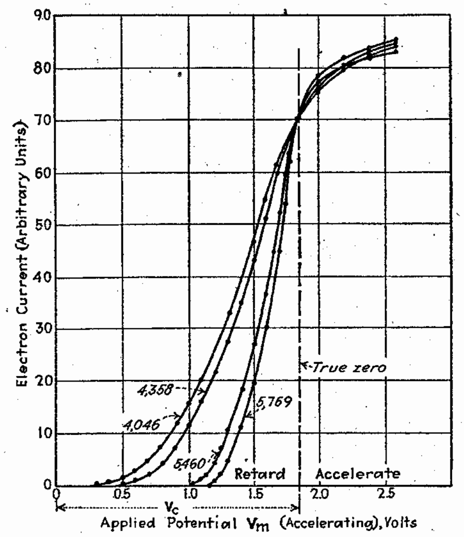

Fig. 6-11.—Photoelectric currents plotted against the applied potential, for several wave lengths of light. The ordinates have been proportionally reduced so that they all have the same value at the point where saturation sets in. This point locates the true zero of potential between the electrodes and indicates the magnitude of the contact potential V_c.

the points of Fig. 6-12 are obtained. They are seen to lie on a straight line in accordance with Einstein's relation, which may be written

$$V_m + V_c = V_0 = \frac{h\nu}{e} - \phi \tag{6-31}$$

where the true stopping potential V_0 is the algebraic sum of the potentiometer reading V_m and the contact potential V_c. The scale on the right of Fig. 6-12 represents the potentiometer readings, which are all 1.85 volts too large; *i.e.*, the contact potential is $V_c = -1.85$. The scale on the left shows the true stopping potentials when corrected by this amount. The intercepts indicate that the emitting surface has a long wave-length limit of 8815 Å ($\nu_0 = 34 \times 10^{13}$ sec.$^{-1}$) and a value of ϕ equal to 1.37 volts. By Eq. (6-9) we see that the contact potential is equal to the difference between the work functions of the emitting and collecting electrodes, so that the work function of the latter is 1.37 − (−1.85) or 3.22 volts. By means of Eq. (6-30) we see that this corresponds to a long wave-length limit of 3830 Å for the collector; the latter is therefore incapable of emitting any electrons under the influence of scattered light of the wave lengths used. This is an essential if the onset of photoelectric current is to occur abruptly. The ratio h/e is given by the slope of the line in Fig. 6-12, if the volts are divided by 300 to reduce them to electrostatic units, yielding the value 1.35×10^{-17}. Taking $e = 4.770 \times 10^{-10}$, we find $h = 6.44 \times 10^{-27}$ erg sec., which is within 2 per cent of the accepted value. It is obvious that any error in choosing the contact potential from the breaks in the curves of Fig. 6-11 will affect only the values of the work functions and long wave-length limits, without influencing the determination of h.

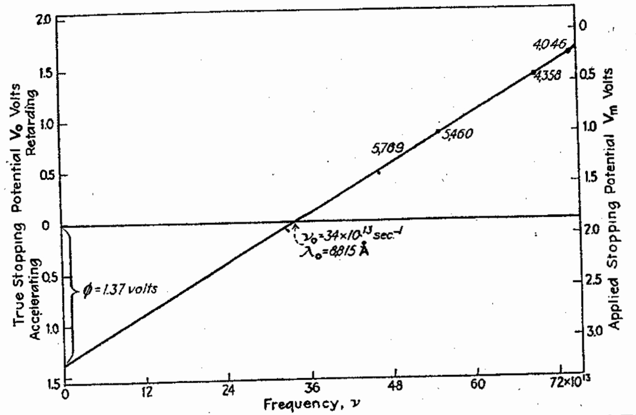

FIG. 6-12.—A plot of the data of Fig. 6-11 to demonstrate the validity of Einstein's equation for photoelectricity. Here the stopping potentials for the emitted electrons are plotted against the frequency of the light. The slope of the resulting straight line is equal to the ratio h/e.

The shape of the photoelectric current curves below saturation is of considerable interest. The general form of the energy distribution curve for electrons in a metal, as shown in Fig. 6-2, explains the sharpness with which the curves of Fig. 6-11 leave the axis. At 0° Abs. this angle should be unmistakably finite, since the electrons in the metal then have a sharply defined upper limit to their energy, which when augmented by the energy of the photon $h\nu$ must be equal to, or greater than, the height of the potential barrier W_a, if the electrons are to escape. At higher temperatures the onset of the photoelectric current becomes less abrupt, due to the rounding off of the energy distribution curve in the metal. The actual energy distribution of the electrons leaving the surface can be computed from the current-voltage curves below saturation if the emitter is small and at the center of a spherical collector, so that the total energy is measured and not merely the component normal to the surface as is the case with plane-parallel electrodes. An analysis by magnetic deflection can be used to calculate the energies directly. Such experimental energy distribution curves agree fairly well with that which would be predicted from the internal distribution curve, similar to Fig. 6-2, on the assumption (doubtless only a first approximation) that the probability of absorption of a photon by an electron is independent of the electron's original energy. If the latter quantity were simply increased by an amount $h\nu$, the energy distribution curve of Fig. 6-2 would merely be shifted to the right along the axis a distance $h\nu$, and the distribution of the electrons that escape would be given by the portion of the curve for which $W + h\nu$ is greater than the potential barrier W_a.

