Photoelectric Effect

Teacher's Handbook

In association with the

Cherenkov Telescope Array

Goldleaf Electroscope Experiment

Duration: 50mins
Prerequisites: Knowledge of the wave theory of light

Overview of Experiment:
The goldleaf electroscope will be used by the teacher to demonstrate to the class the photon model of electromagnetic radiation, and how observations led to the photoelectric equation.

Objectives: - Students will:
- Understand the photon model of EM radiation
- Understand the Plank constant, h; and know the equation $E = hf = \frac{hc}{\lambda}$
- Be able to define the work function, ϕ; and the threshold frequency, f_0
- Know and understand the photoelectric equation, $hf = \phi + KE_{\max}$

Required Materials:
- Goldleaf electroscope
- Cloth, polythene rod, and acetate rod
- Zinc plate
- Desk lamp (not a tungsten-halogen compact bulb, as this emits some UV light)
- Ultraviolet lamp

Background Information:

Photoelectric Effect

When a certain material's surface is exposed to EM radiation of a high enough frequency, the energy from the light is absorbed, and electrons are emitted. This effect is called the Photoelectric Effect. In 1902, Philip Lenard observed that the energy carried by each emitted electron increased as the frequency of the light shining on the material increased. This contradicted James Maxwell's established Wave Theory of Light, which predicted that the energy carried by an electron would increase with intensity, rather than with frequency.

Albert Einstein proposed in 1905 that light is not made up of waves, but instead, of packets of energy that arrive in discrete quanta. These packets were called **photons**. This led to the beginnings of quantum physics, and the concept of **wave-particle duality**.

Each photon has a certain amount of energy, with each photon from the same light source having the same amount of energy. The energy carried by a photon is proportional to the frequency of the light which it is from. The constant of proportionality is called the **Planck's**

Constant (named after Max Planck, one of the founders of quantum theory), and is denoted as h. The energy of a photon can therefore be written as:

$$E = hf = \frac{hc}{\lambda}$$

where f is the frequency of the light. Frequency is equal to $\frac{c}{\lambda}$ where c is the speed of light ($3 \times 10^8\ \mathrm{ms^{-2}}$), and λ is the wavelength of the light. The above equation is called the Planck relation, or the Planck-Einstein equation.

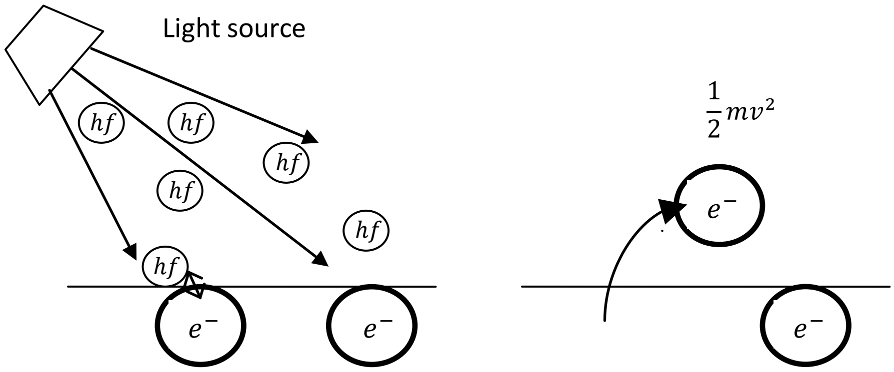


Figure 1 –Each photon carries *hf* amount of energy, and the energy from one photon transfers to one electron when it hits the surface of the material. The electron then uses this energy to escape the forces holding it in the material's structure, and is emitted with an associated kinetic energy.

The energy from one photon is absorbed by the material and transferred to one electron. An emitted electron by the photoelectric effect is called a **photoelectron**. Depending on the material and the frequency, there may or may not be enough energy to emit an electron. The frequency of the light must be above a certain **threshold frequency, f_0,** for the photoelectric effect to take place. Each material has a different threshold frequency. For example, blue light causes sodium to emit electrons, whereas red light does not. In this experiment, we will use zinc, which emits electrons when shone upon by UV light, but not by visible light.

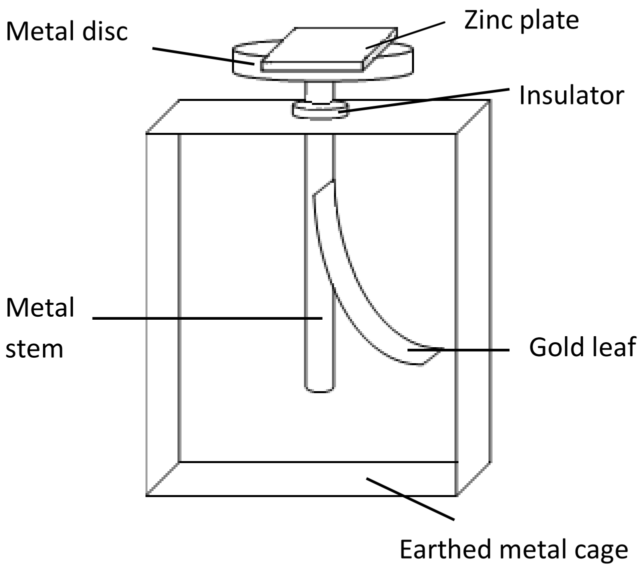
For light above the threshold frequency, once the energy has been transferred from the photon to the electron, the electron will have enough energy to overcome the forces in the structure of the material holding it in. It will escape and be emitted with an associated kinetic energy.

Some electrons will leave with more kinetic energy than others. This is because electrons closer to the surface of the material require less energy to escape than electrons further down. The surface electrons therefore have more leftover energy from the photon to be converted into kinetic energy upon being released. The minimum amount of energy needed for an electron to overcome the forces holding it in the metal is called the **work function, denoted as ϕ.** Only an electron at the very surface would only require ϕ to be emitted. This electron would then have the maximum kinetic energy, $\boldsymbol{KE_{\mathrm{max}}}$. The energy of the photon is therefore equal to the maximum kinetic energy plus the work function:

$$hf = \phi + KE_{\mathrm{max}}$$

where $KE_{\mathrm{max}} = \frac{1}{2}mv^2$, with m in this case being the mass of the electron, and v its velocity.

Goldleaf Electroscope



The electroscope is an instrument used to detect the presence of charge on a piece of material. It can also roughly measure the amount of charge. The goldleaf electroscope was invented in 1787 by Abraham Bennet, as a more sensitive instrument than the other electroscopes at the time.

It is made up of a rod or stem, usually made of brass; a gold leaf attached to the stem; and a metal disc attached to the top of the stem. Charge is transferred onto the disc from the material being tested. The charge then distributes itself evenly through the stem and gold leaf. Because the gold leaf and stem now both have the same charge, they repel each other, causing the gold leaf to rise. The system can be discharged or grounded, and made to become neutral by touching either the material on the disc, or the metal disc. The charges will then travel through your body into the earth.

