# Planck's "quantum of action" from the photoelectric effect (line separation by diffraction grating) with electrometer amplifier

## 1. PURPOSE

- Verify the photoelectric effect.
- Do measurements that enable us to calculate the kinetic energy of the electrons as a function of the frequency of the light.
- Calculate Planck's constant h from these results
- Show that the kinetic energy of the electrons is independent of the intensity of the light.

## 2. PRINCIPLE

A photocell is illuminated with monochromatic light of different wavelengths. Planck's quantum of action, or Planck's constant h, is determined from the photoelectric voltages measured.

## 3. THEORY

In 1887, Heinrich Hertz found that when electromagnetic radiation (light) fell on a metallic surface, the surface emitted electrical charges. Experiment by Phillipp Lenard in 1900 confirmed that these electrical charges were electrons. These electrons were called photoelectrons. This process, whereby light falling on a metallic surface causes the emission of electrons, is called photoelectric effect.

The Photoelectric Effect: If monochromatic light (light of a single frequency v) of intensity I is allowed to shine on a metallic plate (cathode) of a phototube, electrons will be emitted as shown in Fig.1.
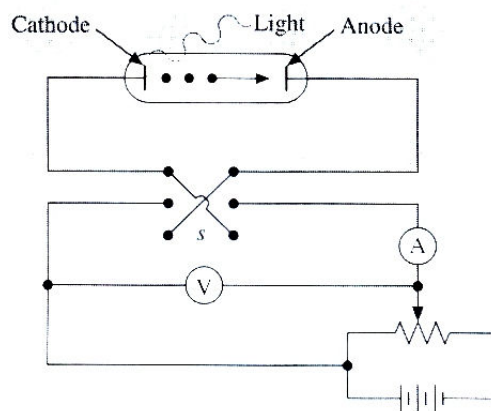


**Figure 1: Schematic diagram for the photoelectric effect.**

Initially, the switch s is thrown to maket he anode positive and the cathode negative. Light is then shone on the cathode of the phototube, causing electrons to be emitted. The positive anode attracts these electrons, and they flow to the anode and then through the connection circuit. The ammeter in the circuit measures the current. Starting with a positive potential V the current is recorded for decreasing values of V. When the potential V is

reduced to zero, the switch s is reversed to make the anode negative and the cathode positive. The negative anode now repels the photoelectrons as they approach the anode. If the electrons have sufficient kinetic energy, they can overcome this repulsion and still land on the anode. If this potential is made more and more negative, however, appoint is eventually reached when the kinetic energy of the electrons is not great enough the overcome the negative stopping potential, and no more electrons reach the anode. The current i , therefore, becomes zero.

A plot of the current *i* in the circuit, as a function of the potential **V** between the plates as shown in Fig.2. If the intensity of the light is increased to $I_2$ and the experiment repeated, second curve shown in the figure is obtained.
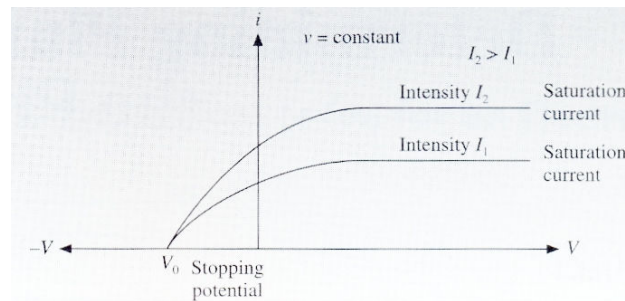


**Figure 2: Current I as a function of voltage V for the photoelectric effect.**

As can be seen on the graph in Fig.2, when the value of V is high and positive, the current i is a constant. This occurs because all the photoelectrons formed at the cathode are reaching the anode. By increasing the intensity I, a higher constant value and current is obtained, because more electrons are then being emitted.

It can also be observed that when the potential is reduced to zero, there is still a current in the tube. Even though there is no electric field to draw them to the anode, many of the photoelectrons still reach the anode because of the initial kinetic energy they possess when they leave the cathode. As the switch s in Fig.1 is reversed, the potential V between the plates becomes negative and tends to repel the photoelectrons. As the potential V is made more negative, the current I decreases, as seen in Fig.2, indicating that fewer and fewer photoelectrons are reaching the anode. When V is reduced to the value $V_o$ , there is no current at all in the circuit; $V_o$ is called the stopping potential. Note that it is the same value regardless of the intensity (both curves intersects at $V_o$).

