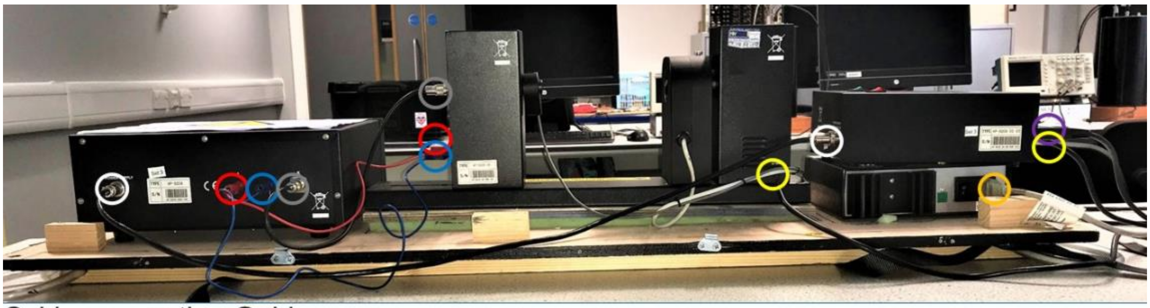
Photoelectric effect

The development of quantum theory in the early 20th century drastically changed our views on the nature of light, allowing us to consider it as a particle as well as a wave. The photoelectric effect was one of the first phenomena to be discovered in which light was seen to act as a particle rather than a wave. As light is shone on a metal surface, it transfers energy to the metal, liberating electrons from its surface. In quantum theory, the light is carried by particles called "photons", whose energy depends on frequency according to relationship, E=hf. The electrons emitted from the metal are liberated by photons. It was Albert Einstein who first proposed the theory that light is carried by discrete packets of energy. Einstein was awarded the Nobel Prize in 1921 for advancing this new idea in physics.

Safety	**Voltage:** The mains voltages are screened in normal use, but please do not handle any of the power cables. **UV radiation:** The UV light source in this experiment has a shutter, which opens automatically when a filter is placed in the slot in front of the photodiode. Please **do not look into the light source** when the shutter is open. **Burning**: The mercury lamp, once turned on, can become very hot. You **must not touch the mercury lamp** during the experiment.

Set up guide for staff	***Instructional videos on how to set up this apparatus are available on the Lancaster Physics/ Outreach/ Lab in a Box webpage.***



Cable connection Guide:

1. Blue and Red Cables: Connect to blue and red plugs, respectively.
2. Grey and White Shielded Cables: Connect and secure as seen on the photograph above.
3. The **Black** cable, highlighted in yellow, will initially be connect to the lamp. It should be connected to the power supply.
4. The second **Black** cable ,highlighted in purple, is connected from the power supply to the grid.
5. The Grey cable, highlighted in orange, is connected from the shutter power supply to the grid.

Figure 1: Photograph showing the photoelectric effect apparatus, with instructions on how to connect each of the cables.

Photoelectric effect

Lancaster University

Background

Imagine electromagnetic radiation (e.g. a beam of light) incident on the surface of a metal. In quantum theory, the light is transported by a beam of particles called photons, which travel as discrete packets, and are sometimes referred to as "light quanta".

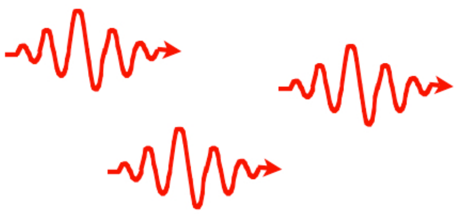


Figure 2: Image of discrete bunches of light, demonstrating its wave particle duality.

In the wave theory of light, the energy carried by the light depends on the intensity of the radiation. However, in the quantum theory of light, the energy E of a photon is related to the frequency ν of its radiation according to the Planck-Einstein law:

$$E = h\nu$$

As light shines on the metal, its photons transfer their energy to the electrons within the metal, freeing them from the metal, and ejecting them from the surface. Each electron is liberated by one photon.

Whether a photon has enough energy to eject an electron depends on its frequency. The smallest amount of energy needed to remove an electron (i.e. liberate it but leave it stationary with no kinetic energy) is called the *work function* of the metal, φ. If a photon of energy $h\nu$ Interacts with an electron, part of its energy will be used to free the electron, and the balance will result in electron kinetic energy, E_{KE}. For a given ν the greatest value of E_{KE} will be:

$$E_{KE} = h\nu - \varphi.$$

1. Describe what will happen to the metal if $h\nu < \varphi$?

....

....

....

....

Photoelectric effect

In this experiment, we will use a potential difference to accelerate or slow down the ejected electrons, as shown in the figure below.

