

4. The Photoelectric Effect

4.1 GENERAL

It was observed as early as 75 years ago that most metals under the influence of radiation (light), especially ultraviolet radiation, emit electrons. This phenomenon was termed photoelectric emission, and detailed study of it has shown:

(a) That the emission process depends strongly on the frequency of the light, and that for each metal there exists a critical frequency such that light of lower frequency is absolutely unable to liberate electrons while light of higher frequency always does. Indeed, for a given surface, if the frequency of the incident radiation is increased, the energy of the emitted electrons increases in some linear relation.

(b) The emission of the electrons occurs within a very short time interval after the arrival of the radiation, and the number of electrons emitted is strictly proportional to the intensity of the radiation.

The experimental facts given above are among the strongest evidence for our present-day belief that the electromagnetic field is *quantized*. They cannot be explained in terms of a continuous energy distribution in the radiation field, but it must be assumed that the field consists of "quanta" of energy

$$E = h\nu$$

where ν is the frequency of the radiation and h is Planck's constant (an expression we have already used in Section 3). These quanta are called *photons*.

Further it is assumed[†] that the electrons are bound inside the metal surface with an energy $e\phi$, where ϕ is called[†] the "work function," and that all such electrons have equal probability of absorbing a photon. It then follows that if the frequency of the light ν is such that

$$h\nu > e\phi$$

it will be possible to eject photoelectrons, while if

$$h\nu < e\phi$$

this is impossible, since the probability that an electron will absorb two photons simultaneously is minimal. In the former case, the excess energy of the quantum appears as kinetic energy of the electron, so that

$$h\nu = \frac{1}{2}mv^2 + e\phi \quad (4.1)$$

[†] See Chapter 3.

which is the famous photoelectric equation formulated by Einstein in 1905. In writing the equation in this form we express the fact that the energy is shared between the electron and the photon only; however, to balance momentum[†] a third body is needed, which in this case is the crystal lattice, which recoils with negligible energy.

Thus in the photoelectric effect we observe the transfer of the total energy of a photon to an electron bound in a lattice. We will see later another transfer mechanism, prevalent at higher photon energies, whereby only part of the energy of the photon is transferred to a free electron: this is the Compton scattering.

Equation 4.1 has been extensively verified for many materials and over a broad range of frequencies. What is experimentally measured is the energy of the emitted photoelectrons against frequency, either with a magnetic field or in a simpler way by a retarding potential technique, as is done in this laboratory exercise. Since the "work function" ϕ is usually not known beforehand, the kinetic energy of the photoelectrons $E_e = \frac{1}{2}mv^2$ is obtained as a function of ν so that the slope of the straight line

$$E_e = h\nu - e\phi$$

yields h , and the intercept at the extrapolated point $\nu = 0$, can give $e\phi$. When a retarding potential V is used to measure E_e , we have $E_e = eV_0$, so that really it is the ratio h/e that is determined:

$$V_0 = (h/e)\nu - \phi \quad (4.2)$$

The arrangement generally used consists of a clean surface of the metal to be investigated, and an anode facing or surrounding the cathode, both sealed in vacuum. When radiation is incident on the cathode, electrons are emitted which reach the anode giving rise to a detectable current if the circuit between anode and cathode is completed through a sensitive current meter as shown in Fig. 1.12. If a negative potential V is applied to the anode, only electrons with $E_e > eV$ can reach the anode, and for some potential V_0 no electrons at all arrive at the anode; this retarding potential multiplied by e is equal to the energy of the fastest electrons emitted. In practice all electrons are not emitted with the same energy, and therefore the threshold at V_0 , is not very sharp; space charge effects further reduce the definition.

An additional consideration, already encountered in the Frank-Hertz experiment is the contact potential difference; namely, the fact that the potential applied and measured across the anode and cathode leads does

[†] Note that in any event the electrons are emitted in a direction opposite to that of the incoming radiation.

