Experiment 5
Planck's Constant

Apparatus:

Photoelectric cell, *DC* source, *DC* milliammeter, Variac (*AC*) (0-260V), *AC* ammeter, Tungsten filament lamp (60 W), Monochromatic filters.

Purpose of experiment:

To measure the value of Planck's constant '*h*'.

Basic methodology:

Light from a tungsten filament lamp (assumed to be a black body source) is passed through a monochromatic filter and made to fall on a photoelectric cell. The slope of the graph $\ln\ I_{ph}\ vs.\ \frac{1}{T}$, leads to a determination of Planck's constant.

I Introduction:

I.1 The electromagnetic radiation emitted by a black body (a perfect absorber and emitter of electromagnetic radiation) is spread continuously over the entire electromagnetic spectrum. It was Planck, who first gave the law for black body radiation based on the idea that electromagnetic radiation is composed of quanta called photon of energy $\varepsilon = h\nu$, where ν is the frequency of radiation and *h* is Planck's constant.

I.2 Planck's law for radiation from a black body gives the spectral energy density of the radiation in the frequency range ν to $\nu + d\nu$. This is denoted as $U(\nu)\,d\nu$ and is given by

$$U(\nu)d\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{\left(e^{\frac{h\nu}{kT}} - 1\right)}d\nu \qquad (1)$$

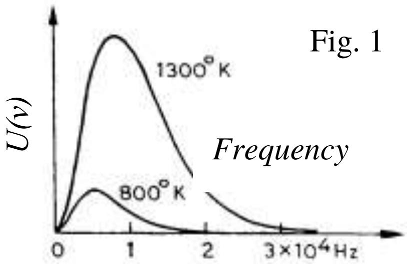

Fig. 1

In eq. (1), $c = 3 \times 10^8$ m/s is the speed of light, $k = 1.38 \times 10^{-23}$ J/K is the Boltzman constant. Fig. 1 shows a graph of $U(\nu)$ vs. ν for given temperatures *T*.

In the high frequency region, where $\frac{h\nu}{kT} \gg 1$, eq. (1) can be approximated as

$$U(\nu) = \frac{8\pi h\nu^3}{c^3}\, e^{-\frac{h\nu}{kT}} \tag{2}$$

showing an exponential decrease in the energy density with frequency.

I.3 In this experiment, a tungsten filament lamp is taken to be a black body radiator. Using a monochromatic filter, radiation with frequency in the visible region is selected. For the range of temperatures of the tungsten filament, the energy density can be taken to be given by eq.(2). The energy density at the chosen frequency is indirectly measured by measuring the photocurrent I_{ph} generated upon exposing a photocell to the radiation. From the properties of the photoelectric effect, it is known that the photocurrent is proportional to the intensity of the radiation. Thus

$$I_{ph} \propto U(\nu) \approx \frac{8\pi h\nu^3}{c^3} e^{-\frac{h\nu}{kT}} \tag{3}$$

or

$$\ln I_{ph} = -\frac{h\nu}{kT} + ln\frac{8\pi h\nu^3}{c^3} = -\frac{h\nu}{kT} + \ constant \tag{4}$$

Hence the graph of $ln\ I_{ph}$ vs. $1/T$ is a straight line of slope of magnitude $h\nu/k$.

I.4 The temperature of the tungsten filament can be varied by changing the current through it. The temperature of the filament can be estimated by measuring the resistance R of the filament. The variation of R with temperature for tungsten is given by the empirical formula (T is expressed in ^oC)

$$R = R_o\,(\,1 + \alpha T + \beta T^2\,) \tag{5}$$

Where,

$\alpha = 5.24 \times 10^{-3}\ (°C)^{-1}$

$\beta = 0.70 \times 10^{-6}\ (°C)^{-2}$.

A calibration graph can be obtained by drawing the graph of eq. (5). Then, knowing the resistance, $R = \frac{V}{I}$ of the filament the temperature T(°C) can be obtained from the calibration graph.

II. Set-up and Procedure

1. Complete the circuit with Tungsten lamp and photocell as shown in Fig. 2
2. Choose and set the color of the monochromatic filter (say red).
3. Using the variac, vary the *AC* voltage to the tungsten filament from 80V to 220 V in steps of 20 V.
4. Measure the *AC* current to the tungsten and the *DC* photocurrent I_{ph}.
5. Repeat the measurements for three filters in all (say red, blue and green).
6. Prepare the calibration graph of *R* (resistance of filament) by using eq. 5 to calculate *R* for value of T (^{o}C) = 400, 600, 800, 1000, …, 2000.

