Year 12
Physics
The Nature of Light

Lesson 4
The photon model of light (Einstein)
Sample resources

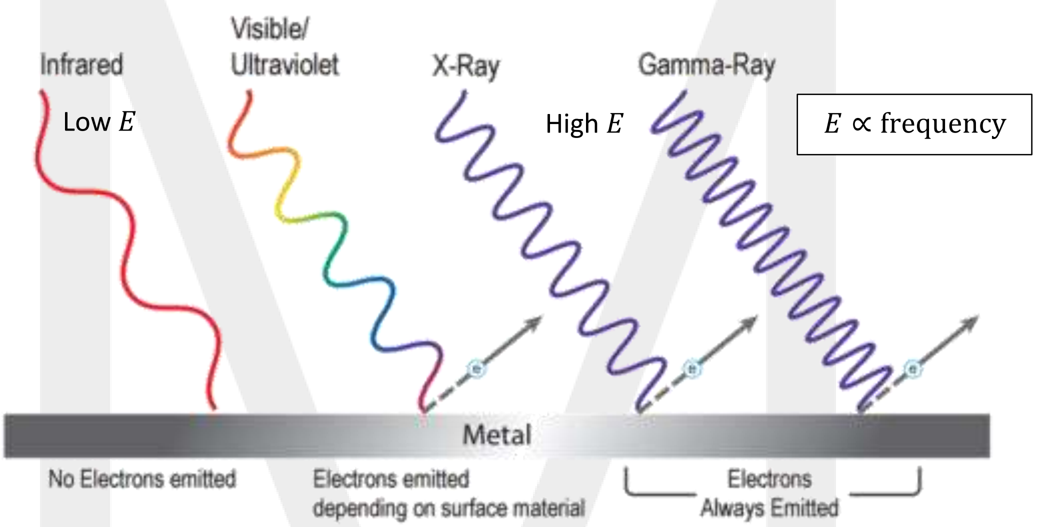
MATRIX
EDUCATION

1. The photoelectric effect

☐ What is the photoelectric effect?

- The photoelectric effect is a phenomenon in which electrons are ejected from a metal when light is shone on the metal surface. Electrons emitted in this manner are called photoelectrons.

- It was observed that whether light causes electrons to be ejected or not depends on its **frequency:**



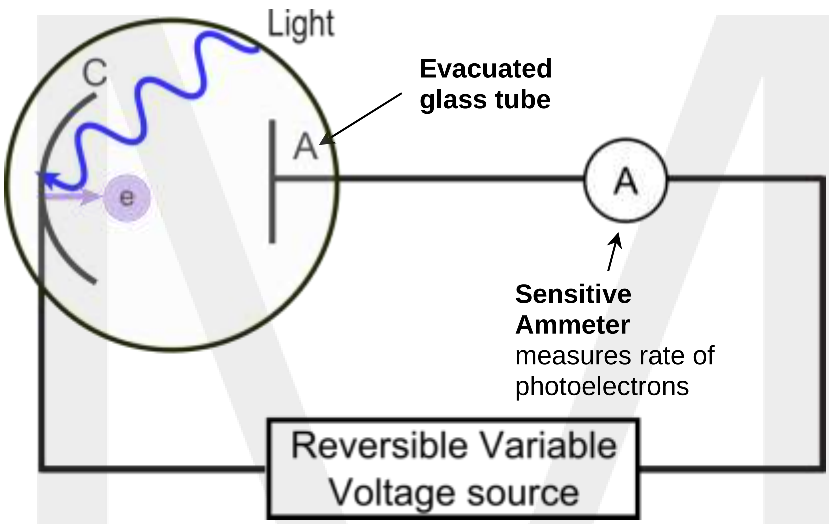
- **Maxwell's theory** of light **could not predict this,** instead predicting that any frequency light would cause photoelectrons. This led Einstein to develop the **photon model of light**.

> Did you know?
> Classical theory says that electromagnetic radiation incident on the surface of a metal will cause the electrons to oscillate. More radiation, of any frequency, will cause electrons to oscillate more. Putting in more and more energy can cause an electron to oscillate so violently that it breaks free from the metal.
>
> Thus any frequency can cause photoelectron emission, whenever enough energy has been absorbed by the electron. This prediction disagreed with experiments.

2. Experiment: The photoelectric effect

☐ Introduction and experimental setup

- Electrons can be **ejected** from a metal surface when light is shone on it.
- The figure below is a schematic diagram of the apparatus that can be used to explore this phenomenon.
- A device that utilises the photoelectric effect is called a **photocell.**



  - An evacuated transparent tube contains a metal plate, C, connected to one terminal of a variable voltage source.
  - Another metal plate, A, is connected to the other terminal of the voltage source.
  - A voltmeter measures the voltage from the power source.
  - An ammeter measures any electrons flowing from C to A.