The potential V is related to the kinetic energy of the photoelectrons. For the electron to reach the anode, the kinetic energy must be equal to the potential energy between the plates.

$$E_k \text{ (electrons)} = E_p \text{ (between the plates)}, \tag{1}$$

$$E_k = e\,V , \tag{2}$$

Where e is the charge on the electron and V is tt-he potential between the plates.

The potential V will act on electrons that have less kinetic energy than that given by Eq.2. When $V = V_o$, the stopping potential, even the most energetic electrons (those with maximum kinetic energy) do not reach the anode. Therefore,

$$E_k \text{ (max)} = e\,V_o . \tag{3}$$

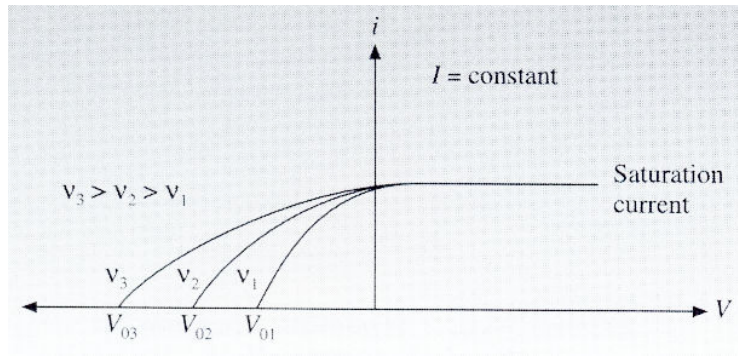If we change the frequency of the incident light we get the graph in Fig.3.

**Figure 3: Current I as a function of voltage V for different light frequencies.**

As the plot in Fig.3 shows, the saturation current (the maximum current) is the same for any frequency of light, as long as the intensity is constant. But the stopping potential is different for each frequency of the incident light. Since the stopping potential proportional to the maximum kinetic energy of the photoelectrons, through Eq.3, the maximum kinetic energy $E_k$ (max) of the photoelectrons is plotted as a function of frequency $v$ and the graph in Fig.4 is obtained.
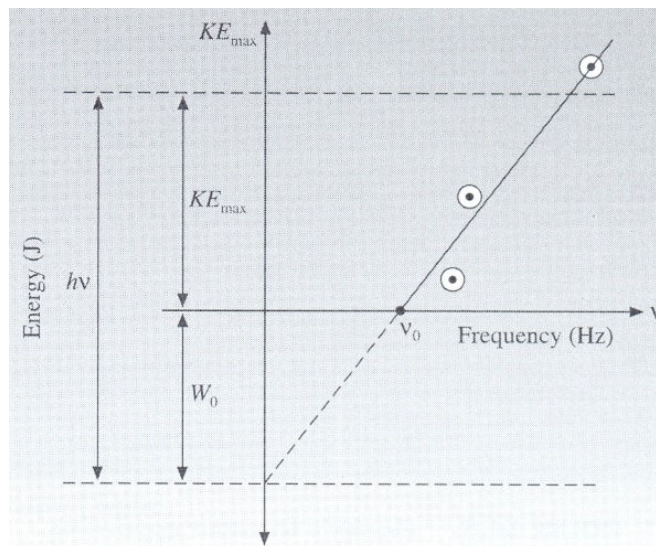


**Figure 4: Maximum kinetic energy $E_{k(max)}$ as a function of frequency $v$ for the photoelectric effect.**

The first thing to observe is that the maximum kinetic energy $E_k$ (max) of the photoelectrons is directly proportional to the frequency $v$ of the incident light, that is,

$$E_k \text{ (max) } \alpha \ v . \tag{4}$$

The second thing to observe is that there is a cutoff frequency $v_o$ , below which there is no photoelectric emission. That Is, no photoelectric effect will occur at all unless the incident light has frequency higher than the threshold frequency $v_o$. For most metals, $v_o$ lies in th ultraviolet region of the spectrum, but for the alkali metals it lies in the visible region, and for cesium it lies in the infrared region.

### Einstein's Theory of the Photoelectric Effect

In 1905, Albert Einstein proposed a revolutionary solution for the problem of the photoelectric effect. Einstein assumed that the energy of the electromagnetic wave was not spread out equally along the wavefront, but rather it was concentrated into little bundles of energy called photons. As the wave progressed, the energy did not spread out with the wavefront, but stayed in the photon bundle. Max Planck had earlier formulated the quantization of radiant energy in bundles of photons each possessing energy such that,

$$E = h\nu , \qquad\qquad (5)$$

where $\nu$ is the frequency of the radiation and, h is a new universal constant, called Planck's constant, which has value $h = 6{,}626 \times 10^{-34}$ J.s. Einstein assumed that this concentrated bundle of radiant energy struck an electron on the metallic surface. The electron then absorbed this entire quantum of energy ($E = h\nu$) . A portion of this energy is used by the electron to break away from the solid, and the rest shows up as the kinetic energy of the electron = incident absorbed energy – energy to break away from solid.

