Purpose

- Demonstrate the different predictions of the classical wave and quantum model of light with respect to the photoelectric effect.
- Determine an experimental value of Planck’s constant.

Equipment

- Photocell with housing
- Mercury spectral lamp with power supply
- Digital multimeter (DMM)
- Interference filters
- Variable transmission filter

Theory

§3.1 Introduction

The emission and absorption of light was an early subject for investigation by Max Planck. As Planck attempted to formulate a theory to explain the spectral distribution of emitted light based on a classical wave model, he ran into considerable difficulty. Classical theory (Rayleigh-Jeans law) predicted that the amount of light emitted from a blackbody would increase dramatically as the wavelength decreased, whereas experiment showed that it approached zero. This discrepancy became known as the ultraviolet catastrophe.

Experimental data for the radiation of light by a hot, glowing body showed that the maximum intensity of emitted light also departed dramatically from the classically predicted values (Wein’s Law). In order to reconcile theory with experimental results, Planck was forced to develop a new model for light called the quantum model. In this model, light is emitted in small, discrete bundles or quanta.
§3.2 Planck’s quantum theory

In 1901, Planck published his law of radiation. In it, he stated that an oscillator, or any similar physical system, has a discrete set of possible energy values or levels; energies between these values never occur.

Planck went on to state that the emission and absorption of radiation is associated with transitions or jumps between two energy levels. The energy lost or gained by the oscillator is emitted or absorbed as a quantum of radiant energy, the magnitude of which is expressed by the equation:

\[ E = hf \]  

where \( E \) equals the radiant energy, \( f \) is the frequency of the radiation and \( h \) is a fundamental constant of nature. The constant, \( h \), became known as Planck’s constant.

§3.3 The photoelectric effect

In photoelectric emission, light strikes a material, causing electrons to be emitted. The classical wave model predicted that as the intensity of incident light was increased, the amplitude and thus the energy of the wave would increase. This would then cause more energetic photoelectrons to be emitted. The new quantum model, however, predicted that higher frequency light would produce photoelectrons with higher energy, independent of intensity, while increased intensity would only increase the number of electrons emitted (or photoelectric current).

In the early 1900s, several investigators found that the kinetic energy of the photoelectrons was dependent on the wavelength, or frequency, and independent of intensity, while the magnitude of the photoelectric current, or number of electrons was dependent on the intensity as predicted by the quantum model. Einstein applied Planck’s theory and explained the photoelectric effect in terms of the quantum model using his famous equation:

\[ E = hf = K_{\text{max}} + \phi \]  

where \( K_{\text{max}} \) is the maximum kinetic energy of the emitted photoelectrons and \( \phi \) is the energy needed to remove them from the surface of the material (the work function). \( E \) is the energy supplied by the quantum of light known as a photon.

§3.4 The \( h/e \) experiment

If light impinges on the photocathode, photoelectrons are emitted due to the exterior photoelectric effect, under the condition that the energy of the light quanta is higher than that required for electrons to exit the photocathode (work function \( \phi \)). The kinetic energy of photoelectrons \( K \) increases with the energy \( hf \) of the light quanta:

\[ K = hf - \phi \]
The photoelectrons reach the anode and load the latter negatively. The difference of potential increases up to a limit $V$, which is reached when the complete kinetic energy $K$ of the photoelectrons is required to overcome the difference of potential $V$ which has built up:

$$K = eV$$

(4)

where $e$ is the electron charge equals to $1.602 \times 10^{-19} \text{C}$.

From equations (3) and (4), one obtains

$$eV = hf - \phi$$

(5)

If $V$ is measured at least for two wavelengths, the two unknown factors $h$ and $K$ can be determined from equation (5). Normally, however, more than two measurements are made and $V$ is plotted as a function of $f$. After equation (5) is modified to

$$V = hf - \phi e$$

(6)

it becomes apparent that this is a straight line with slope $h/e$. The work function may be assessed from the negative ordinate section. However, for PbS cathodes, this value does not have the significance of a physical constant, as it is significantly influenced by the manufacturing technology of the photocathode. Once $h$ has been determined, $\phi$ can be calculated from the intersection of the compensating straight line with the abscissa, the so-called limit frequency $f_{\text{min}}$ (the long wave limit wavelength $\lambda_{\text{max}} = c/f_{\text{min}}$ is more usual), for which $V = 0$. In this case, $\phi = hf_{\text{min}}$.

### 4 Experimental Procedure

**Part I: The relationship between energy, wavelength and frequency**

According to the quantum model of light, the energy of light is directly proportional to its frequency. Thus, the higher the frequency, the more energy it has. With careful experimentation, the constant of proportionality, Planck’s constant, can be determined.

