Photoelectric effect

- **analyse the photoelectric effect with reference to:**
  - **– evidence for the particle-like nature of light**
  - **– experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency**
  - **– kinetic energy of emitted photoelectrons: $E_{k\,max} = hf - \varphi$, using energy units of joule and electron-volt**
  - **– effects of intensity of incident irradiation on the emission of photoelectrons**
- **describe the limitation of the wave model of light in explaining experimental results related to the photoelectric effect.**

Paper	Multiple choice	Short Answer	Idea	Marks	%	Type
2022	15		Particle model for light	1	81%	Concept
	17		E = hf	1	73%	Calculation
		14a	Cut off voltage	1	73%	Concept
		14b	I vs V graph, with change in I	2	89%	Concept
		14c	I vs V graph, with change in f	2	67%	Concept
		14d	Work function, from graph	1	65%	Concept
		14e	Planck' constant, graph	2	54%	Calculation
		14f	Limitation of wave model	1	63%	Concept
2022 NHT	16		Basic concept	1	NA	Concept
		15a	I vs V graph interpretation	2	NA	Concept
		15b	I vs V graph interpretation	2	NA	Concept
		15c	Work function	2	NA	Calculation
2021	16		KE_{max}	1	35%	Concept
	18		Power of light source	1	36%	Calculation
		15	Planck' constant	3	65%	Calculation
		16	Model for light	2	42%	Explanation
2021 NHT	18		PE effect	1	NA	Concept
		15a	$KE_{max} = hf - \phi$	2	NA	Explanation
		15b	$KE_{max} = hf - \phi$	2	NA	Explanation
		15c	Model application	3	NA	Explanation
2020	15		Wave/particle model	1	62%	Concept
	16		KE v f graph, work function	1	78%	Concept
	20		KE v f graph, work function	1	36%	Concept
		15a	Photocurrent vs V graph	2	61%	Concept
		15b	Photocurrent vs V graph	1	70%	Concept
		15c	Photocurrent vs V graph	1	32%	Explanation
2019	16		∆ light intensity	1	77%	Concept

		16a i	Gradient of KE vs f graph	2	57%	Calculation
		16a ii	KE vs f graph intercept	1	44%	Calculation
		16a iii	KE vs f graph intercept	1	56%	Calculation
		16b	Graph, work function	2	74%	Concept
2019 NHT		16a	Stopping voltage	3	NA	Calculation
		16b	Concept	2	NA	Calculation
		16c	Concept	3	NA	Explanation
2018	17		Gradient of graph, KE vs f	1	70%	Concept
		13a	Photon energy, E = $\frac{hc}{\lambda}$	3	33%	Calculation
		17a i	Concept	1	80%	Concept
		17a ii	Concept	2	30%	Explanation
		17b	Gradient of graph	2	55%	Calculation
		17c	Graph, work function	2	45%	Concept
2018 NHT	16		Concept	1	NA	Concept
	17		Work function	1	NA	Calculation
		16a	Gradient of KE vs f graph	2	NA	Calculation
		16b	KE vs f graph intercept	1	NA	Concept
		16c	Graph, work function	1	NA	Concept
		16d	KE vs f graph concept	2	NA	Concept
		17	Concept explanation	6	NA	Explanation
2017		17a	Current vs PD graph	2	33%	Calculation
		17b	Current vs PD graph	2	58%	Concept
		17c	Concept explanation	5	42%	Explanation

Photoelectric effect questions can be grouped into the following ideas.

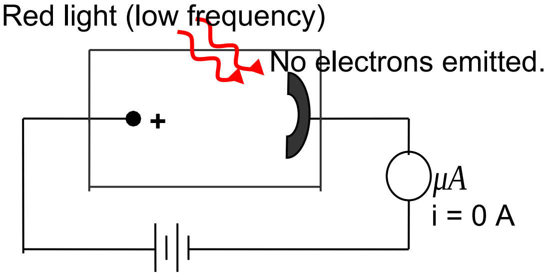
Photoelectric effect	
Basic concepts	Worked example 1
Particle model explanation	Worked example 2
Limitation of wave model	Worked example 3
Application of $KE_{max} = hf - \phi$	Worked example 4
KE vs frequency graph	
Concept	
Gradient, Planck's constant	Worked example 6
Vertical intercept, work function	Worked example 8
Horizontal intercept, cut-off frequency	Worked example 7
Current vs PD graph	
Concept	Worked example 9
Effects of change in intensity	Worked example 10
Effects of change in wavelength	Worked example 11
Cut–off voltage	Worked example 13
Explanation	Worked example 14
Energy of photon, $E = \frac{hc}{\lambda}$, power	Worked example 12