The saturation portion of the current-voltage curves exhibits many of the same characteristics as the analogous part of the thermionic diagrams. Strong fields effectively lower the work function. This is most marked in the case of composite surfaces. A factor influencing the photoelectric effect, that is not present in the case of currents from heated filaments, is the so-called *reverse emission*. Electrons may be released from the surface intended as the collector because of light scattered to it, unless its work function is sufficiently high to prevent this. Such emission has the result of lowering the curves of Fig. 6-11 in the region below saturation, and it introduces considerable uncertainty in the exact points of departure of the curves from the axis, with consequent error in the determination of the ratio h/e.

6-9. Experiments on Photoelectricity.—Verification of the linear relation between photoelectric current and intensity of illumination can be made with any ordinary photo cell. A tube with a composite surface, such as the Western Electric type 3-A is very satisfactory, as the currents are so large that a sensitive galvanometer may be used to record them.

The experimental set-up is indicated in Fig. 6-13. An Ayrton shunt and galvanometer are connected in series with the cell and a battery of from 20 to 50 volts. The illumination may be supplied by a 100-watt incandescent lamp, preferably with a frosted bulb, as the angular distribution of the emitted light is more uniform. With this arrangement the light intensity or energy density per unit area decreases as the square of the distance from the lamp. The galvanometer currents are recorded as the lamp is placed at various distances, D, from the cell, and a plot of the current against $1/D^2$ yields a straight line. In order to calculate, from the slope, the number of electrons liberated per photon falling on the surface, the source would have to be monochromatic and the energy radiated per second at that wave length would have to be known, as well as the transmission coefficient of the bulb of the photo cell.

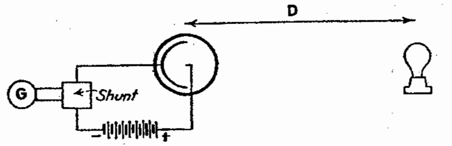

FIG. 6-13.—A diagrammatic sketch of an apparatus to demonstrate that the photoelectric current varies directly with the light intensity.

For an accurate evaluation of the ratio h/e a tube of special design must be employed, since the reverse emission from the collector in ordinary tubes prevents a reliable determination of the stopping potentials for various wave lengths. A photoelectric cell, such as has been described by Olpin,[1] has been used to obtain the data given in Figs. 6-11 and 6-12, through the courtesy of the Bell Telephone Laboratories. In order to eliminate reverse emission, the light-sensitive surface is deposited on the emitting electrode in the chamber B (see Fig. 6-14). This electrode is then allowed to slide down the glass rod inside the tube, until it is surrounded by the soot-covered nickel cylinder in chamber A. This cylinder acts as the collecting electrode. The work function of the sodium surface, activated with sulphur, is only 1.37 volts, so that light of wave length shorter than 8800 Å is capable of ejecting electrons from it. On the other hand, radiation of wave length greater than about 3800 Å cannot free electrons from the cylinder, because of its large work function of 3.22 volts. Hence, in the range from 3800 to 8800 Å, a photoelectric current can be caused only by the sodium surface.

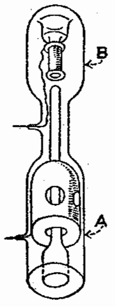

FIG. 6-14. The photoelectric cell, designed to eliminate reverse emission from the collector, used in the determination of h/e.

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[1] OLPIN, *Phys. Rev.*, **36**, 251 (1930).

The schematic arrangement for the use of this tube is shown in Fig. 6-15. The most convenient source of illumination is a small quartz or glass mercury arc. The mercury lines in the visible can be obtained with great intensity from such a source; if of quartz, the arc should be properly housed for protection of the operator from the strong ultra-violet radiation, which may cause serious burns. With an arc that runs on direct current, it is advisable to include a large inductance in the circuit, such as a transformer winding, to promote steadiness of operation. The adjustable resistance R_a limits the current to its rated value. If a mercury arc is not available, a powerful incandescent tungsten-filament lamp may be used; smaller photoelectric currents will be obtained, however, and a very accurate calibration of the monochromator is required.