The stem and leaf are housed in an earthed metal cage. If the gold leaf accumulates too much charge, it will rise enough so that it touches the metal cage, and the system will discharge. This prevents the gold leaf from getting damaged. Sometimes there will be a vacuum inside the metal cage. This stops the charge from leaking into the air and ionising the air particles. The insulator between the stem and cage keeps the charge only on the stem.

Procedure:

Before the Class:

1. Read through the whole chapter to familiarise yourself with the material.
2. Print off a set of worksheets for each student.
3. Set up the apparatus as shown in the diagram, and familiarise yourself with the goldleaf electroscope by going through the experiment quickly.

In Class:

(The demonstration(steps 2-8) should take approximately 20mins)

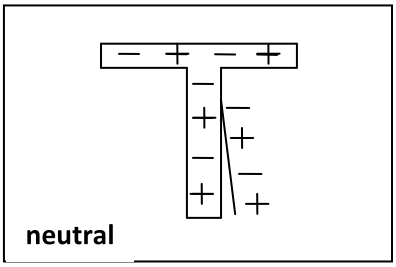
1. Introduce the lesson with a class discussion of what the students already know about light and EM radiation, i.e. how they are made up of waves. Explain to them about the concept of wave-particle duality and how the lesson will be exploring how these ideas came about.
2. Explain that the goldleaf electroscope is used to detect charge. Explain how each of the components of the electroscope works.

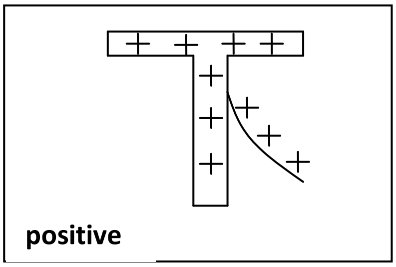
3. Rub the polythene rod with the cloth to charge the rod negatively. Transfer this negative charge by touching the zinc plate on the electroscope with the rod. The plate is now negatively charged, making the metal disc, stem and gold leaf nega
   The gold leaf will rise as it is repelled by the stem. Touch the plate with a finger to discharge the system, and to observe the gold leaf falling back down as the system becomes neutral.
4. Repeat the Step 3 with an acetate rod to show the gold leaf rising when the system is positively charged. Discharge the system again by touching the plate.
5. Charge the plate negatively again using the polythene rod. Shine UV light onto the zinc plate, and watch the gold leaf fall back down.
6. Charge the plate negatively again, and shine visible light from the desk lamp onto the zinc plate. The gold leaf does not fall.
7. Vary the brightness of the visible light to show that no matter how bright the light is or how long you shine it, the gold leaf does not fall. This shows that the amount of light does not affect whether the plate gets discharged. Only the *frequency* affects it.
8. Now charge the plate positively. Shine visible light on the plate to show that the gold leaf does *not* fall. Shine UV light on the plate to show that the gold leaf does *not* fall. This implies that only *negative* charges leave the plate when UV light is shone upon it. This negative charge is electrons, e^- s.
9. Explain that the emission of electrons by light is called the *photoelectric effect*, and that the emitted electrons by this process are called *photoelectrons*.
10. Hand out the worksheets, and give the students 10-15mins to fill them in independently up to the Explanation section. Go through the answers as a class.
11. Explain and discuss with them the observations and explanations. Pause for a few minutes at the appropriate places for them to fill in the sheets for the Explanation section. This should take approximately 15mins.
12. Ask students to answer the practice questions.

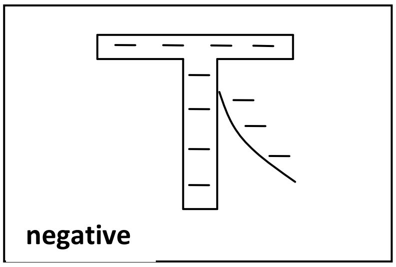
Model Answers to Worksheets:

How the Goldleaf Electroscope Works

The goldleaf electroscope is used to detect ***charge***. When the stem and leaf become charged, the gold leaf is ***repelled*** by the stem, and ***rises***. When the charge leaves the system, so that the stem and leaf are ***neutral***, the gold leaf ***falls***.


neutral


positive


negative

For a negatively charged zinc plate:

Conclusions:

The UV light discharged the zinc plate, but the visible light did not. The amount of light or the intensity of the light does not affect whether the plate gets discharged or not. Only the *frequency* affects it.

For a positively charged zinc plate:

Conclusions:

The charge that leaves the plate when UV light is shone on it, are negative. The negative charges are electrons.

Explanation:

1. The emission of electrons by light is called the ***photoelectric effect***.
Electrons emitted by the photoelectric effect are called ***photoelectrons***.

2. The amount of energy in light depends on the frequency, not the intensity. Light does not arrive in a continuous stream, but arrive in packets or energy. These packets are called *photons*. One photon has a limited amount of energy, with each photon from the same light source having the same amount of energy.

3. Electrons are only emitted from the zinc plate when the light is above a certain frequency. This frequency is called the ***threshold frequency***, and is represented by the symbol, f_0

4. Different elements need different amounts of energy to release electrons by photoelectric emission. This is because of their structure.

5. Electrons closer to the surface of the material require less energy to escape than electrons deeper in. They therefore have more leftover energy to be converted into kinetic energy once they have been released.

Practice Questions Answers:

1. a. The threshold frequency is the minimum frequency corresponding to a minimum energy required for an electron to be emitted via photoelectric emission, for a particular material.
   b. The work function is the minimum energy required for an electron to escape the forces holding it in the material's structure.

2. $h\frac{c}{\lambda} = \phi + \frac{1}{2}mv^2$

3. $E = hf = 6.63 \times 10^{-34} \times 1 \times 10^{15} = 8.0223 \times 10^{-19}\text{J} = \frac{8.0223\times10^{-19}}{1.6\times10^{-19}}\text{eV}$
$= 5.0139375\text{eV} = 5.01\text{eV}(3\text{s.f.})$

4. $\phi = 4.3 \times 1.6 \times 10^{-19}\text{J} = 6.88 \times 10^{-19}\text{J}$

$$KE_{\max} = h\frac{c}{\lambda} - \phi = 6.63 \times 10^{-34} \times \frac{3 \times 10^8}{4 \times 10^{-8}} - 6.88 \times 10^{-19}$$
$$= 4.2845 \times 10^{-18}\text{J} = 4.28 \times 10^{-18}\text{J}(3\text{s.f.})$$
$$= \frac{4.2845\times10^{-18}}{1.6\times10^{-19}}\text{eV} = 26.778125\text{eV} = 26.8\text{eV}(3\text{s.f.})$$

5. Increasing the temperature of the material would make the atoms vibrate more, making it more difficult for the electrons overcome the forces holding it in the st Goldleaf Electroscope Experiment work function would therefore increase.
6. A photon is a packet of energy.
    a. There are more photons in a brighter light.
    b. There are more photons in visible light than UV light if they have the same intensity. This is because there is more energy in each photon of UV light. The intensity is proportional to the total amount of energy, so the energy is split up into fewer photons for UV light.