**P1.** The experimental setup is shown as in Figure 1. The spectral lamp which is connected to the ballast coil should be switched on about 15 minutes before the first measurement is carried out.

**P2.** The amplifier input is shorted by pressing button ‘0’ when the light entry of the photocell is closed. Whilst the button ‘0’ is depressed, the read-out on the measurement amplifier is set to zero by means of the ‘0’ setting knob.

**P3.** Slide the five different colours interference filters carefully one after another towards the square hole which face the opening of the photocell.
**P4.** Open the sliding shutter and record the indicated stopping potential $V$ by using the DMM and record that measurement in Data Table 1.

**P5.** Close the sliding shutter, change to another filter and repeat until the measurements have been carried out with all filters.
Part II: Classical wave model versus quantum model of light

According to the photon theory of light, the maximum kinetic energy, $K_{\text{max}}$, of photoelectrons depends only on the frequency of the incident light, and is independent of the intensity. Thus the higher the frequency of the light, the greater its energy. In contrast, the classical wave model of light predicted that $K_{\text{max}}$ would depend on light intensity. In other words, the brighter the light, the greater its energy.

This experiment investigates both of these assertions. Part A selects two spectral lines from a mercury light source and investigates the maximum energy of the photoelectrons as a function of the intensity. Part B selects different spectral lines with two different intensities and investigates the maximum energy of the photoelectrons as a function of the colour of the light.

Part IIA: Electron maximum kinetic energy versus light intensity

P1. Close the sliding shutter of the photocell and discharge the measuring amplifier via the ‘zero’ button.

P2. Slide the interference filters so that only one of them (580 nm) falls upon the opening of the photocell.

P3. Place the variable transmission sheet in front of the interference filter. Open the sliding shutter so that the light passes through the transmission sheet and reaches the photocell. Record the stopping potential as given by the DMM voltage reading in Data Table 2.

P4. Repeat step P1 and change to another variable transmission sheet and record the new DMM reading in Data Table 1.

P5. Repeat step P4 until you have tested all the transmission sheets.

P6. Repeat steps P1–P5 using a second colour (546 nm) from the interference filter.

Part IIB: Electron maximum kinetic energy versus light frequency

P1. Close the sliding shutter of the photocell and discharge the measuring amplifier via the ‘zero’ button.

P2. Slide the interference filters so that only one of them falls upon the opening of the photocell.

P3. Place the variable transmission sheet (100%) in front of the interference filter. Open the sliding shutter so that the light passes through the transmission sheet and reaches the photocell. Record the stopping potential as given by the DMM voltage reading in Data Table 3.
P4. Repeat steps P1–P3 until you have tested all the four colour filters.

P5. Repeat steps P1–P4 using a different variable transmission sheet (66%).

5 Data Processing

D1. Perform a suitable linear least squares fit to the data in Data Table 1. Determine the slope and intercept with the corresponding uncertainties of the least squares fit to the data.

D2. Plot a suitable graph as well as the best fitted line obtained above.

D3. Determine your best experimental value for Planck’s constant with the corresponding uncertainties. Use percentage discrepancy to compare your experimental value for the Planck’s constant with the accepted value, $h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s}$.

**Hint:** The percentage discrepancy is defined as

$$\text{Percentage discrepancy} = \left| \frac{\text{Experimental value} - \text{Accepted value}}{\text{Accepted value}} \right| \times 100\%$$

D4. Determine the amount of energy is required to eject an electron from the metal surface inside the h/e apparatus’s photodiode with the corresponding uncertainty.

D5. Determine the minimum frequency, $f_{\text{min}}$, of the light such that it will eject an electron from the photodiode inside the h/e apparatus with the corresponding uncertainty.

D6. Determine either the wavelength or frequency of the unknown filter with the corresponding uncertainty.

6 Questions

Q1. Based on your data in Data Table 2, what is the nature of the relationship between the stopping potential and the intensity of light? Describe qualitatively the effect that passing different amounts of the same coloured light through the variable transmission filter has on the stopping potential and thus the maximum kinetic energy of the ejected photoelectrons.

Q2. Based on your data in Data Table 3, deduce the nature of the relationship between the stopping potential and the frequency of the light. Describe qualitatively the effect that different colours of light (frequency) had on the stopping potential and thus the maximum kinetic energy of the ejected photoelectrons.

Q3. State and explain whether this experiment (part II) supports a wave or a quantum model of light based on your experimental results.