- We can thus change:
  - Frequency of light.
  - Intensity (light power) of light.
  - Voltage across cathode and anode.

- We are interested in measuring the effects on:
  - Number of photoelectrons per second (electrical current).
  - Largest kinetic energy of photoelectrons.

☐ In-class exercise

- Simulation: The photoelectric effect. Click "Download", "Keep", and run the downloaded application. Select Sodium.

- Use this simulation to determine qualitatively how current and the maximum kinetic energy of photoelectrons are affected by the following changes in independent variables:

Experiment 1

Independent Variable	Control Variables	Dependent Variables
Frequency of light	Intensity = 50% Voltage = 1 V	Current Kinetic energy

- As frequency increases, what is the effect on the
  - Current[1]
  - Kinetic energy (how fast photoelectrons emerge from the photocathode C)[2]

Experiment 2

Independent Variable	Control Variables	Dependent Variables
Intensity	Voltage = 1 V Frequency = low ($\lambda = 700\ nm$)	Current Kinetic energy

- As intensity increases, what is the effect on the
  - Current[3]
  - Kinetic energy[4]

Experiment 3

Independent Variable	Control Variables	Dependent Variables
Intensity	Voltage = 1 V Frequency = high ($\lambda = 400\ nm$)	Current Kinetic energy

- As intensity increases, what is the effect on the
  - Current[5]
  - Kinetic energy[6]

Experiment 4

Independent Variable	Control Variables	Dependent Variables
Voltage	Intensity = 100% Frequency = very high ($\lambda = 250\ nm$)	Current Kinetic energy

- As voltage of plate A increases from negative to positive, what is the effect on the
  - Current (enable the ‘Current vs Battery voltage’ Graph)[7]
  - Kinetic energy[8]

☐ Conclusions

- Recall that in Maxwell's theory, the current and kinetic energy of photoelectrons depend only on intensity of light:

Property	Depends on
Number of photoelectrons per second	Intensity of light
Largest kinetic energy of photoelectrons	Intensity of light

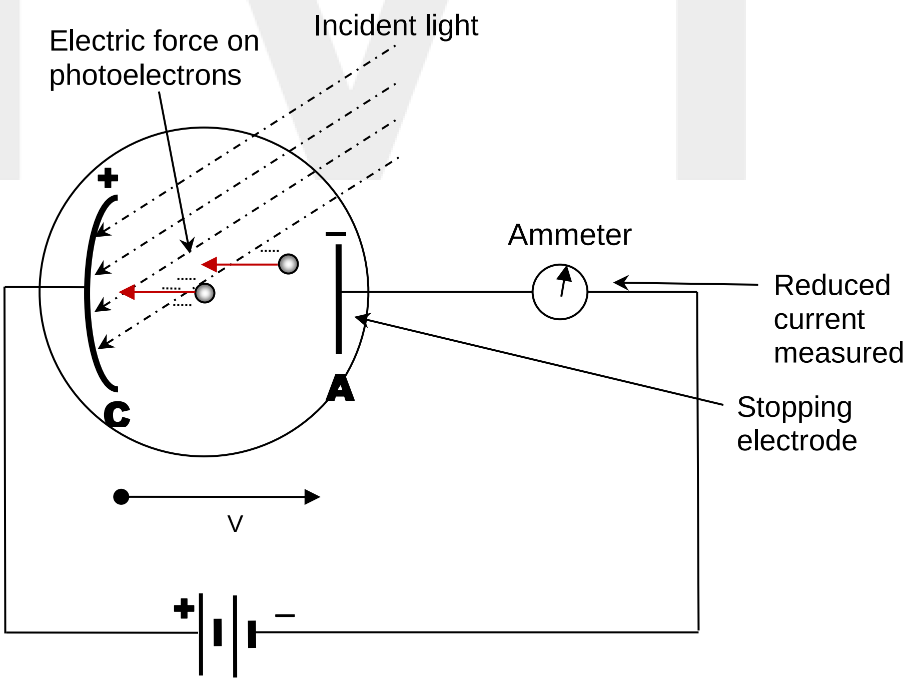
- What are your conclusions from your investigation of the photoelectric effect?

Property	Depends on
Number of photoelectrons per second[9]	
Largest kinetic energy of photoelectrons[10]	

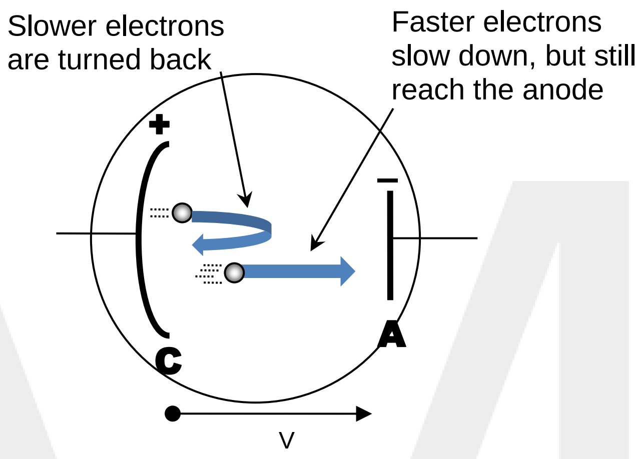
- The above observations for the photoelectric effect could not be explained by classical theories.