The energy for the electron to break away from the solid is called the work function of the solid is denoted by W. Therefore, the final maximum kinetic energy of the photoelectrons

$$E_k (max) = h\nu - W , \qquad\qquad (6)$$

Which is known as Einstein's photoelectric equation.

This equation can be plotted if $E_k$ (max) is placed on the y-axis, and the frequency $\nu$ of the incident light is placed on the x-axis. The result is a straight line, the same as in Fİg.4. Using the standard equation for a straight line, y= a x + b, we see that the slope of the line is Planck' s constant h. The value of the intercept is found by nothing that, when $E_k$ (max)=0 ; $\nu = \nu_o$ and, therefore,

$$\nu_o = W, \qquad\qquad (7)$$

Therefore, Einstein's equation can also be written as

$$E_k (max) = h\nu - h\nu_o . \qquad\qquad (8)$$

For light frequancies equal to or less $\nu_o$ , there is not enough energy in the incident wave to remove the electron from the solid, and hence there will be no photoelectric effect. This explains why there is a threshold frequency, below which there is no photoelectric effect.Einstein's theory of the photoelectric effect is outstanding because it was the first application of quantum mechanics. Light should now be considered as having not only a wave character but also a particle character.
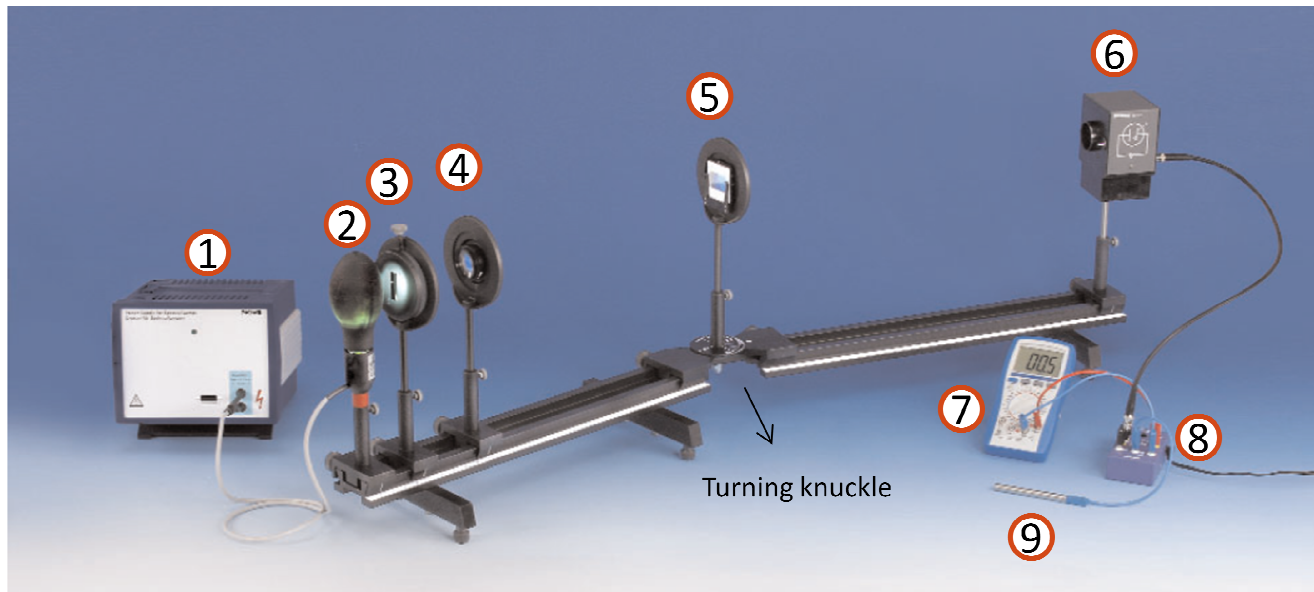
# 4.PROCEDURE



Turning knuckle

**Figure 5:** *Experimental set-up*

1. Power Supply
2. Mercury high pressure lamp 80 W
3. Adjustable slit
4. Lens , *f*=+100 mm
5. Diffraction grating, 600 lines/mm
6. Photocell
   o The detector will use the photoelectric current to charge a capacitor. This will eventually cause the capacitor to reach the stop voltage, and the current will cease.
7. Digital multimeter
8. Electrometer Amplifier
9. Support rod, 100 mm with axial hole

Set up the equipment as seen in Fig. 1.