Photoelectric effect

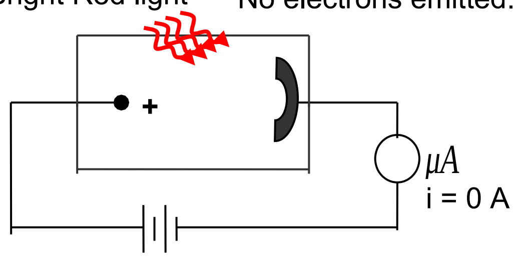
The discovery of the photoelectric effect dramatically changed the way scientists were thinking about light. The particle model had lost support since Young's double slit interference experiments. The wave model could not explain the photoelectric effect. It sometimes happens that when light falls on certain metals, electrons are ejected from the metal. These electrons are known as photoelectrons.

The experiment can be used to show that the number of electrons ejected depends upon the light intensity. As the light intensity increased, so did the size of the current. More electrons were escaping from the metal when the light was brighter.

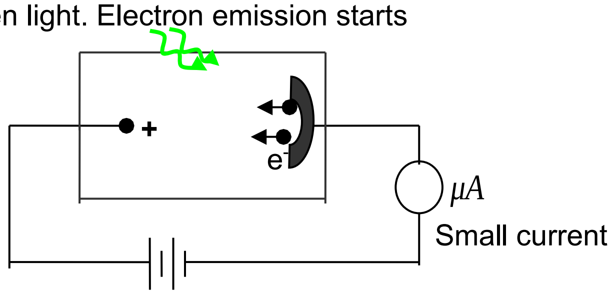
Red light (low frequency)



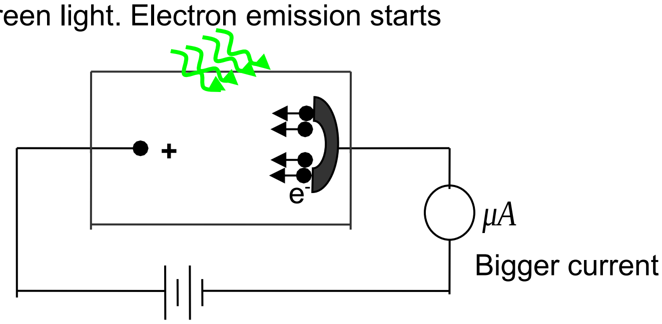
Bright Red light No electrons emitted.



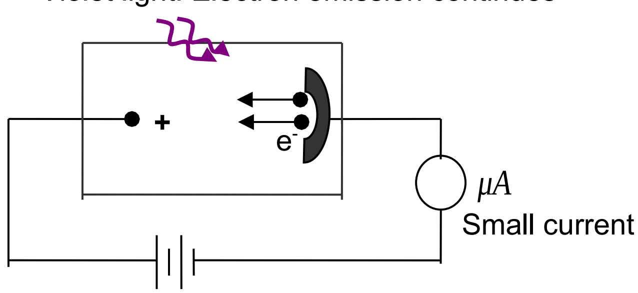
Green light. Electron emission starts



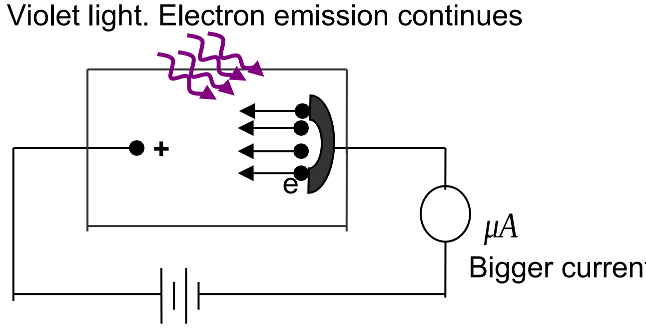
Green light. Electron emission starts



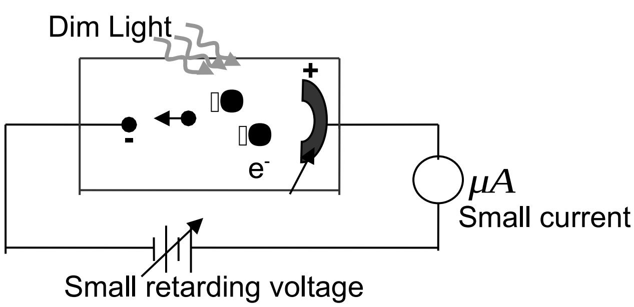
Violet light. Electron emission continues