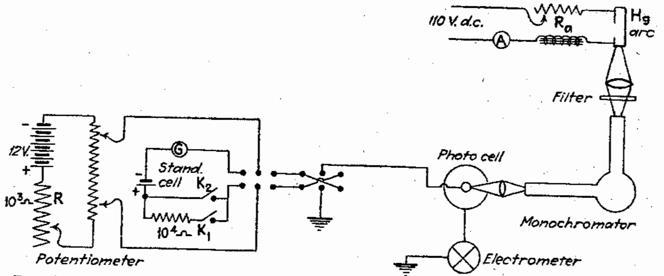

FIG. 6-15.—An arrangement for the photoelectric determination of the ratio h/e, by measurement of the stopping potentials for electrons liberated by different wave lengths.

The light is focused by means of a large condensing lens on the slit of a monochromator. A suitable instrument, where the highest accuracy is not essential, is a small constant-deviation spectroscope, which may be converted into a monochromator by replacing the eyepiece with a slit. In such an instrument there is inevitably a certain amount of scattered light not of the proper wave length reaching the exit slit, but as only light of shorter wave length is troublesome for photoelectric work, various filters may be inserted between the source and monochromator to cut out wave lengths shorter than that for which the instrument is adjusted. This is not absolutely essential, but the filters shown in the table on page 222 are suggested.

Two holes are provided in the collecting electrode of the photo cell, so that the light falling on the emitting surface through one opening may be observed through the other for adjustment. A small lens may be used to concentrate the light from the monochromator on to the surface. After adjusting the line up of the instruments by visual observation of the brilliant yellow or green lines, the fainter colors may be obtained with maximum intensity by looking into the exit slit of the monochromator with a small mirror while the dial is turned, or by adjusting this control near the approximately correct position until a maximum photoelectric current is obtained, with an accelerating field of 5 or 6 volts. The accuracy with which a particular spectral line may be isolated depends upon the dispersion of the monochromator; if the close groups in the table below cannot be separated, an error of about 0.5 per cent in the wave number will be introduced. Unless extreme care is used, this is generally within the other limits of error of the procedure described.

Line used		Filter	Short wave-length cut-off
λ	$\tilde{\nu}$		
6,234.35 Å	16,035.8 cm.$^{-1}$	Wratten 29 or Corning 243	6,000 Å
6,123.47	16,326.1		
6,072.63	16,462.9		
5,790.66	17,264.5	Wratten 23	5,600
5,769.60	17,327.5		
5,460.74	18,307.5	Wratten 16	5,200
4,916.04	20,335.9	Corning 351	4,700
4,358.34	22,938.1	Corning Noviol A, 2 mm.	4,100
4,347.50	22,995.3		
4,339.23	23,039.1		
4,077.83	24,515.9	Corning 306	3,950
4,046.56	24,705.4		
3,662.88	27,293.2	Quinine sulphate in water. 3 mg./cm.^{3}. 10 mm., or Corning 597, 3.2 mm. and 10 per cent $CuSO_4$ solution. 20 mm.	3,600 3,600
3,654.83	27,353.3		
3,650.15	27,388.4		

The electrostatic shielding around the photo cell may conveniently be a thin galvanized-iron spouting 6 in. in diameter and 20 in. long; this acts also as a light shield. The upper and lower ends are fitted with light-tight caps, the photo cell being supported by a clamp passing through a hole in the upper one. The tubular metal shield around the lead wire from the collecting electrode to the electrometer enters through a hole in the spouting, and two other holes are cut in it for the admission of light and for observation. This latter opening may be covered with black paper when not in use; the light shield between the monochromator and the spouting may be a black-paper cylinder waxed into place. It is

impossible to overemphasize the necessity of excluding from the photo cell absolutely all stray light, if satisfactory results are to be obtained. All the metal shields should be soldered together and thoroughly grounded; the wire from the emitting surface to the battery is insulated with cotton or rubber and may be passed through one of the end caps. For the intense light from a mercury arc, an ordinary Dolezalek electrometer used with the constant-deflection method is quite satisfactory, but for feebler sources a Compton electrometer or direct-current amplifying tube (such as the General Electric FP-54 pliotron) should be used. Details of technique may be found in Appendix A.

The retarding or accelerating potentials are supplied by a potentiometer and a reversing switch. The Leeds and Northrup type K is convenient, since it reads directly up to 16 volts, but the simpler type consisting merely of a set of calibrated resistances can also be used. If the normal range of the instrument is 1.6 volts, and if it is capable of maintaining its calibration for five times the normal current, potentials up to 8 volts can be obtained. The method of calibration for the higher range is simply to set the dials for one-fifth the voltage of the standard cell and to vary the external resistance R until the galvanometer shows no deflection when the keys K_1 and K_2 are closed in the usual manner. In this adjustment the actual potentials are five times the dial readings.

The method of procedure is to adjust the monochromator for the desired wave length and to reduce the retarding potential, in small steps, from a few volts to zero; then to throw the reversing switch and increase the accelerating field from zero to the potential at which saturation is reached. In the region where the photoelectric current is about to set in, the potential changes should be very small, about 0.05 volt; these critical regions may be found in a rough preliminary survey.