not equal the potential that the electron traveling from the cathode to the anode has to overcome. To see this, consider Fig. 1.13, where ϕ_C represents the work function of the cathode and $\phi_A \neq \phi_C$ is the work function of the anode. The external voltage V' is applied between metallic junctions and we may neglect the ohmic voltage drop in the leads; thus the electrons *inside* the anode are at potential V' higher than the electrons *inside* the cathode. The energy losses around the loop of Fig. 1.13 must, however, be zero, and the arrows indicate the direction for which an electron *loses* energy in the field (namely, negative potential); if V is the potential seen by the free electron, we obtain

$$-e\phi_C + eV + e\phi_A - eV' = 0$$

or

$$V = V' - (\phi_A - \phi_C) \quad (4.3)$$

The term $(\phi_A - \phi_C)$ is the contact potential difference (cpd) and usually $\phi_A > \phi_C$. Therefore the measured potentials V' must be corrected according to Eq. 4.3 in order to be used in Eq. 4.2. One way of finding the contact potential difference is to normalize all curves to the same saturation current and observe for what (common) value of V' saturation sets in; this must correspond to the point where V changes over from retarding to accelerating—namely, from Eq. 4.3, $V = 0$ or $V' = \phi_A - \phi_C = \text{cpd}$.

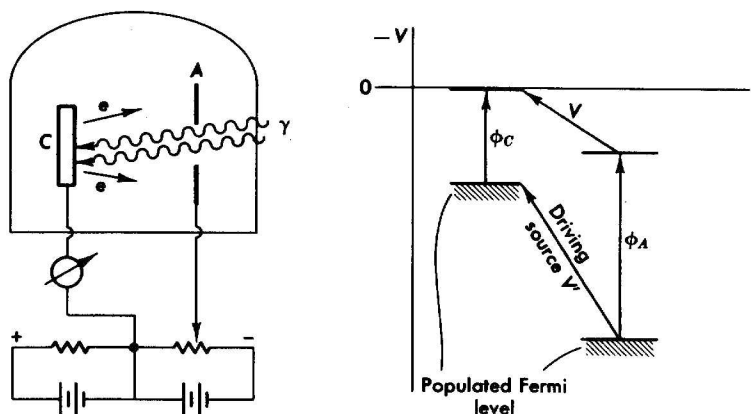


FIG. 1.12 (Left) Schematic of a setup for detecting the photoelectric effect; the anode can be made either negative or positive with respect to the cathode.

FIG. 1.13 (Right) Potential at anode (-) and cathode (+) of photoelectric cell; w and w' are the work functions of anode and cathode, respectively. Note that $\phi - V - \phi' + eV' = 0$ so that the potential seen by the free electron is $V = V' - (\phi - \phi')$.

By combining Eqs. 4.1 and 4.3 we note that if emission stops for an applied *retarding* potential V_0' , then

$$V_0 = V_0' + (\phi_A - \phi_C) \quad (4.3b)$$

further

$$e|V_0| = \frac{1}{2}mv^2 = h\nu - e\phi_C \quad (4.1b)$$

so that

$$|V_0'| = (h/e)\nu - \phi_A \quad (4.2b)$$

namely, a plot of the *applied* stopping potential (without cpd corrections) vs. ν yields a line of slope h/e but with an intercept at $\nu = 0$ equal to the work function of the *anode* rather than to the work function of the cathode predicted by Eq. 4.2.

4.2 THE EXPERIMENT

To perform the experiment we need a source of monochromatic light, at several frequencies, the photoelectric cell, and a sensitive current detecting device.

In this laboratory the photocell is of special construction (Leybold catalogue 55877) with a potassium (coated) cathode and an anode which consists of a platinum ring (Fig. 1.14). A special casing is available for pro-

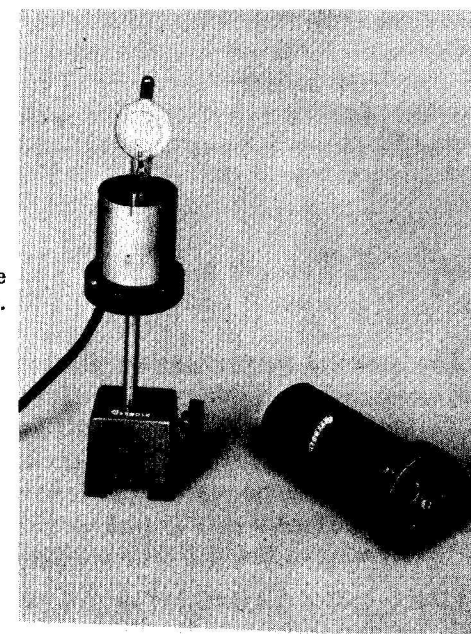


FIG. 1.14 A photocell made by the Leybold Company (Catalog No. 55877).

tection, electrostatic shielding, and adequate insulation of the anode contact.