■ Place the high pressure mercury vapor lamp and the photocell at opposite ends of the optical bench.
■ Place the diffraction grating into a diaphragm holder and mount it with a lens holder to the turning knuckle.
■ Place the optical slit at 9 cm and the lens at 20 cm from the end of the bench, where the lamp is. Adjust the lens in a way that the slit's image is focused on the photocell housing's entrance.
■ Set the slit width such that its image matches the photocell's entrance width.
■ A piece of white paper fixed with adhesive tape to the photocell housing will help with adjusting. The white paper's fluorescence will also help finding the ultraviolet lines.
■ Connect the electrometer amplifier as seen on Fig. 2. To avoid problems with electrostatic influence, it is better to plug the end of the cable used to bring the electrometer amplifier entrance on ground potential into the support rod with hole and to plug a connecting plug into the socket of the electrometer amplifier entrance. If you hold the rod firmly in your hand, your body is brought to the same potential as the experiment and touching the connecting plug with the rod will discharge the amplifier's entrance properly. Otherwise the electrostatic charge of your body will cause an influence charge on the amplifier's entrance in the moment of unplugging the ground cable from the electrometer.

Figure 6: *Connection of the electrometer amplifier*



Figure 7: *Atomic spectrum of mercury*

- Set the digital multimeter's range to 2 V.
- By turning the arm of the optical bench, bring the photocell entrance to the first slit image.
- Discharge the electrometer amplifier entrance and open the light entrance of the photocell housing. Wait until the voltage reading is steady – or if not, discharge again.
- Bring the photocell entrance to the different slit images successively and note down light wavelength and corresponding voltage. To avoid having the UV fractions from second order diffraction falsify the measured values for the yellow and red spectral lines, place colour filters in front of the entrance diaphragm with the aid of an attachable diaphragm holder (525-nm coloured glass for the yellow spectral line and 580-nm coloured glass for the red spectral line).
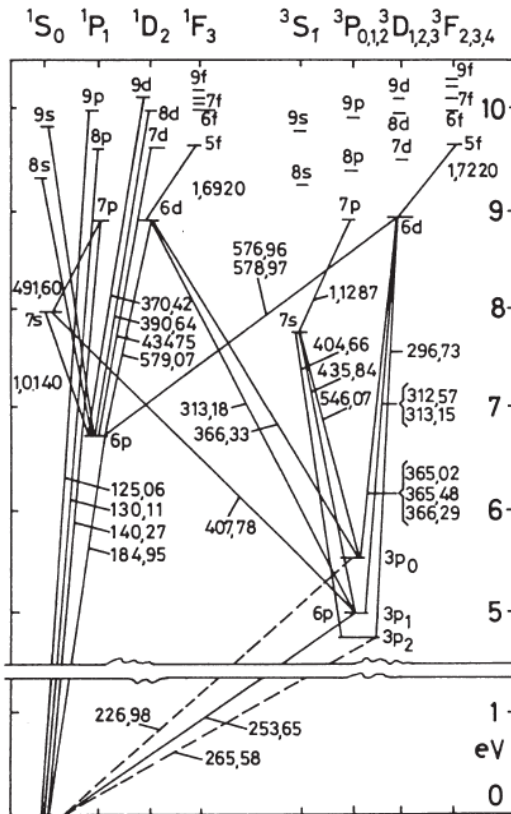- Note down the measured voltage and the wavelength of the light.

The frequency $f$ of the light is calculated from the wavelength $\lambda$ by $f = c/\lambda$ with the speed of light c = $3.10^8$ m/s. The wavelengths are measured by the angle $\vartheta$ at which the diffracted light apears by $\lambda = d.sin\vartheta$ for first order constructive interference with $d = 1\ mm/600$ for the 600 lines per mm grating or else are identified as the strongest emission lines of mercury in the lamp at (see Fig.3):

366 nm (6 $^1D_2 \rightarrow$ 6 $^3P_0$, 6 $^3D_{1,2,3} \rightarrow$ 6 $^3P_0$)      nearly invis. violet