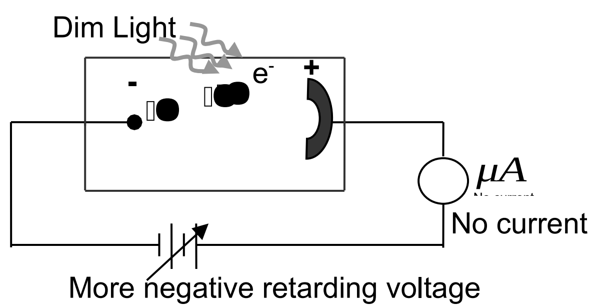


Violet light. Electron emission continues



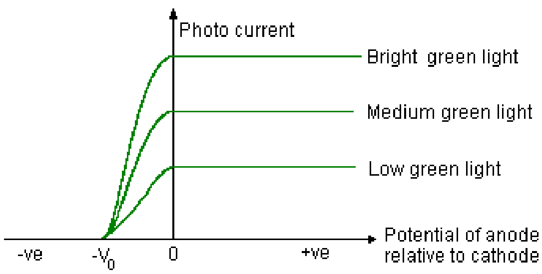
When the battery is reversed, some important results are obtained.

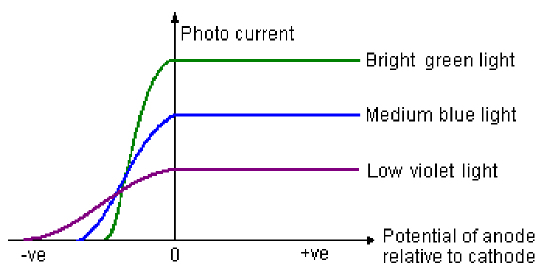




- As the anode is made more negative fewer electrons get across the tube- this means that the ejected electrons must have a range of kinetic energies. Electrons with little or no KE are stopped as soon as the anode becomes negative - those with the most KE being stopped by V_c volts. Energetic electrons come from the surface, less energetic electrons from below the metal surface.
- The value of V_c, the cut off voltage, depends upon the colour, not the intensity of the light. With most metals, low frequency light will not generate electrons.
- More intense light generates more electrons, but does not increase their energy.

When the frequency (i.e. colour) of the light shining on the metal changes, there is a frequency at which the electrons begun to be emitted from the metal. This is called the THRESHOLD or CUT-OFF FREQUENCY (f_c). Below this frequency, no emission occurs, even for very intense light.





These results cannot be explained using wave mechanical ideas. These would suggest that the energy carried by the wave would be distributed among all the atoms of the metal, building up until sufficient energy was available to ionise the atoms.

Thus intense light should produce a current more quickly than dim light. This is not so; electron emission is a factor of frequency not intensity. The results can be explained if it is assumed that light comes in random packets and not waves. The energy of one of these photons is transferred to one atom only, not spread to many, and hence the photoelectrons are observed immediately.

Einstein's explanation

Einstein's explanation of the photoelectric effect was that each photon of light gave up its energy completely when it collided with an electron in a metal.

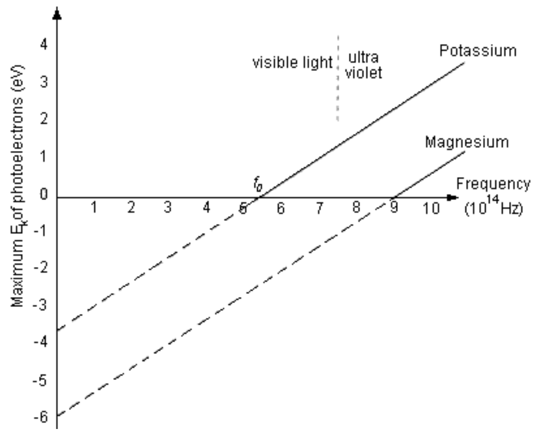
The energised electron used up some of this energy in overcoming the binding force of the atoms in the metal and escaped with the remaining energy.

