1 A2: The Photoelectric Effect - Measurement of the Planck constant

(Reference: Mansfield and O'Sullivan pp. 362–365)

In 1899 J.J. Thomson found that under certain conditions electrons are emitted from a clean metal surface when it is exposed to electromagnetic radiation (light). This phenomenon is called *The Photoelectric Effect*. Three years later P. Lenard studied how the energy of these electrons varied with the intensity of the light and found to his surprise that there was no dependence at all. Doubling the light intensity only doubled the number of electrons emitted, but did not affect the energies of the emitted electrons.

However, Lenard had a very powerful arc lamp with sufficient intensity to study the photoelectric effect using light in different wavelength ranges. He found that the maximum energy of the ejected electrons did indeed depend on the wavelength and that shorter wavelength (higher frequency) would lead to electrons ejected with more energy. Below a certain frequency, f_0, no electrons would be emitted at all, regardless of the radiation intensity.

Theory

The threshold frequency f_0 depends on the particular metal and requires a quantum explanation, which was given by Einstein in 1905. He assumed that the incoming radiation should be thought of as quanta of energy hf, with f being the frequency. One such quantum can be absorbed by one electron, which then uses the energy gained to try to escape from the material. If the electron is some distance into the material, some energy will be lost as it moves towards the surface. Additionally, an electrostatic potential has to be overcome as the electron leaves the surface. The energy necessary for that is usually called the work function, ϕ. The most energetic electrons emitted will be those very close to the surface, and they will leave the cathode with the kinetic energy

$$K_{\max} = hf - \phi \; . \tag{1.1}$$

If the metal (the cathode) is placed in an evacuated tube and a second electrode (the anode) is introduced to collect the electrons, a current flows if a suitable potential difference is applied between the anode an cathode. The kinetic energy of the electrons can then be measured experimentally by making the anode voltage V progressively more negative with respect to the cathode until the electron current drops to zero. At this point the field energy, $eV_{\max}$, equals the kinetic energy

$$eV_{\max} = K_{\max} \ . \tag{1.2}$$

Secondly, when the photon energy equals the work function of the metal, $hf_0 = \phi$, no excess energy is available to be transferred into kinetic energy for the electrons, $K_{\max} = 0$, and no electrons are ejected. From eqs. (0.1) and (0.2) we obtain

$$eV_{\max} = hf - hf_0 = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) \tag{1.3}$$

$$\Rightarrow \qquad V_{\max} = \frac{hc}{e}\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) \ . \tag{1.4}$$

Varying the frequency of the incoming light and plotting $\frac{1}{\lambda}$ against $V_{\max}$ will therefore yield a straight line with a slope $\frac{hc}{e}$ which intercepts the $V_{\max}$ axis $\left(\frac{1}{\lambda} = 0\right)$ at

$$V_{\max}(0) = -\frac{hc}{e\lambda_0} = -\frac{\phi}{e} \ . \tag{1.5}$$

Measuring the slope and the intercept, one can therefore determine Planck's constant h and the work function ϕ of the metal. [using $c = 3 \times 10^8$m/s and $e = 1.6 \times 10^{-19}$C]

Because the work functions of pure metals are greater than 4 eV and the typical quantum energy of visible light is about 2 eV, ultraviolet radiation is needed to produce photoemission from pure metal cathodes. To produce photoemission with visible radiation we use a caesium antimony cathode (with low work function) in this experiment.

Procedure

The wavelength of the incident light is determined by using filters to isolate narrow wavelength ranges from the continuous spectrum of a tungsten filament of a desk lamp. When the light hits the cathode, a current starts flowing (if the anode-cathode voltage is zero) and a potentiometer is used to give the anode an increasing negative potential with respect to the cathode until this current falls to zero ($V = V_{\max}$).

Since the current will be small as $V_{\max}$ is approached it must be amplified for a sensitive measurement. The d.c. signal of the electron current is therefore transformed into

an a.c. signal which is amplified by an a.c. amplifier and monitored by a cathode ray oscilloscope (CRO). The transformation to an a.c. signal is achieved by operating the tungsten filament lamp from the a.c. mains (50Hz). The filament is heated and cooled every half cycle of the mains so that the intensity of the light varies at twice the mains frequency (100Hz). The photoelectric current, which varies at this frequency, is passed through a resistor and the a.c. voltage across the resistor is amplified by an a.c. amplifier and displayed on the CRO. As V_{max} is approached the photocurrent and the CRO signal go to zero.

The voltage V_{max} is measured by a digital voltmeter connected to the monitor output whenever the button switch is pressed. The output of the amplifier, marked ' OUT', is displayed on the CRO. The earth terminal on the output should be connected to the earth terminal on the CRO. The 40W tungsten filament lamp should be placed about 20 cm from the photodiode and kept in this position for each filter.

Measure V_{max} for each wavelength (each filter) available to you and repeat this measurements a few times, to be able to do an error analysis of your data.

As a second experiment, measure V_{max} for a single filter for three different distances between the lamp and the photodiode and show that V_{max} does not depend on the light intensity.

Note: If V is increased beyond V_{max}, a current starts flowing again and a signal reappears on the CRO. This occurs because some of the incident radiation is reflected from the cathode and falls on the anode. Although the anode is made of material of high work function, some of the low work function cathode material is deposited on the anode during manufacture of the tube so that light falling on the anode produces a current in the opposite direction. This reverse current is always present but is only seen when $V > V_{\text{max}}$. This is one of the effects which give rise to the low value of h obtained in this experiment. A further effect is that, for electrons in the cathode with energy greater than ϕ, there is a finite probability that these may not escape the surface but may instead be reflected. The calculated value of h may therefore be lower than the published value by a factor of two or more.

Analysis

Plot V_{max} against $\frac{1}{\lambda}$ and determine h and ϕ (in SI units) from it. Calculate error bars for your measured data and analyse the sources of errors in the experimental setup. Compare your results for h and ϕ to literature values.

No.	Colour	Pass-band [nm]	$\frac{1}{\lambda}$ [m^{-1}]
600	violet	380-450	$2.6 - 2.2 \times 10^6$
602	blue	440-490	$2.3 - 2.0 \times 10^6$
603	blue-green	470-520	$2.1 - 1.9 \times 10^6$
605	yellow-green	530-570	$1.9 - 1.75 \times 10^6$
607	orange	575-610	$1.75 - 1.65 \times 10^6$
608	red	≥ 620	$\leq 1.6 \times 10^6$

Filter Details

The full pass-band transmitted by each filter should be shown on the graph (rather than a single wavelength at the centre of the pass-band).