The optical system is mounted on an optical bench as shown in Fig. 1.15. The light source is a high-pressure mercury discharge (Will Corp. 17391); it is focused onto slit 1 and then dispersed in the direct vision prism (Leybold 46604). Slit 2 selects the desired wavelength. The direct vision prism consists of a combination of two crown glass and one flint glass prisms and passes medium wavelengths without refraction.

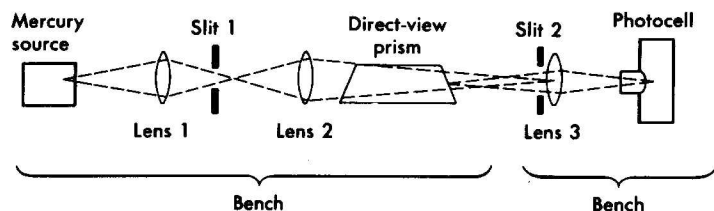


FIG. 1.15 Optical system for photoelectric effect measurement.

When the system is set up, the source must be focused on slit 1, and the image of the slit focused on lens 3; a sharp image of the spectral line can then be obtained on the photocathode by adjusting the prism and photocell positions. Since the system is chromatic, each line must be refocused independently. Obviously it is easier to make these adjustments in a darkened room or with the help of black cloth.

Care must be taken that the incident radiation contains only the line chosen for the investigation, and that it does not hit the platinum anode.† This can be achieved by placing an appropriate mask in front of the photocell.

The mercury lines most readily available are

Yellow	at	5770 Å and 5790 Å
Green	at	5461 Å
Blue-green	at	4916 Å (weak)
Blue	at	4358 Å mainly, and at 4343, 4339 Å
Violet	at	4047 Å

The electrical connections are shown in Fig. 1.16. The photocurrent is measured with a Keithley electrometer connected to the photocathode while the anode is returned to ground through a variable d-c voltage which provides the desired retarding or accelerating field. Since the voltages applied between anode and cathode are very small, appropriate corrections must be made for the voltage drop produced in the meter, due to the photocurrent flowing in the large input impedance.

† Due to scattering a small fraction of the incident radiation reaches the anode.

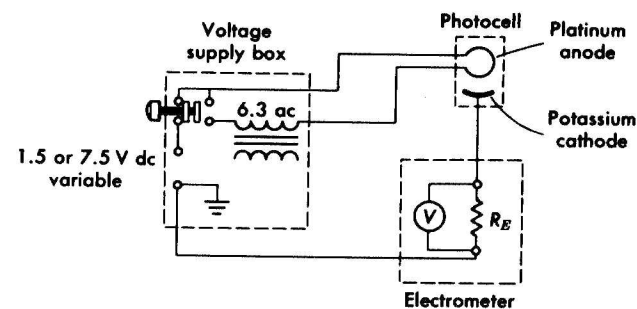


FIG. 1.16 Wiring diagram for photoelectric effect measurement.

Provisions exist for connecting the anode ring to a 6.3-V a-c supply; thus the anode may be heated in order to evaporate any potassium traces that have deposited on it. It is usually adequate to close the circuit momentarily, since long heating will destroy the anode. The retarding (or accelerating) potential is obtained from a fixed source and a calibrated resistive network, which must, however, be checked against a potentiometer.

In performing the experiment, after the desired line has been focused on the photocathode, the current is measured as a function of the voltage applied between anode and cathode. In principle the accelerating potential should be increased (in appropriate steps) until saturation is reached; this is, however, difficult to achieve with the photocell described here.‡ The decelerating potential should also be decreased until zero current is observed and beyond that point, to assure that the current remains zero.

Frequently, as is the case with this particular apparatus, a reverse current is observed leveling off at approximately 10^{-12} amp; this is attributed to photoemission from the anode and introduces difficulties in the exact determination of the stopping potential V_0' . Nevertheless, it is possible to obtain significant results if the same consistent criterion is used at all wavelengths for obtaining V_0' .

Since the current variations in the vicinity of the stopping potential are of the order of 10^{-13} amp, their measurement becomes difficult and special care must be exercised. Leakage current across the glass face of the tube must be minimized, as by surrounding the bulb base with a moisture absorber (silica gel), especially on humid days. The cathode contact must be kept very clean (with alcohol and hot air), all leads on the high-impedance side must be coaxially shielded, and the appropriate connectors must be used. The electrometer and apparatus should be protected from vibrations and stray field pickup. Dark current must be monitored and appropriate corrections applied.