The energy that the electron uses up to escape from the metal is called the BINDING ENERGY or WORK FUNCTION (ϕ) of the metal. Hence the work function (binding energy) is the difference between the energy of the incident photon and the maximum KE of the electrons that are ejected. This quantity is a property of the metal and varies from metal to metal.

Thus the maximum Kinetic energy of the escaped electron is given by

Kinetic Energy of Photoelectron: $E_K = qV_c = hf - \phi$

Kinetic Energy vs Frequency graph.



If a graph of the KE of the ejected electrons is plotted against the frequency of the incoming light the following can be deduced:

- There is a threshold frequency below which the electrons are not emitted.
- Different metals have different threshold frequencies
- The gradient of the graph is the same for all metals, it is Planck's constant
- The equation of the graph, an energy equation, is $E_k = hf - \phi$ where E_k is the Kinetic Energy of the ejected electrons, h a universal constant and ϕ a constant for the material.
- The constant h is Planck's constant and has the value of 6.63×10^{-34} J s, 4.14×10^{-15} eV s
- ϕ is either called the work function or the binding energy of the metal.

The gradient, $h = \frac{\text{rise}}{\text{run}}$

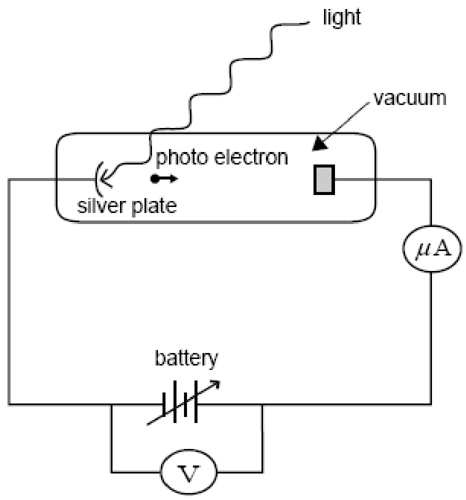
$\therefore h = \frac{\Phi}{f_0}$

$\therefore \phi = hf_0$

Worked example 1: Photoelectric effect: Basic concepts.

Experimental work was carried out to investigate the photoelectric effect by shining light onto a particular metal surface. Measurements were made of the number and maximum kinetic energy of the emitted electrons from this particular metal surface for different frequencies and intensities of light.

The apparatus shown was set up to investigate the photoelectric effect.



Using this apparatus it is found that light of wavelength 254 nm (2.54×10^{-7} m) ejects photoelectrons from a silver plate. The work

1999 Question 1, 2 marks

Which **one** of the statements **(A – D)** was **not** one of the findings?

A The ability to eject electrons from this metal depended only on the frequency of light.

B At frequencies below the 'threshold frequency' no electrons were ejected from the metal no matter how high the light intensity was.

C The 'stopping potential' for the photoelectrons was independent of the light intensity.

D The maximum kinetic energy of the photoelectrons depended only on the intensity of the light.

Solution	**Current study design:**
The maximum KE is given by KE = hf – φ.	**2022 Question 15 (81%)**
Where h is Planck's constant, f is the frequency of the light and φ is the work function of the metal.	**2022 Question 17 (73%)**
∴ D (ANS), (55%)	**2022 NHT Question 16**
	2021 Question 16 (35%)
	2021 NHT Question 18
	2018 Question 17a i (80%)

Worked example 2: Photoelectric effect: Particle model explanation.

2009 Question 2, 3 marks

Einstein's explanation of the photoelectric effect reopened the question about the nature of light. Explain briefly how the results of the photoelectric effect experiment supported a competing model to the one supported by Young's double-slit experiment.

Solution

The photoelectric effect supports the particle model of light. The following findings were not able to be satisfactorily explained using a wave model:

Minimum frequency, i.e. energy, required to emit an electron (threshold frequency)

Energy of emitted electrons was dependent on the frequency of the incident light

Below the threshold frequency, increasing the intensity of the incident light did not produce emitted electrons.

More intense light was explained by the particle model as more particles with the same energy, whereas the wave model explained more intense light as a wave of greater amplitude.

The PE experiment showed that when light was shone on a metal surface, electrons were ejected.

The wave model predicts that more intense light should produce electrons with greater energy. The particle model predicts more intense light, should produce more electrons with the same energy.