7. $hf = \phi + \frac{1}{2}mv^2$

$$v = \sqrt{(hf - \phi) \times \frac{2}{m_e}}$$

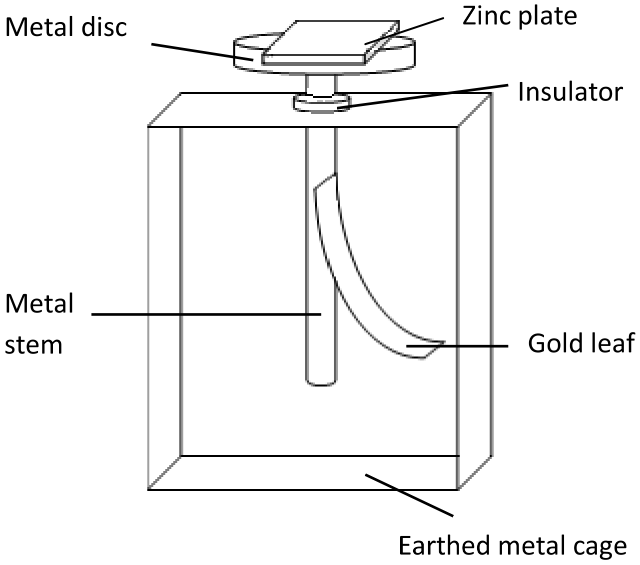
$$= \sqrt{(6.63 \times 10^{-34} \times 2 \times 10^{16} - 4.08 \times 1.6 \times 10^{-19}) \times \frac{2}{9.11 \times 10^{-31}}}$$

$$= 5.260961585 \times 10^6 \mathrm{ms}^{-1} = 5.26 \times 10^6 \mathrm{ms}^{-1} (3\mathrm{s.f.})$$

Student's Worksheet

PHOTOELECTRIC EFFECT

Goldleaf Electroscope Experiment



How the Goldleaf Electroscope Works

Fill in the blanks with the words in the box at the bottom.

The goldleaf electroscope is used to detect__________. When the stem and leaf become charged, the gold leaf is ________________ by the stem, and ___________. When the charge leaves the system, so that the stem and leaf are __________, the gold leaf ________.

rises falls charge repelled
attracted positive neutral

Sketch your observations of the stem and leaf when the electroscope is neutral, positively charged, and negatively charged in the boxes below.

neutral

positive

negative

For a negatively charged zinc plate:

Observations:

- When *UV* light is shone on the zinc plate, the gold leaf falls, meaning it has been discharged.
- When *visible* light is shone on the zinc plate, the gold leaf remains charged and does not fall.
- No matter how high the intensity of the visible light is, or how long it shines, the gold leaf does not fall.

Conclusions:

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<u>For a positively charged zinc plate:</u>

Observations:

- The gold leaf does not fall when either UV or visible light are shone on the zinc plate, meaning it does not get discharged.

Conclusions:

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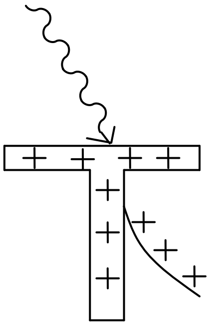
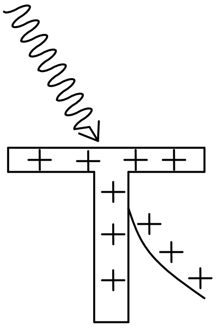
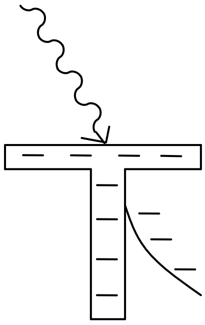


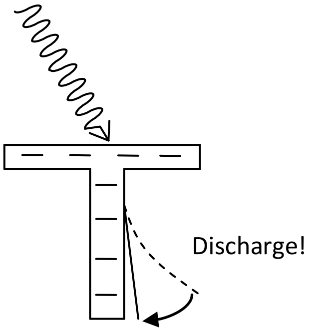
Positive with visible



Positive with UV



Negative with visible



Negative with UV

<u>Explanation:</u>

1. The emission of electrons by light is called the _______________________________.

Electrons emitted by the photoelectric effect are called ___________________________.

2. Normal wave theory suggests that radiation with a lower intensity will have lower energy. We would therefore expect that if you shone light at a high intensity, more electrons would be emitted than shining a dim light. We would also expect more electrons to be emitted if we shone light for a longer period of time. However, this isn't the case! No matter how long you shine visible light or how bright it is, we will never observe the photoelectric effect using a zinc plate. Also, when we shine low intensity UV light on the zinc plate, photoelectric emission begins immediately.

What does this suggest about how the energy in light is related to intensity and frequency?

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3. Electrons are only emitted from the zinc plate when the light is above a certain frequency. This frequency is called the ____, and is represented by the symbol, f_0

4. The threshold frequency is different for different materials. For example, blue light causes sodium to emit electrons, but red light does not. UV light causes zinc to emit electrons, but visible light does not.
Why is this?

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5. In the photoelectric effect, all the energy from one photon is transferred to one electron. This energy helps the electron escape from the forces in the structure that are holding it in. It can be shown by further experiments that some electrons leave the metal with more energy than others, i.e. they travel faster.
Explain this.

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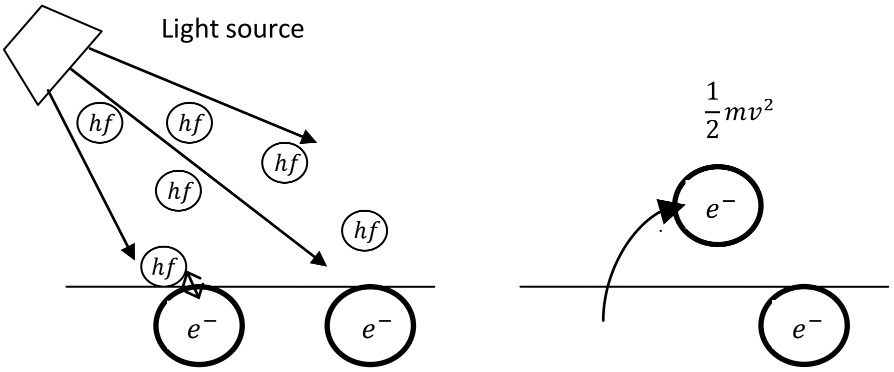
Quantum Theory of Light

We have established that the energy of radiation is related to the frequency of the light. In fact, the energy is *directly proportional* to the frequency. This can be summarised by the equation:

$$\boxed{E = hf}$$

where E is the energy of radiation (measured in Joules, J)
f is the frequency of the radiation (measured in Hz)
h is a constant, called the Planck Constant. It is equal to 6.63×10^{-34}Js



Photoelectric Equation

We have found out that electrons are emitted with different energies because of their location in the material's structure. The minimum amount of energy for an electron to overcome the forces holding it in the material, is called the **work function**, and is denoted by the symbol ϕ **.** The energy carried by a photon is therefore equal to the work function plus the leftover energy. The leftover energy is the maximum kinetic energy the emitted electron can have.