‡ Mainly due to geometrical considerations.

Finally, caution must be exercised in using the mercury source, since its envelope transmits ultraviolet light, which can cause serious damage to the eyes and sunburn to the skin.

4.3 ANALYSIS OF THE DATA

The data presented below were obtained by students.[†] The five lines of mercury mentioned in the previous section were used, and the photocurrents near saturation due to these lines were in the following proportion:

Yellow	1.00
Green	1.50
Blue-green	0.44
Blue	1.70
Violet	0.55

These yields are a combination of the intensity of the spectral lines, their attenuation in the optical system, and the photosensitivity of the cathode, which is not the same at all wavelengths. In analyzing the data as mentioned before it is useful to normalize all photocurrents to the same saturation

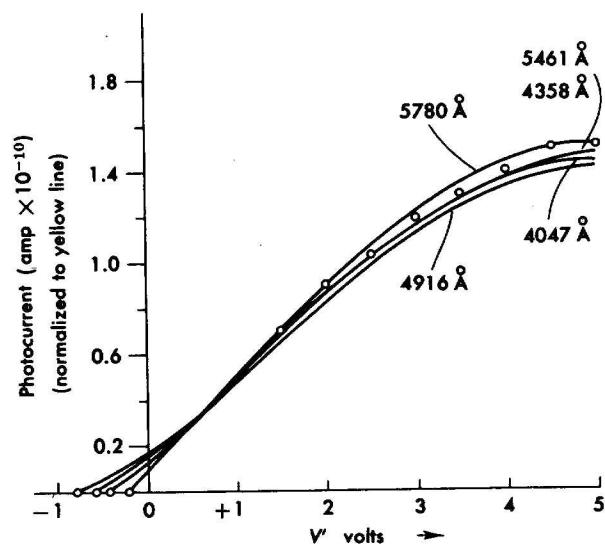


FIG. 1.17 Photocurrent as a function of anode voltage. The currents have been normalized to the yield from the yellow lines ($\lambda = 5780 \text{ \AA}$).

[†] D. Owen and D. Sawyer, class of 1963.

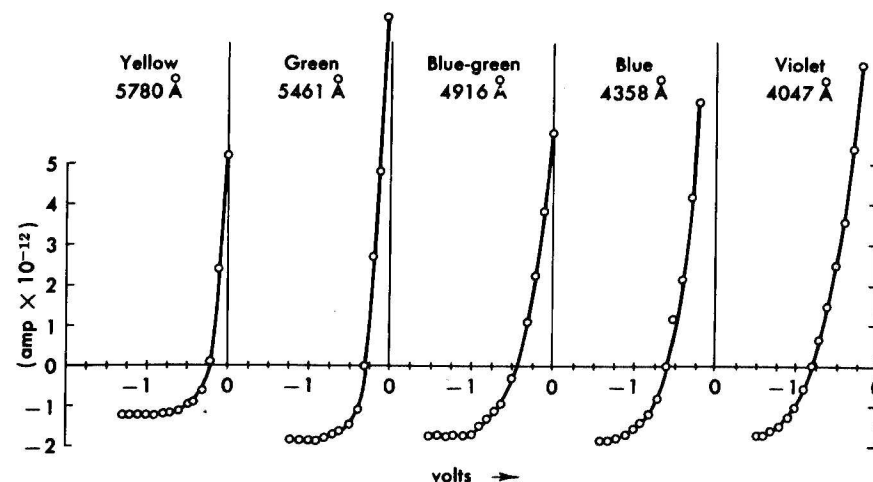


FIG. 1.18 Photocurrent for different wavelengths as a function of stopping potential; the same normalization as in Fig. 1.17 has been used. Note the reverse current due to photoemission from the anode.

tion value; the results of such normalization for the five wavelengths are shown in Fig. 1.17. We note that in the accelerating region the curves are quite similar, and the small differences can be attributed to observational errors.

On the other hand, Fig. 1.18 represents the region close to the stopping point, but separately for each wavelength; the normalized photocurrents are shown. In spite of the reverse current it is possible to read off the stopping potential for each line; the difficulty arises rather from the apparent zero slope of the curves.[†] From these curves values of V_0' have been obtained (a) by forming the intersection of the tangents to the limiting branches of the curves, and (b) by estimating the voltage at which the current curve begins to rise. These values are given in Table 1.2.