Einstein was able to explain the PE effect using Planck's photon model, which assumes a particle model of light. (60%)

Current study design:

2021 Question 16 (42%)

2021 NHT Question 15c

2019 NHT Question 16c

2018 Question 17a ii (30%)

2018 NHT Question 17

2017 Question 17c (42%)

Worked example 3: Photoelectric effect: Limitations of the wave model.

2012 Question 1b, 3 marks

In an effort to eject photoelectrons from the aluminium plate, Vishvi increases the intensity of the light beam, but still finds that no photoelectrons are emitted. Explain how this observation supports the particle model of light, but not the wave model of light.

Solution

The particle model predicts that increasing the intensity will increase the number of incident photons, but the photons will still have the same energy. Therefore the photons will not have sufficient energy to release an electron from the metal surface. Therefore there will not be any current.
The wave model predicts that increasing the intensity will increase the energy to a level to eject photoelectrons. (45%)

Current study design:

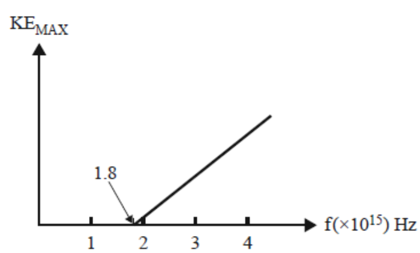
2022 Question 14f (63%)

Worked example 4: Photoelectric effect: Application of $KE_{max} = hf - \phi$.

A group of students carry out an experiment where light of various frequencies is shone onto a metal plate.

The maximum kinetic energy of the emitted electrons for each frequency is recorded and the results are plotted to produce the graph shown.

Take Planck's constant as 6.63×10^{-34} J s.



2014 Question 20a, 2 marks

Calculate the work function of the metal in joules.

Solution

Use $\phi = hf_0$

$\therefore \phi = 6.63 \times 10^{-34} \times 1.8 \times 10^{15}$

$\therefore \phi = 11.934 \times 10^{-19}$

$\therefore \phi = 1.2 \times 10^{-18}$ J (ANS), (75%)

Current study design:

2022 NHT Question 15c

2021 Question 15 (65%)

2021 NHT Question 15a

2021 NHT Question 15b

2019 NHT Question 16a

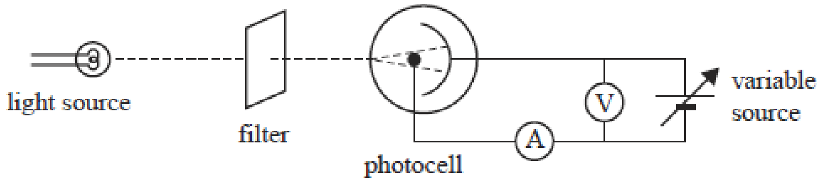
2019 NHT Question 16b

2018 NHT Question 17

Worked example 5: KE vs frequency graph: Concept.

2012 Question 1b, 3 marks

Emily is conducting an experiment to investigate the photoelectric effect. The apparatus is shown below. It consists of a light source, a filter and a photocell (a metal plate with a collecting electrode in a vacuum tube).



Emily uses various filters to shine a particular wavelength on the photocell.

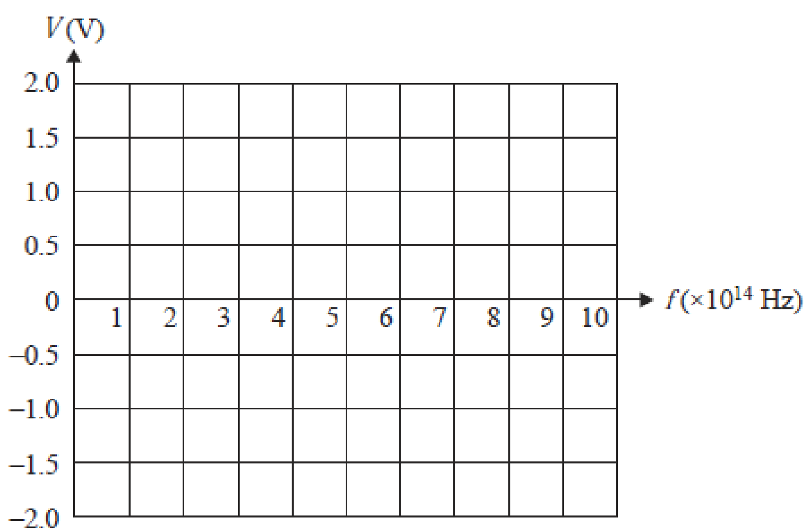
She increases the voltage (V) until the current just goes to zero and records this voltage. Emily repeats this process for different frequencies.