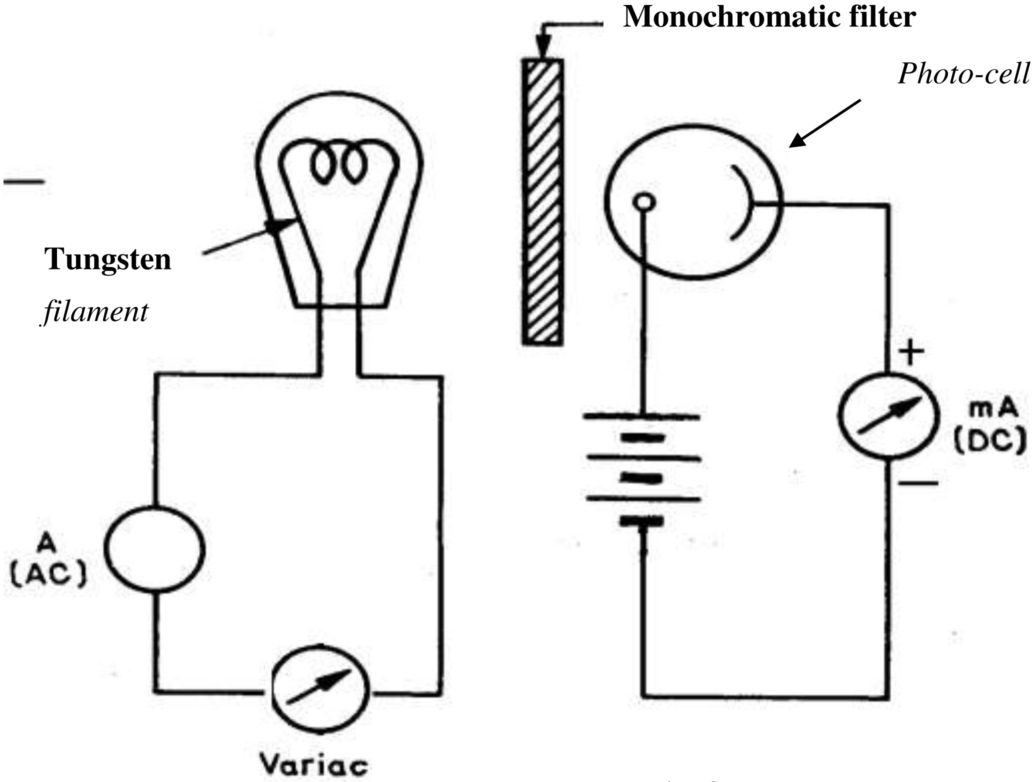

Fig. 2

Plot and fit the calculated value of R vs. T by a best-fit straight line.

7. Calculate the resistance $R = \frac{V}{I}$ from your measurement and use the calibration graph to read off temperature of the filament, against the value of the resistance.

Exercises and Viva Questions:

1. What is the meaning of the quantity $U(\nu)$ in Planck's black body radiation law ?
2. Give the approximate forms for the energy density for $\frac{h\nu}{kT} << 1$ *and* $\frac{h\nu}{kT} >> 1.$ and corresponding laws.
3. What is the purpose of using a photocell in this experiment?
4. Use the energy density expression to argue how the photocurrent should change upon varying the frequency, keeping the variac voltage the same. How will I_{ph} change if frequency is kept constant but the variac voltage is varied? Verify your expectations from your observations.
5. Argue how I_{ph} would change as the variac voltage is changed if the tungsten lamp were allowed to illuminate the photocell without using a filter in between. What frequency would contribute most to the photocurrent?
6. Study the photoelectric effect and list the characteristics of the photoelectric effect that can only be explained by the quantum nature of light.

7. Is our assumption that $I_{ph} \propto U(\nu)$ always right ? Is it true that radiation of any frequency will give rise to a photocurrent?
8. Look up the value of work function of tungsten and calculate the cut off frequency ν_0 for tungsten.
9. We have taken the tungsten filament to be a black body radiator. What qualitative changes should we expect if it were to be taken to be an imperfect black body radiator?
10. What is the significance of Planck's constant in Physics?

References :

1. "Physics", M. Alonso and J. Finn, Addison Wesley 1992.
2. "Modern Physics", A. Beiser, McGraw Hill Inc., 1995