We therefore have the equation:

$$\boxed{hf = \phi + KE_{\max}}$$

where $KE_{\max} = \frac{1}{2}mv^2$ is the maximum kinetic energy of an emitted electron.

$KE_{\max}$ occurs for an electron situated at the surface of the material, as it requires the least amount of energy to be released.

Practice Questions

1. Describe what is meant by the terms:
    a. Threshold frequency
    b. Work function

2. How is the wavelength of light related to the work function and kinetic energy of an emitted electron? Write an equation down summarising this.

3. For radiation with a frequency of $1.00 \times 10^{15}\mathrm{Hz}$, what is the energy carried by a photon, in electronvolts?

4. Light with a wavelength of $4.00 \times 10^{-8}\mathrm{m}$, is shone upon a zinc plate with a work function of 4.30eV. Calculate the maximum kinetic energy in Joules and electronvolts an electron could have if emitted via the photoelectric effect.

5. Would the work function of a material change if the temperature of the material was increased? If so, how would it change?

6. What is a photon? Are there more photons in:
    a. brighter light or dimmer light, both with the same frequency?
    b. UV light or visible light with the same intensity?

7. Aluminium has a work function of 4.08eV. If light with a frequency of $2 \times 10^{16}\mathrm{Hz}$ is shone on aluminium, calculate the maximum velocity an emitted electron can have.

Photoelectric Cell and Stopping Potential Experiment

Duration: 50mins

Prerequisites:

- Understanding of the photoelectric effect
- Knowledge and understanding of the terms ‘work function’ and ‘threshold frequency’
- Knowledge of the photoelectric equation in the form: $hf = \phi + KE_{\max}$
- Knowledge of the equation: $E = hf$

Overview of Experiment:

A circuit is set up by the teacher and is used to find the stopping voltage of a photoelectric cell. Planck’s constant, *h*, will also be determined.

Objectives: - Students will:

- Understand how the photoelectric cell circuit works and how to determine the stopping voltage, V_S
- Understand and know the equation $hf = \phi + QV_S$
- Know how to determine Planck’s constant graphically

Required Materials:

- Photoelectric cell
- Picoammeter
- Voltmeter
- Variable resistor
- Voltage supply
- Sufficient wires
- White light source, and various coloured filters
- Computer with spreadsheet software for each pair of students, or one computer and spreadsheet software for the teacher, or a sheet of graph paper for each student
- Set of worksheets for each pupil (supplied at the bottom of the section)

Background

Photoelectric effect

Please see pages 2-3 of this document.

Photoelectric cell circuit

In the circuit shown in Figure 2, overleaf, the photoelectric cell produces a current when light falls on it. Electrons escape the negatively charged cathode and flow to the positively charged anode. The current therefore flows clockwise around the circuit. The current produced is registered by the ammeter. The voltmeter also shows that there is a voltage. When the cell is switched on, it produces a current that flows anticlockwise around the circuit, opposing the current produced by the photoelectric cell.

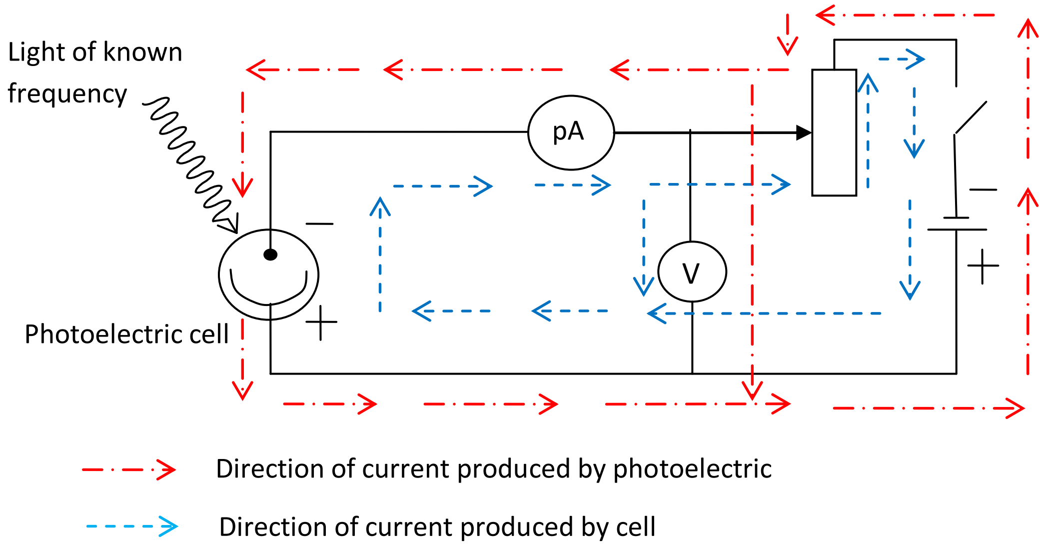


Figure 2 –Circuit with a photoelectric cell, used to determine the stopping potential of light of a known frequency.

As the cell's current is increased, the photoelectric cell's current decreases, until no current is produced by the photoelectric cell. At this point, the ammeter will give a reading of 0A, but the voltmeter will still read a voltage. This voltage is the **stopping voltage, V_S**.

At the stopping voltage, no electrons pass between the electrodes in the photoelectric cell. The potential energy created by the cell pushes the electrons back, so the kinetic energy of the emitted electrons equals the potential energy it gains, meaning no electrons reach the anode from the cathode.

We can summarise this by rewriting $hf = \phi + \frac{1}{2}mv^2$ as:

$$hf = \phi + QV_S$$

where Q is the charge of the electron ($1.6 \times 10^{-19}\mathrm{C}$). This is another form of the photoelectric equation.

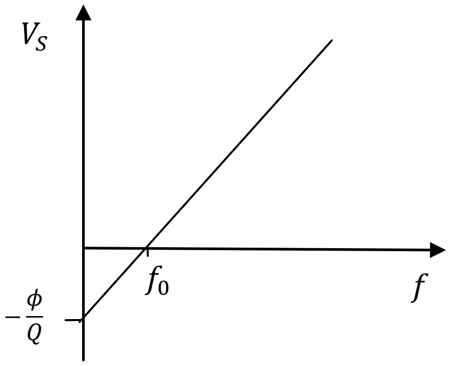
Finding Planck's constant, h

If we rearrange the photoelectric equation to get:

$$V_S = \frac{h}{Q}f - \frac{\phi}{Q}$$

we can plot a linear graph of V_S against f, where V_S is on the y-axis, f is on the x-axis, $\frac{h}{Q}$ is the gradient, and $-\frac{\phi}{Q}$ is the y-intercept.