Her results are shown in the table below.

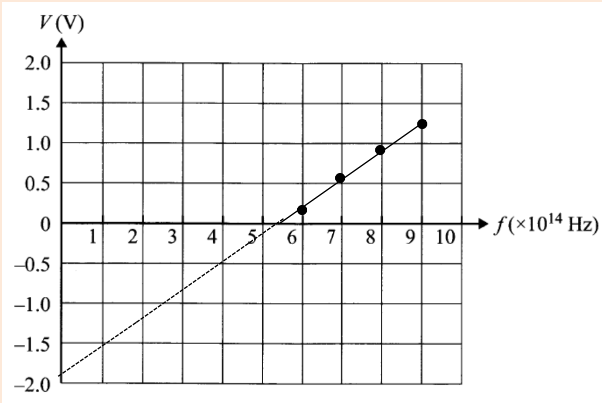
Frequency (Hz)	Voltage (V)
6.0×10^{14}	0.16
7.0×10^{14}	0.52
8.0×10^{14}	0.88
9.0×10^{14}	1.20

2016 Question 19a, 2 marks

On the axes below, plot Emily's data and draw the graph of voltage versus frequency.



Solution



(87%)

Current study design:

2020 Question 20 (36%)

2019 Question 16a i (57%)

2019 Question 16a ii (44%)

Worked example 6: KE vs frequency graph: Gradient, Plank's constant.

Worked example 7: KE vs frequency graph: Horizontal intercept, cut-off frequency.

Worked example 8: KE vs frequency graph: . Vertical intercept, work function

2016 Question 19b, 3 marks

From the graph, determine the value Emily would have found for each of the following.

Planck's constant	eVs
Threshold frequency	Hz
Work function of the metal	eV

Solution

Plank's constant is the gradient of the line.
You MUST use two points from your graph.

Use h = $\frac{1.20 - 0.16}{(9.0 - 6.0) \times 10^{14}}$

∴ h = $\frac{1.04}{3.0 \times 10^{14}}$

∴ h = 3.5×10^{-15} eVs (ANS)

Threshold frequency = 5.5×10^{14} Hz (ANS)

The answer box includes the units of Hz, therefore this has to be the horizontal intercept.

Work function = 1.9 eV (ANS)
The answer box includes the units of eV, therefore this has to be the vertical intercept.
The work function is always positive, as it is the energy required to release an electron.
(53%)

Current study design:

2022 Question 14e (54%)

2018 Question 17b (55%)

2018 NHT Question 16a

Current study design:

2018 NHT Question 16b

Current study design:

2022 Question 14d (65%)

2020 Question 16 (78%)

2019 Question 16a iii (56%)

2019 Question 16b (74%)

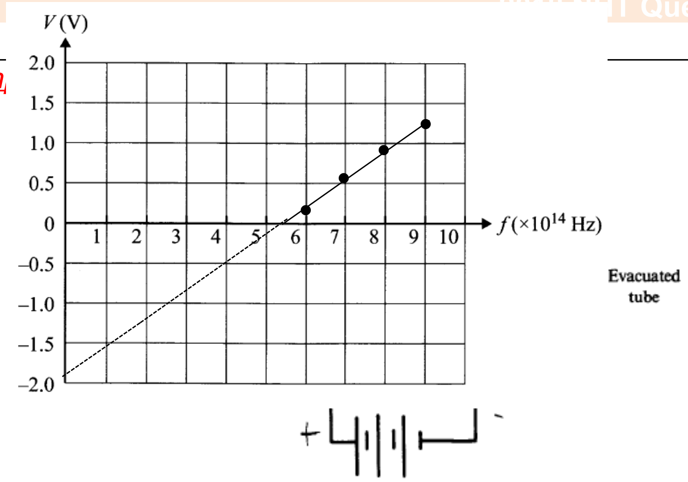
2018 Question 17 (70%)

2018 Question 17c (45%)

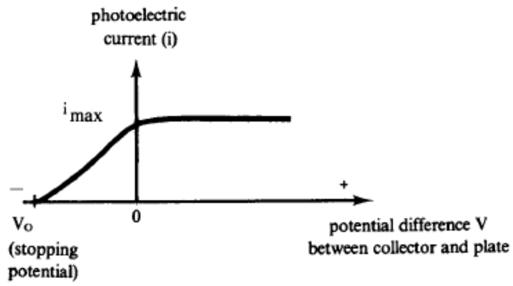
2018 NHT Question 16c

2018 NHT Question 16d

Worked exam



The figure above represents a photo-electric tube, in which light of a particular frequency and constant intensity strikes the plate; electrons of charge e are emitted and travel to the collector. As the potential difference between the collector and plate is varied, the current measured by the milli-ammeter varies as shown below.



