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 \( \nu \) 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\(^\dagger\) that the electrons are bound inside the metal surface with an energy \( e\phi \), where \( \phi \) 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 \( \nu \) 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

\[ h \nu = \frac{1}{2}mv^2 + e\phi \]  \hspace{1cm} (4.1)

\(^\dagger\) See Chapter 3.

4. The Photoelectric Effect

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" \( \phi \) is usually not known beforehand, the kinetic energy of the photoelectrons \( E_e = \frac{1}{2}mv^2 \) is obtained as a function of \( \nu \) 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:

\[ V_0 = \frac{(h/e)}{\nu} \phi \]  \hspace{1cm} (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...
1. Experiments on Quantization

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 \( \phi_C \) 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

\[
V = V' - (\phi_A - \phi_C)
\]  

(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 \(V'' = \phi_A - \phi_C = \text{cpd}\).

4. The Photoelectric Effect

By combining Eqs. 4.1 and 4.3 we note that if emission stops for an applied retarding potential \(V'\), then

\[
V_0 = V' + (\phi_A - \phi_C)
\]

(4.3b)

further

\[
e\left| V_0 \right| = \frac{1}{2}mv^2 = h\nu - e\phi_C
\]

(4.1b)

so that

\[
\left| V_0 \right| = \left(\frac{h}{e}\right)\nu - \phi_A
\]

(4.2b)

namely, a plot of the applied stopping potential (without cpd corrections) vs. \(\nu\) 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 58577) 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. 1.12 (Left) Schematic of a setup for detecting the photoelectric effect; the anode can be made either negative or positive with respect to the cathode.](image)

![Fig. 1.13 (Right) Potential at anode (−) and cathode (+) of photoelectric cell; \(\phi\) and \(\phi'\) 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 \(V = V' - (\phi - \phi')\).](image)
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 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 $V'_s$ 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:

- **Method (a)**
  \[ h/e = (3.84 \pm 0.55) \times 10^{-14} \text{ V-sec} \]
  \[ \text{intercept at } V' = +1.2 \text{ V} \]

- **Method (b)**
  \[ h/e = (3.84 \pm 0.4) \times 10^{-14} \text{ V-sec} \]
  \[ \text{intercept at } V' = 1.6 \text{ V} \]

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

† D. Owen and D. Sawyer, class of 1963.
Multiplying by the charge of the electron \( e = 1.6 \times 10^{-19} \) coulombs we obtain

\[
h = (6.14 \pm 0.8) \times 10^{-24} \text{ joules-sec}
\]

to be compared with the accepted value of

\[
h = 6.61 \times 10^{-24} \text{ joules-sec}
\]

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

- anode, platinum \( \phi_A = 5.29 \text{ V} \)
- cathode, potassium \( \phi_C = 2.15 \text{ V} \)

And thus cpd = 3.14 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).