The result is a graph that looks like:



Note that when the stopping voltage is 0V, as in there is no opposing voltage, the frequency is not 0Hz. This is because there is still a threshold frequency, f_0, which the frequency of the light must be above for photoelectric emission to take place.

Procedure 1 – Teacher Demonstrating Experiment to Students

Before the Class:

1. Read through the whole chapter to familiarise yourself with the material.
2. Print off a set of the worksheets for each student.
3. Set up the apparatus as shown in the diagram, and familiarise yourself with the equipment by going through the experiment quickly.
4. Set up a computer and open a blank spreadsheet (e.g. in Microsoft Excel) if you will be the only one plotting a graph for the students. Set up a computer and open a blank spreadsheet for each pair of students if the students will be plotting graphs in pairs. If the students will be using graph paper to plot graphs, then no computer is needed.
5. Draw the circuit in Figure 2 on the board, minus the dotted arrows showing the directions of the currents. Draw the circuit in Figure 3 on the board.

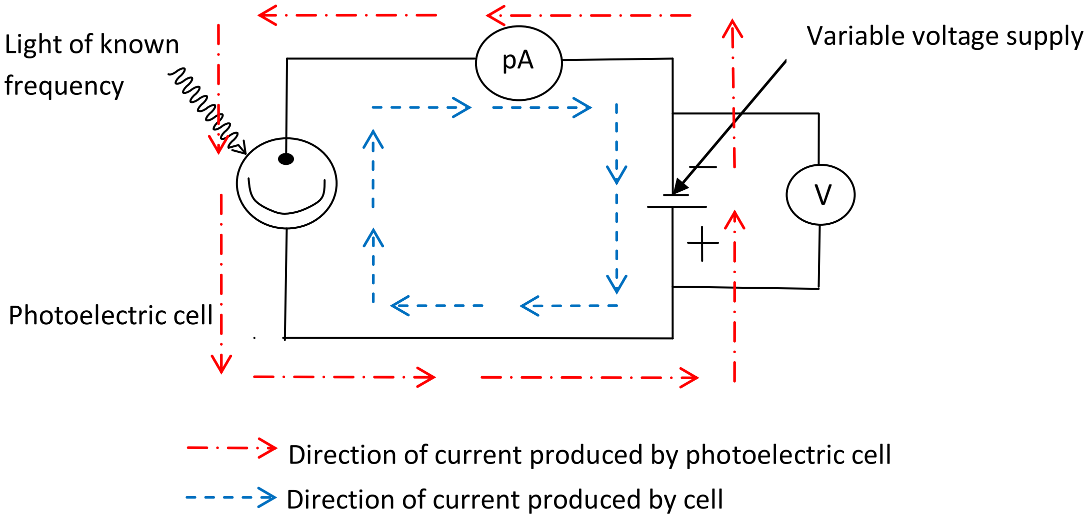


Figure 3 - Simplified circuit diagram of photoelectric cell and stopping potential experiment

In Class:

1. Recap with the class:
    a. The photoelectric effect
    b. The terms ‘threshold frequency’, f_0; and ‘work function’, ϕ
    c. The photoelectric equation: $hf = \phi + KE_{\max}$
    d. The equation: $E = hf$

2. Explain the set up of the apparatus. Explain how the photoelectric cell is made up of an anode and cathode, and how a current is produced between them via the photoelectric effect.
3. Shine white light onto the photoelectric cell to demonstrate a current being registered by the picoammeter. Switch on the cell, and vary the voltage using the variable resistor until a current of 0A is registered by the picoammeter.
4. Explain this phenomenon to the class.
5. Hand out the worksheets and write the frequencies of the different coloured filters on the board, while the students draw the circuits from Figures 2 and 3 in the space provided in the worksheet.
6. Allow time for them to fill in the first section of the description of the experiment in the worksheets.
7. Explain how the photoelectric equation can be rewritten as $hf = \phi + QV_S$
8. Let students work through the ***'Finding h'*** section of the worksheet, and then discuss their answers.
9. Ask the students to copy down the frequencies in the provided table. If a range of frequencies is shown on the filters, ask the students to find the mean value of the frequency, and then to write this value in the table.
10. Use each coloured filter in front of the white light in turn, shining it on the photoelectric cell with the cell on. Vary the variable resistor until there is 0A of current showing on the picoammeter. Ask the students to record down the voltage shown on the voltmeter at this point, in their tables.
11. Go through the voltages obtained by the class, then either:
    a. Enter the values of the frequencies and the corresponding stopping voltages into the spreadsheet. Plot a graph with V_S on the y-axis, and f on the x-axis. Fit a linear line to the plots, extending it to $f = 0$, and find the gradient of the line. Or:
    b. Let the students plot the values of the in pairs, and let them determine the gradients. The students may need help with finding the gradient. If this is the case, you should talk them through the procedure on the board as a class.
    c. Provide each student with a sheet of graph paper, and ask them to plot the values, and draw a linear line of best it, ensuring they leave enough room to extend the line of best fit to the y-axis.
12. Let the students sketch this graph in the worksheet. Allow students to work through the rest of the ***'Results'*** section of the worksheet.
13. Discuss the values of Planck's constant they deduce, and allow students to attempt the practice questions. The practice questions could instead be set as homework.

Model Answers to Worksheets

How the Circuit Works...

The photoelectric cell has a positive ***anode,*** and a negative ***cathode***. When light falls on the photoelectric cell, ***electrons*** are released from the ***cathode***, creating a current. The current produced flows in a ***clockwise*** direction around the circuit, and is registered by the picoammeter. The voltmeter also shows that there is a voltage.

When the cell is switched on, it produces a current which flows ***anticlockwise*** around the circuit, opposing the photoelectric cell's circuit. As the cell's current is increased, the photoelectric cell's current ***decreases***, until no current is produced by the photoelectric cell at all. At this point, the ammeter will give a reading of 0A, but the voltmeter will still read a non-zero voltage. This voltage is called the ***stopping voltage***, denoted as V_S.