1981 Question 47, 1 mark

Why is the photo-electric current constant at positive values of *V*?

A. The electric field between the collector and the plate remains constant as *V* is increased; thus increases in *V* do not increase the kinetic energy of the emitted electrons.

B. For a particular light intensity, there is a corresponding number of electrons emitted per second; when all of these have been collected, further increases in *V* do not increase the current.

C. All the photo-electrons have the same mass, charge, and kinetic energy, and none of these quantities is affected by changes in *V*.

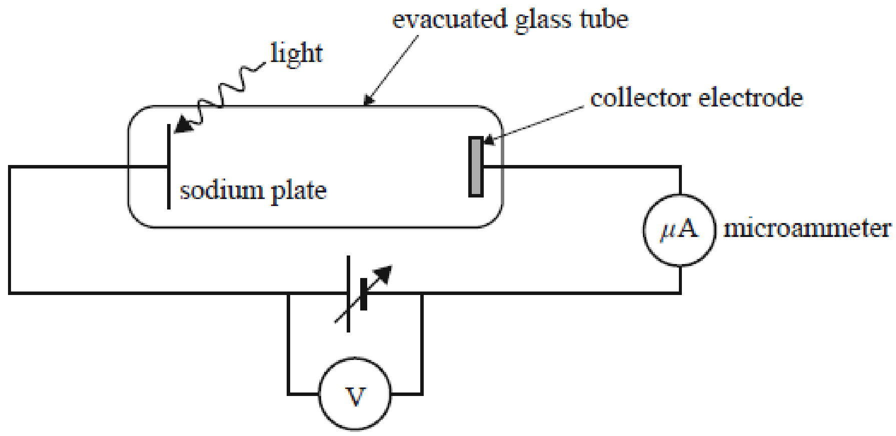
D. Ohm's Law applies to the photo-electric tube; as *V* is increased, its resistance increases, and so the current remains constant.

Solution	**Current study design:**
The light intensity is constant, and the number of electrons emitted is dependent on the incident intensity. Therefore once the collector is positive in relation to the emitter, all the electrons will travel across. Increasing the potential, won't change the current, as it is only dependent on the intensity of the light (constant).	2022 Question 14a (73%) 2022 NHT Question 15a 2022 NHT Question 15b

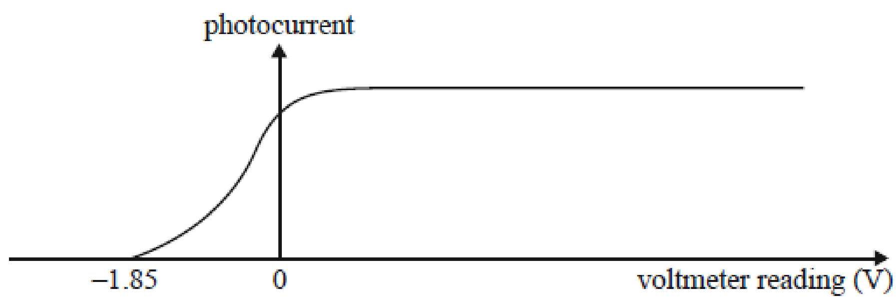
∴ B (ANS), (74%)

Worked example 10: Current vs PD graph: Effects of change in intensity.

Students are investigating the photoelectric effect by shining monochromatic light with a frequency of 1.00×10^{15} Hz onto a sodium plate. Their apparatus is shown below.



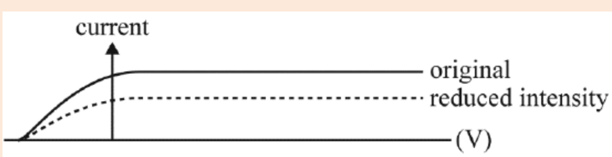
The graph shows the relationship between the photocurrent and the reading on the voltmeter.