A plot of these stopping voltages and the least-squares fit are shown in Fig. 1.19. We see that in both cases a correct order of magnitude of h/e is obtained namely:

$$\text{Method (a)} \quad h/e = (3.84 \pm 0.55) \times 10^{-15} \text{ V-sec} \\ \text{intercept at } \nu = 0 \quad V' = +1.2 \text{ V}$$

$$\text{Method (b)} \quad h/e = (3.84 \pm 0.4) \times 10^{-15} \text{ V-sec} \\ \text{intercept at } \nu = 0 \quad V' = 1.6 \text{ V}$$

[†] It should be a finite slope, but this is not observed in the present arrangement because of the reverse current.

TABLE 1.2
RETARDING POTENTIALS REQUIRED TO STOP PHOTOEMISSION AS OBTAINED FROM
FIG. 1.18

Line	Retarding potentials	
	(a)	(b)
Yellow	-0.25 V	-0.7 V
Green	-0.40	-0.8
Blue-green	-0.70	-1.0
Blue	-0.82	-1.3
Violet	-1.15	-1.5

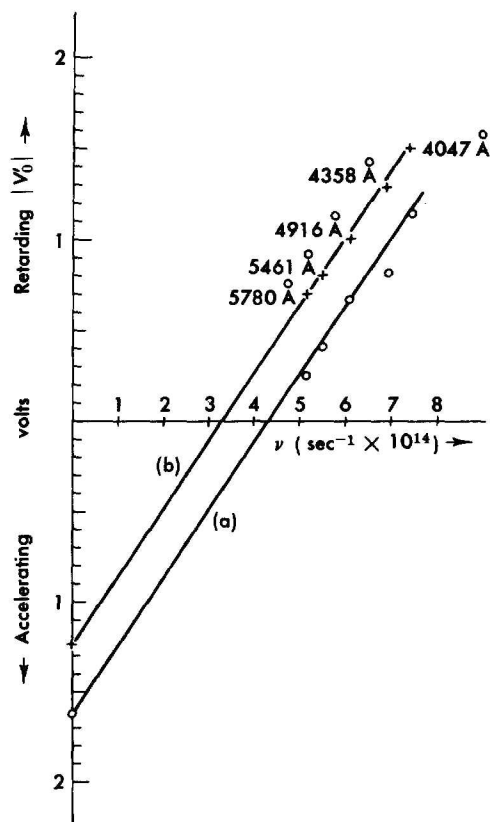


FIG. 1.19 Plot of applied stopping potential versus frequency. Lines (a) and (b) refer to the data of Table 1.2.

Multiplying by the charge of the electron $e = 1.6 \times 10^{-19}$ coulombs we obtain

$$h = (6.14 \pm 0.8) \times 10^{-34} \text{ joules-sec}$$

to be compared with the accepted value of

$$h = 6.61 \times 10^{-34} \text{ joules-sec}$$

While the value obtained for h/e is quite satisfactory it is not possible to draw any conclusions with regards to the cpd. The known values for the work functions are

$$\text{anode, platinum } \phi_A = 5.29 \text{ V}$$

$$\text{cathode, potassium } \phi_C = 2.15 \text{ V}$$

And thus $\text{cpd} = 3.14 \text{ V}$. This value is in qualitative agreement with the saturation data of Fig. 1.17. However, from Fig. 1.18 we are inclined to deduce $\phi_A \approx 1.5 \text{ V}$ rather than $\approx 5 \text{ V}$; this fact, is a further indication that cathode material had deposited on the anode while these data were obtained.

Thus we have seen in three basic experiments that fundamental quantities of nature, such as the electric charge, the energy of electrons bound in an atom, and the energy of the electromagnetic field are quantized: that is, they cannot take any of a continuous set of values but only discrete ones. This fundamental characteristic of our world was first formulated in 1901, when Max Planck introduced it as the basic hypothesis for his theoretical interpretation of the spectrum (continuous in frequency) of a heated black body. It has led to a serious revision of both the method of thought and the mathematical tools of physics.

A slightly more detailed description of these experiments, including references to the original literature can be found in G. P. Harnwell and J. J. Livingood, *Experimental Atomic Physics*. New York: McGraw-Hill (1961).