Finding h

1. $hf = \phi + QV_S$
   $QV_S = hf - \phi$

$V_S \quad = \frac{h}{Q}f - \frac{\phi}{Q}$

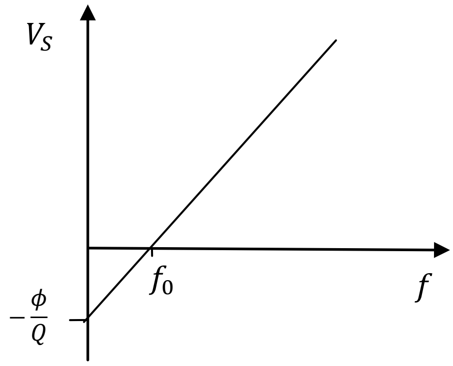
2.

$$\frac{h}{Q} = \frac{6.63 \times 10^{-34}}{1.6 \times 10^{-19}} = 4.14 \times 10^{-15}$$

3. $-\frac{\phi}{Q}$

4. To determine the value of h, plot V_S against f, and find the gradient. The gradient is $\frac{h}{Q}$ and rearrange this to get $h = \text{gradient} \times Q$

Results



Answers to Practice Questions

1. $V_S = \frac{KE}{Q} = \frac{2.43\times10^{-19}}{1.6\times10^{-19}} = 1.51875\text{V} = 1.52\text{V (3s.f.)}$

2. $\phi = \frac{hc}{\lambda} - QV_S = \frac{6.63\times10^{-34}\times3\times10^{8}}{2.4\times10^{-6}} - 1.6 \times 10^{-19} \times 0.45 = 1.0875 \times 10^{20}\text{J}$
$= \frac{1.0875\times10^{20}}{1.6\times10^{-19}}\text{eV} = 0.067968\ldots\text{eV} = 0.080\text{eV(3s.f.)}$

3. Set up a circuit as shown in Figure 2, and plot V_S against f. Find the y-intercept of the graph, which equals $-\frac{\phi}{Q}$ and rearrange this to get $\phi = -\text{y intercept} \times Q$

4. $hf \quad = \phi + QV_S$

The threshold frequency will correspond to a stopping voltage of 0V. So we get:

$hf_0 \quad = \phi$

$f_0 \quad = \frac{\phi}{h}$

$\frac{\phi}{h}$ is a constant, and we can find its value using the V_S and f values for red light.

$$\frac{\phi}{h} = f - \frac{QV_S}{h} = 4.8 \times 10^{14} - \frac{1.6 \times 10^{-19}}{6.63 \times 10^{-34}} = 4.58280\ldots \times 10^{14}$$

$f_0 \quad = 4.58 \times 10^{14}\text{Hz}$

Student's Worksheet

PHOTOELECTRIC EFFECT

Photoelectric Cell and Stopping Potential Experiment

Figure 1 – Circuit of the photoelectric cell & stopping potential experiment

Figure 2 – Simplified circuit of photoelectric cell & stopping potential experiment, showing the directions of currents

How the Circuit Works...

Fill in the blanks with the words at the bottom. Some words may be used more than once, or not at all.

The photoelectric cell has a positive ___________, and a negative ____________. When light falls on the photoelectric cell, __________________ are released from the _____________, creating a current. The current produced flows in a _____________________________ direction around the circuit, and is registered by the picoammeter. The voltmeter also shows that there is a voltage.

When the cell is switched on, it produces a current which flows _______________________________ around the circuit, opposing the photoelectric cell's circuit. As the cell's current is increased, the photoelectric cell's current ____________________, until no current is produced by the photoelectric cell at all. At this point, the ammeter will give a reading of 0A, but the voltmeter will still read a non-zero voltage. This voltage is called the _____________________________, denoted as V_S.

electrons cathode clockwise anticlockwise anode increases
decreases work function stopping voltage photons

Rewriting the Photoelectric Equation

We already know that the photoelectric equation can be written as:

$$hf = \phi + KE_{\max}$$

At the stopping voltage, the electrons are no longer flowing from the cathode to the anode in the photoelectric cell, so no current is produced. At this point, the potential energy gained by an emitted electron must equal its kinetic energy, so that the electron is forced to stop.

We can deduce that the photoelectric equation can be rewritten as:

$$\boxed{hf = \phi + QV_S}$$

where Q = charge of electron = 1.6×10^{-19} Coulombs (C)

Finding h

1. Rearrange the equation $hf = \phi + QV_S$ so that V_S is the subject. Do this in the space below.

We can plot a linear graph of this equation, where V_S is on the y-axis, and f is on the x-axis.

2. What would the value of the gradient of the graph be?

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3. What would the y-intercept of the graph be?

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4. Describe how you would determine the value of Planck's Constant, h, using the graph.

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Results

Colour	f **(Hz)**	V_S **(V)**

Sketch the graph of the result in the space below.

Figure 3 – Graph of how the stopping voltage of a photoelectric cell varies with the frequency of the light shone upon it.

The threshold frequency, f_0, is given by the x-intercept. Remember, the light needs to be above a certain frequency before electrons are emitted. Therefore, even with no repelling voltage, the electrons do not get emitted and do not reach the anode of the photoelectric cell, if they are not above the threshold frequency. The stopping voltage is therefore zero.

Label the y and x-intercepts on your sketch in Figure 3.

5. What is the threshold frequency for the photoelectric cell?

6. Calculate the value of h using the gradient of the graph. Compare this to the actual value of h.

Practice Questions

1. The maximum kinetic energy of an electron emitted by photoelectric emission is $2.43 \times 10^{-19}\mathrm{J}$. What is the stopping voltage required to stop this electron?

2. Light with a wavelength of $2.4 \times 10^{-6}\mathrm{m}$ is shone on a photoelectric cell, and the stopping voltage is found to be 0.45V. What is the work function of the photoelectric cell in eV?

3. Describe how you can graphically determine the work function of a photoelectric cell, using a circuit with a variable voltage supply, an ammeter, and a voltmeter.

4. The stopping voltage for red light of frequency $4.8 \times 10^{14}\mathrm{Hz}$ is found to be 0.09V. Calculate the threshold frequency of the same photoelectric cell.

How Photocurrents Vary

Duration: 50mins

Prerequisites:

- Understanding of the photoelectric effect
- Knowledge and understanding of the terms 'work function' and 'threshold frequency'
- Knowledge of the photoelectric equation in the forms: $hf = \phi + KE_{\max}$ and $hf = \phi + QV_S$
- Knowledge of the equation: $E = hf$
- Understanding of how to determine the stopping voltage of a photoelectric cell and Planck's constant

Overview of Demonstration:

A circuit is set up by the teacher to demonstrate how the photocurrent produced by a photoelectric cell varies with voltage for light of different intensity and frequency. Animations are used to aid the students' understanding.