2013 Question 21c, 2 marks

The intensity of the light is now reduced and the experiment is repeated. The students obtain a new graph of photocurrent against voltage. Sketch the new graph on the diagram above.

Solution



With the intensity of the light reduced, there will be less photoelectrons released from the metal, so the current will be reduced (vertical – intercept).

As the same light is used, the max KE of the ejected photoelectrons will remain the same, therefore the cut-off voltage will remain the same (horizontal – intercept). (60%)

Current study design:

2022 Question 14b (89%)

2020 Question 15a (61%)

2019 Question 16 (77%)

2018 NHT Question 16

2017 Question 17b (58%)

Worked example 11: Current vs PD graph: Effects of change in wavelength.

2013 Question 21d, 2 marks

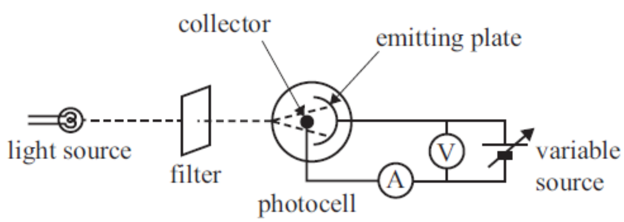
The students change the light source to one with a different frequency. They observe that the photocurrent is zero and remains at zero regardless of the size or sign of the voltage.

Explain this observation.

Solution	**Current study design:**
If the photocurrent remains zero, even when the collector voltage is positive, then this means that there are no photoelectrons being ejected. This means that the incident photons do not have enough energy to release a photoelectron. Therefore the energy of the incident photons, given by E = hf, must be less than the work function of sodium. **Therefore the frequency of the light is less than the cut –off frequency. (25%)**	**2022 Question 14c (67%)**

Worked example 12: Current vs PD graph: Energy of photon, E = $\frac{hc}{\lambda}$, power.

Students set up the apparatus shown below to study the photoelectric effect. The apparatus consists of a light source, a filter and a photocell (a metal emitting plate on which light falls and a collecting electrode/collector, all enclosed in a vacuum tube).



2017 NHT Question 18a, 2 marks

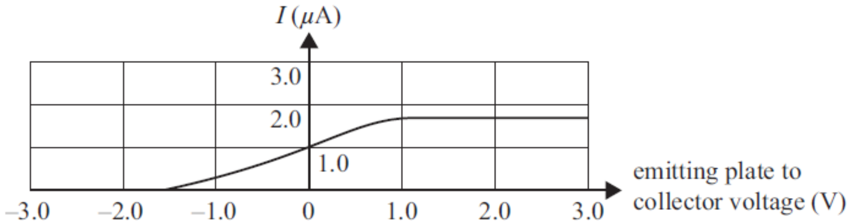
The students allow light of 500 nm to shine on the photocell.

Determine the energy of each photon of this light.

Solution	**Current study design:**
Use E = $\frac{hc}{\lambda}$. **∴ E_{photon} =** $\frac{4.14 \times 10^{-15} \times 3 \times 10^{8}}{500 \times 10^{-9}}$ **∴ E_{photon} = = 2.5 eV (ANS)**	**2021 Question 18 (70%)** **2020 Question 15 (62%)** **2018 Question 13a (33%)**

Worked example 13: Current vs PD graph: Cut-off voltage.

The students then begin the experiment with the collector negative, with respect to the emitting plate. They gradually reduce the voltage to zero and then increase it to positive values. They measure the current in ammeter A and plot the graph as shown below.



2017 NHT Question 18b, 1 mark

Using the graph above, determine the maximum kinetic energy of the emitted photoelectrons.

Solution

The work done to stop the photoelectron is given by qV, where q is the charge and V is the voltage.
In this case the charge is ‘e’.
Therefore the work done to stop the photoelectron is 1 × V when measured in eV, which is the voltage required to stop the most energetic photoelectron and hence reduce the current to zero.
∴ 1.5 eV (ANS)

Current study design:

2020 Question 15b (70%)

2017 Question 17a (33%)

Worked example 14: Current vs PD graph: Explanation.

2017 NHT Question 18d, 2 marks

Explain why the graph above is a flat, straight line beyond V = +1.0 V.

Solution

When the collector is positive to the emitter, all the photoelectrons that are ejected reach the collector. Therefore making the collector more attractive will not increase the number of electrons reaching it, so the current remains constant.

Current study design:

2020 Question 15c (32%)