405 nm (7 $^3S_1 \rightarrow$ 6 $^3P_2$)      violet
436 nm (7 $^3S_1 \rightarrow$ 6 $^3P_1$)      turquois
546 nm (7 $^3S_1 \rightarrow$ 6 $^3P_0$)      green
578 nm (6 $^1D_2 \rightarrow$ 6 $^1P_1$, 6 $^3D_{1,2,3} \rightarrow$ 6 $^1P_1$)      yellow

## 4.Experimental Determination of the Photoelectric Effect

Half of the inside of the high-vacuum photo-cell is metal-coated potassium-cathode. The anular anode is opposite the cathode. If a photon of frequency f strikes the cathode, then an electron can be ejected from the metal (external photoelectric effect) if there is sufficient energy. Some of the electrons thus ejected reach the (unilluminated) anode so that a voltage is set up between anode and cathode, which reaches the limiting value U after a short (charging) time. The electrons can only run counter to the electric field set up by the voltage U if they have the maximum kinetic energy, determined by the light frequency f,

$$h\,f - W = \frac{m}{2} V^2 \qquad \text{(Einstein equation)}$$

where W is the work function from the cathode surface, V = electron velocity, m = rest mass of the electron.

Electrons will thus only reach the anode as long as their energy in the electric field is equal to the kinetic energy:

$$e \, v - W = \frac{m}{2} V^2$$

with e = electron charge: $1.602 \cdot 10^{-19}$ Js.

An additional contact potential $\varphi$ occurs because the surfaces of the anode and cathode are different:

$$e \, U + \varphi = \frac{m}{2} V^2$$

If we assume that W and ɸ are independent of the frequency, then a linear relationship exists between the voltage U (to be measured at high impedance) and the light frequency f:

$$U = \frac{(W + \varphi)}{e} + \frac{h}{e} f$$

If we assume $U = \alpha + b f$ to the values measured in Fig.8 we obtain:

$h = (6.7 \pm 0.3) \cdot 10^{-34}$
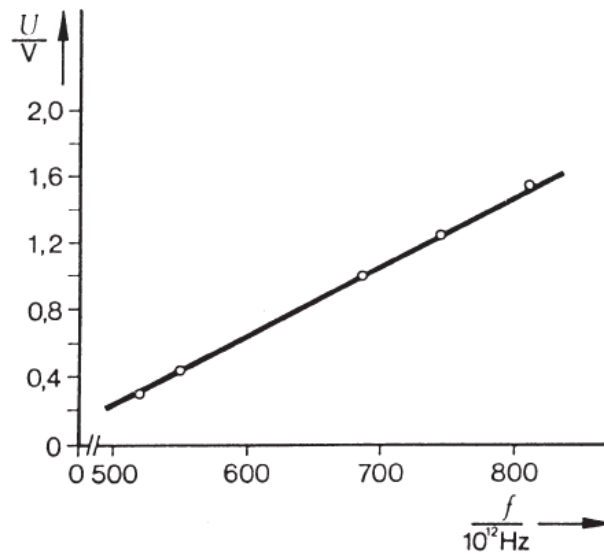
Literature value : $h = 6.62 \; 10^{-34}$ J.s



**Figure 8: Voltage of the photo-cell as a function of the frequency of the irradiated light.**

### Summary:

The most important experimental observations must be found during the experiment:

1. The kinetic energy of the photoelectrons ( as determined by the reverse voltage needed to completely stop the flow of electrons from cathode to anode) is independent of the intensity of the light, but is a liner function of the frequency of the radiation.
2. There is a maximum wavelength beyond which photoemission does not occur; the value of this maximum depends of the composition of the surface (W).
3. The saturation photocurrent is directly proportional to the light intensity.

## Questions:

1. What is the most important general statement you can make from the results of your experiment?
2. Explain why the photoelectric effect is so important to quantum mechanics.
3. Explain why there is a cutoff frequency in the photoelectric effect.
4. Even if the bias voltage is zero, you can still measure a photocurrent. Explain why?
5. If a material has a work function of 2.0 eV, what is the longest wavelength to which a photocathode made of this material will be sensitive?
6. When the anode is positive with respect to the cathode, why does the current not rise immediately to its saturation value? What happens to the electrons which do not reach anode?

## Reference:

1. Peter J.Nolan and Raymond E.Bigliani, Experiments in Physics (1995) p.415.
2. Alan M.Portis and Hung D.Young, Berkeley Physics Laboratory-3 p.9.
3. Phywe Laboratory Experiments "Planck's "quantum of action" from the photoelectric effect (line separation by diffraction grating) with electrometer amplifier" LEP 5.1.05-05 Lab Manual, Phywe Systeme GMBH & Co. KG D-37070 Göttingen.