Objectives: - Students will:

- Understand how photocurrents varies with voltage
- Understand and explain how photocurrents vary with voltage for light of different intensity and frequency
- Be able to sketch graphs of how photocurrents vary voltage for light of different intensity and frequency

Required Materials:

- Photoelectric cell
- Picoammeter
- Voltmeter
- Variable resistor
- Voltage supply
- Sufficient wires
- White light source, and two coloured filters
- Set of worksheets for each pupil (supplied at the bottom of the section)
- Animations provided with this document (not yet completed)

Background Information

Photoelectric effect

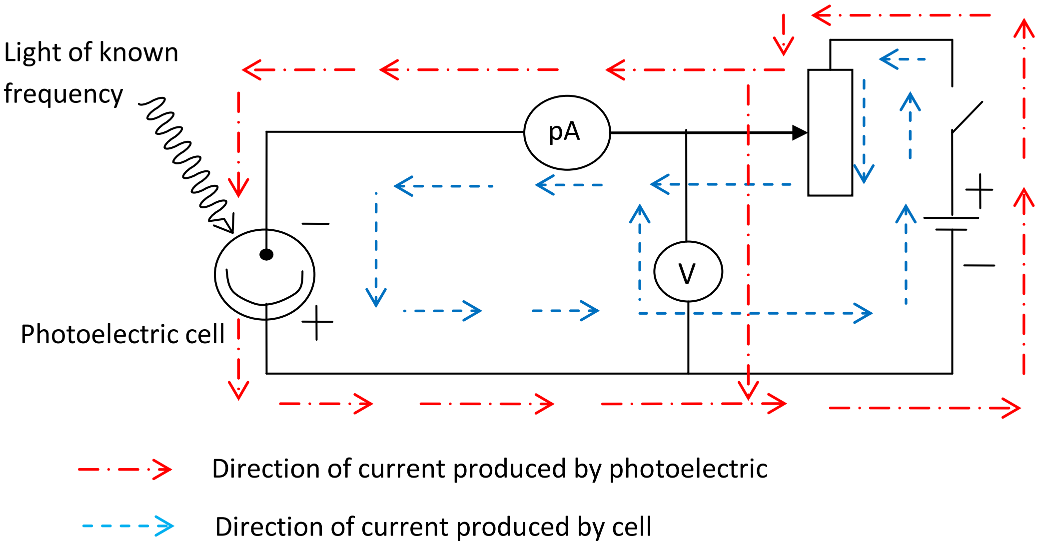
Please see pages 2-3 of this document.

Photoelectric cell circuit

Please see pages 12-14 of this document.

Adjusted Photoelectric Cell Circuit

In this demonstration, the same circuit from Figure 2 on page 13 will be used, but with the cell connected the other way so that the current it produces flows clockwise.



The current produced by the cell now aids the photocurrent (the current produced by the photoelectric cell). There is no longer any repelling force in the photoelectric cell. We can use this adjusted circuit to explore how the photocurrent varies with voltage.

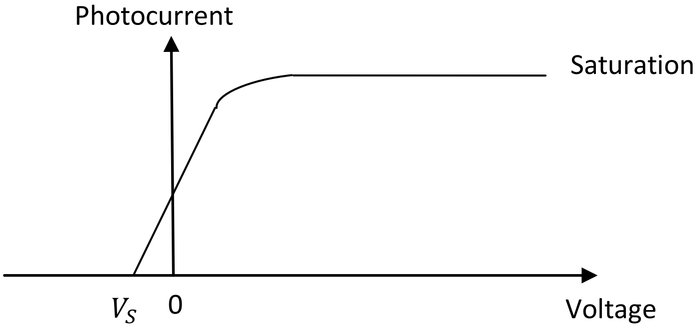


Figure 4 - Graph of how photocurrent varies with voltage for a photoelectric cell illuminated with monochromatic light of a particular intensity

- As the voltage is increased using the variable resistor, the current increases, as the direction of the voltage now assists the current produced by the photoelectric cell.
- There is a limited number of photons arriving on the photoelectric cell per second, so there is a limited number of electrons that can be released per second. This means that the photocurrent produced has an upper limit, and saturates, no matter how high the voltage is.
- There is still a current at 0V because electrons are still being emitted via the photoelectric effect, when the light is shining on the photoelectric cell.
- When the voltage is negative, there is a repelling force acting on the electrons from the photoelectric cell again. The current decreases until the kinetic energy of the electrons equals the potential energy gained, at which point, the current is 0A.

- The voltage at $I = 0$ (where I is the photocurrent), is the stopping voltage.

Varying Brightness (Intensity)

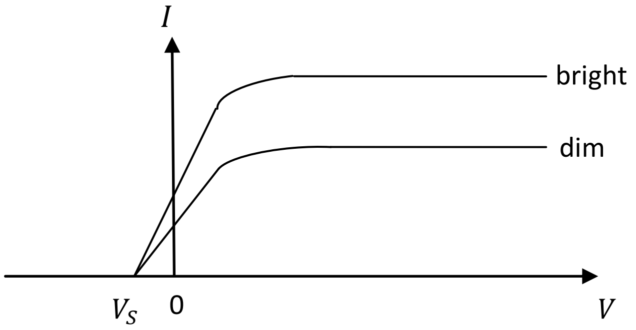


Figure 5 - Graph of how photocurrent varies with voltage for light of the same frequency, but with varying intensity

- Brighter light has more photons arriving per second. This means more electrons are emitted per second. This gives a higher saturation current.
- The stopping voltage is the same because the light has the same frequency. Each photon has the same amount of energy, so the electrons at the surface acquire the same amount of energy, and need the same amount of energy to be stopped.

Varying Frequency

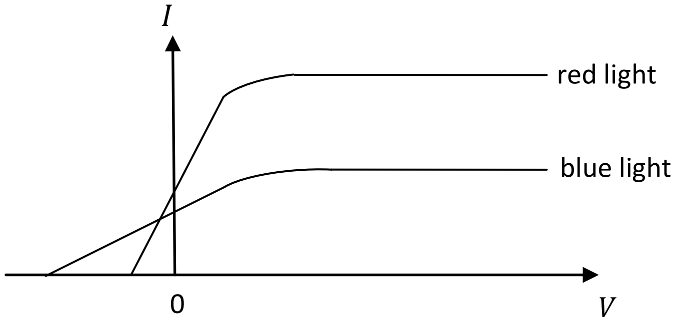


Figure 6 - Graph of how photocurrent varies with voltage for light of the same intensity, but with two different frequencies

- The stopping voltage for blue light is greater in magnitude than that of red light. This is because photons in blue light have a higher energy, so the electrons are emitted with a higher kinetic energy, and require more energy to stop them.
- The saturation current is less for blue light. This is because both radiations have the same intensity, so have the same total energy arriving at the photoelectric cell per second. However, blue light has a higher amount of energy per photon, so the total amount of energy is divided into a smaller number of photons. Therefore, there are less photons arriving per second, but each photon has a higher energy. The red light has a larger number of photons, but each with a smaller amount of energy.

Procedure:

Before Class:

1. Read through the whole chapter to familiarise yourself with the material.
2. Print off a set of the worksheets for each student.
3. Set up the apparatus as shown in the diagram, and familiarise yourself with the equipment by going through the demonstration quickly.

In Class:

1. Recap with the class:
   a. The photoelectric effect
   b. The term ‘threshold frequency’, f_0
   c. The photoelectric equation in the forms: $hf = \phi + KE_{\max}$ and $hf = \phi + QV_S$
   d. The equation: $E = hf$, and how each photon carries this amount of energy
   e. The photoelectric cell and stopping potential experiment
2. Shine the lamp with a coloured filter on the photoelectric cell. Demonstrate how the photocurrent varies with voltage using the variable resistor. Note down key values of the photocurrent and voltage on the board (i.e. when voltage is 0, when the photocurrent is 0, the current and voltage when the current reaches saturation). Observe how the trend is linear up to saturation.
3. Discuss with the class the observations and explanations.
4. Play animation 1, while explaining it
5. Sketch a graph of the results on the board, and discuss the significance of each part.
6. Vary the intensity of the light, and note down key values as in Step 2. Explain the observations, with the help of animation 2.
7. Keeping the intensity of the light the same, use different coloured filters and note down key values as in Step 2. Explain the observations, with the help of animation 3.