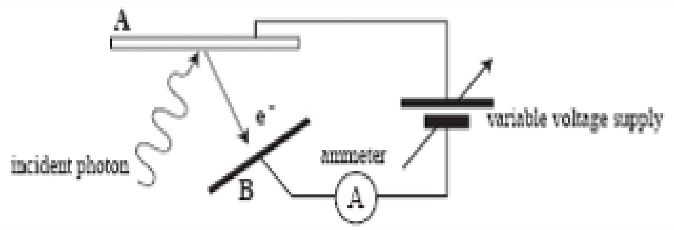


Figure 3: Schematic of the photoelectric effect.

If **B** is positive with respect to **A**, all the electrons will be attracted to **B** and collected. But if **B** is negative with respect to **A**, it will repel the negatively charged electrons, slowing them down.

As the negative voltage on **B** is increased, there will be some value V_o at which all the emitted electrons are stopped and no current flows. This occurs when $eV_o = E_{KE}$. Hence, the following photoelectric formula can be derived:

$$eV_o = h\nu - \varphi,$$

$$V_o = \frac{h}{e}\nu - \frac{\varphi}{\mathrm{e}}.$$

Thus we can use this formula to determine the Planck constant h.

2. In relation to the above formula, describe the relation between V_o and ν? Consider the graphical interpretation where V_o and ν would be the x and y axis. What would be the gradient and intercept of this function?

....

....

....

....

....

....

Photoelectric effect

Lancaster University

Task 1	The experiment uses a mercury lamp as a light source. The light from the lamp is focussed by a simple lens through a filter onto a photocell. The photocell consists of a highly evacuated tube containing a loop of platinum and a potassium film. The platinum acts as the metal target for this experiment. The light from the mercury lamp strikes the platinum and releases electrons from its surface. Platinum has been chosen for this experiment because it has a very high work function. The potassium film is connected to a screw socket at the bottom of the photocell. A positive or negative bias voltage can be applied to this socket to accelerate or decelerate the electrons. The potassium film is also attached to a metal cap at the top of the tube, which in turn is connected to a very sensitive current meter. This enables the arrival rate of electrons to be measured. In this experiment, you will apply a negative bias (so that electrons are repelled from the platinum), and measure the stopping voltage V_o. Wavelength filters are provided to illuminate the potassium surface with frequencies of light. These filters transmit light in a narrow band of wavelengths **(± 10 nm)** around the wavelength stated on the filter. When a filter is placed in the apparatus, a micro switch opens the shutter on the mercury lamp.

Question 1	With the lamp switched off, insert one of the filters into the apparatus and set the bias voltage to zero (the bias voltage is controlled by the left-hand dial in the “voltage adjust“ panel on the meter). Check that no stray light can reach the photocell. Turn on the lamp and you should immediately get a non-zero current reading on the meter. As you increase the bias voltage, the current will slowly decrease until it reaches zero. At this point, the bias voltage is equal to the stopping voltage, V_o. Note: increase the bias voltage a bit more and the current becomes negative (our simple theory predicts that there should be no current). Measure V_o for the 5 filters available, which have a wavelength range of 365 - 577 [nm]. Make sure that the distance between the light source and the photocell remains fixed throughout your measurements. You can obtain an estimate of the uncertainty in V_o by repeating a measurement at one wavelength 2 or 3 times. Consider the questions below.

Photoelectric effect

Lancaster University

1. What do you think are the main sources of uncertainty in your measurements?

   ....

   ....

   ....

   ....

2. In this experiment, you are told the wavelength λ of each filter. How can you derive the frequency ν for each measurement? The speed of light is $c = 3.0 \times 10^8$ [m/s].

   ....

   ....

   ....

Record your measurements in the table below.

Wavelength λ [nm]	Frequency ν [Hz]	Stopping Voltage V_o [V]

Photoelectric effect

Lancaster University

Question 2 Plot a graph of V_o against the frequency ν (**not the wavelength**) and draw the uncertainties in V_o and the filter bandwidth as error bars. You may use the grid below or a program such as Excel.

Photoelectric effect

Lancaster University

Now answer the following questions:

1. Are your data points consistent with a straight line? If not, what do you think is the reason behind the disagreement?

   ....

   ....

   ....

   ....

2. Draw a line through your points, and calculate the value of h/e from the gradient, estimating its uncertainty. Compare your result with the known value of $h/e = 4.014 \times 10^{-15}$[Js$C^{-1}$] .

   Given that $e = 1.60 \times 10^{-19}$ [C], calculate Planck's constant h, estimating a uncertainty. Compare your result with the known value of $h = 6.63 \times 10^{-34}$ [Js]?

   ....

   ....

   ....

   ....

   ....

   ....

3. Using the same methodology as before calculate the value of φ/e and the work function φ from intercept of the graph, estimating uncertainties in these quantities. Does your result agree with the known value of $\varphi = 3.69 \times 10^{-19}$ [J]?

   ....

   ....

   ....

   ....

   ....

Photoelectric effect

Lancaster University

Question 3	Was the experiment successful? How do you think the experiment could be improved?
	....
	....
	....
	....
	....
	....