Student's Worksheet

PHOTOELECTRIC EFFECT

How Photocurrents Vary

The circuit used to determine the stopping voltage and Planck's constant can be used with its cell connected the other way. This means that the cell produces a current that no longer acts against the **photocurrent** (current produced by photoelectric cell), but assists it.

We will explore how the photocurrent varies with voltage for this circuit, in different types of light.

Using monochromatic, dim light only

Sketch a graph of your observations:

Figure 1 – Graph of how photocurrent varies with voltage, when shining a monochromatic dim light on a photoelectric cell

Observation:
As the voltage increases, the photocurrent increases linearly.

Conclusions:

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Observation:
The photocurrent reaches a maximum, at which it saturates. The current does not increase with increasing voltage after a certain voltage has been reached.

Conclusions:

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Observation:
There is still a photocurrent when the voltage is at 0V.

Conclusions:

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Observation:
When the voltage is negative, the photocurrent decreases linearly, until it is 0A.

Conclusions:

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<u>Varying Brightness – Using a bright light and a dim light of the same frequency</u>

Sketch a graph of your observations:

Figure 2 – Graph of how photocurrent varies with voltage, when shining light of the same frequency, but with different intensities

Observation:
When shining brighter light, the photocurrent saturates at a higher value.

Conclusions:

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Observation:
The stopping voltage is the same for both the bright and dim lights.

Conclusions:

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<u>Varying Frequency – Using red light and blue light of the same intensity</u>

Sketch a graph of your observations:

Figure 3 – Graph of how photocurrent varies with voltage, when shining light of the same intensity, but with different frequencies

Observation:
The stopping voltage for blue light is greater in magnitude than that of red light.

Conclusions:

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Observation:
The photocurrent saturates at a lower value for blue light.

Conclusions:

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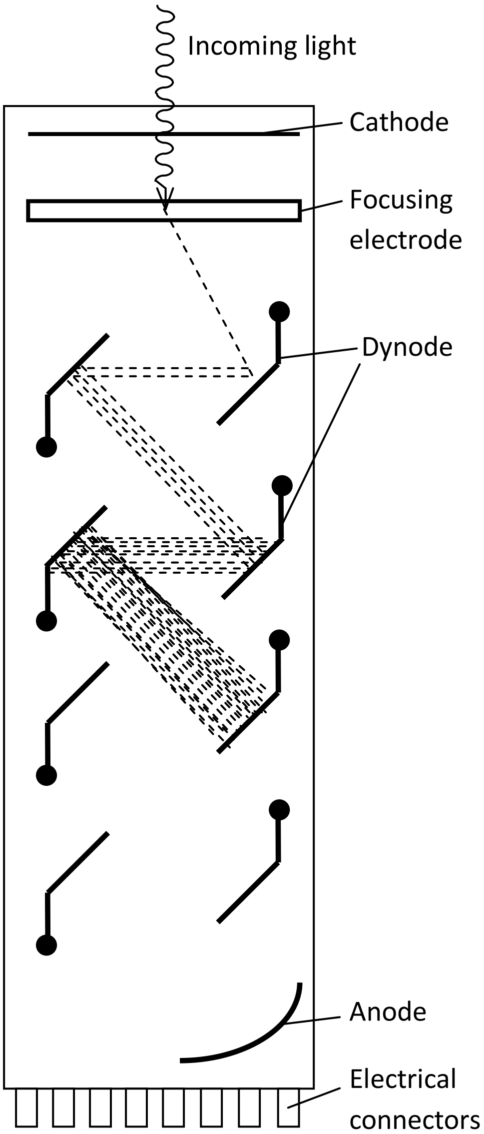
Photomultiplier Tubes

The CTA will use photomultiplier tubes (PMTs) to detect the flashes of light created when a gamma ray hits the atmosphere. The flashes of light are extremely faint, so need to be amplified for a detector to register it. PMTs amplify the signal by multiplying the number of counts detected from incoming light.

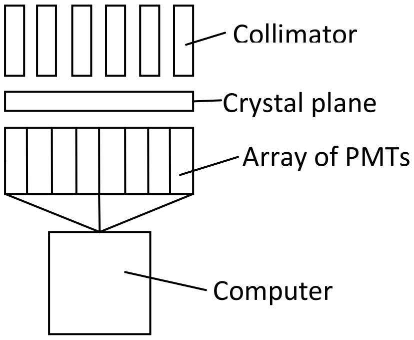
PMTs make use of the **photoelectric effect**, and secondary emission. Secondary emission is when electrons are fired at a metal surface, causing further emission of more electrons. By using many stages of secondary emission, a small number of electrons can be multiplied as much as 100 million times!



- Incoming photons hit the cathode, which emits electrons due to the photoelectric effect.
- The electrons get focussed by the focusing electrode, towards the first dynode.
- Each dynode is at a more positive voltage than the previous one.
- The electrons are accelerated towards the first dynode, and arrive with a greater energy than it had when it was first emitted.
- When the electron strikes the first dynode, more low energy electrons are emitted, increasing the number of electrons.
- The electrons are then accelerated towards the 2nd dynode, and the same happens. Each time the electrons hit a dynode, more and more electrons are emitted, so that the number of electrons has been multiplied to a very large number.
- At the end of the PMT, the electrons hit the anode, causing a sharp current pulse in the system. This can be fed to a computer.

Gamma Camera

The gamma camera makes use of PMTs, just like the CTA**.** It is made up of one or more flat crystal planes, which act as detectors. These are optically coupled to an array of PMTs. A gamma source is inserted into the human body (by injection, inhalation, or ingestion), and gamma rays are emitted through the body. When a photon from the gamma ray hits the crystal plane, it knocks off an electron from an atom in the crystal, and a faint flash is produced. PMTs situated behind the crystal detect this faint flash from various angles and distances, and amplify it. This allows a computer to calculate the strength and location of the gamma ray source.



Collimator

The collimator is made of highly absorbing material, e.g. lead. They decrease the amount of scatter and filters out wave orientations leaving only one wave orientation. The simplest collimators are simply made up of parallel holes.

Scintillation counter

The scintillation counter is composed of 4 components:

- sheet of scintillator (crystal plane)
- light guide
- PMT
- PMT base

The crystal plane is highly polished and light travels along it by total internal reflection. The light guide transmits the scintillations to the PMT. The PMT multiplies the signal, and the PMT base drives the PMTs and reads out the final signal.