☐ Measuring maximum kinetic energy of the photoelectrons

- In a real photoelectric experiment we can't see the electrons, we can only measure values of current and voltage.
  - How do we determine the **number of photoelectrons** that reach the A terminal per second?[11]
  - How do we measure the maximum kinetic energy of the photoelectrons?[12]
- Let's investigate how to measure maximum kinetic energy. Use the photoelectric effect simulation again.
  - Set the incident frequency so that photocurrent is detected.
  - What happens if you make the A electrode negative (see diagram below)?[13]



- Photoelectrons can be ejected in a range of speeds. With a negative A electrode, what happens to the slowest photoelectrons?[14]



– When A is negatively charged we thus call it the **stopping electrode**.

– The work the electric field does on the electrons (of charge $-e = -1.6 \times 10^{-19}$ C) is $W = qV = eV$. How much kinetic energy do the photoelectrons require at C in order to make it to the stopping electrode at voltage V?[15]

– As the stopping electrode is made more **negative**, more electrons will be repelled before reaching it.

– At some voltage, even the electrons with the **highest kinetic energy $E_{K(max)}$** will be repelled, indicated by the **current dropping to zero**. This voltage is the **stopping potential V_s**.

– Since the stopping potential V_S was just enough to stop the fastest photoelectrons, the maximum kinetic energy of the photoelectrons is

$$\boldsymbol{E_{K(max)} = qV = eV_s}$$

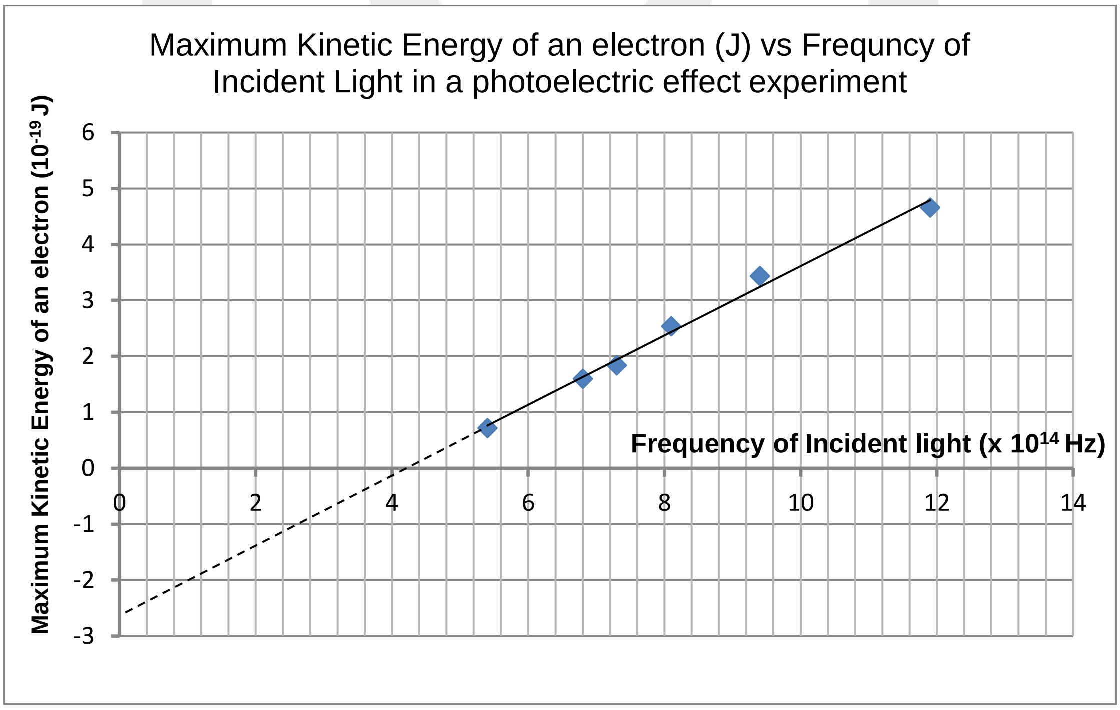
where $e = 1.602 \times 10^{-19}$ C is the magnitude of charge on an electron, and V_S is the stopping voltage.

Results: Changing the frequency of light

- Data from a photoelectric experiment where **stopping voltage** is measured for different **light frequencies** is shown in the table.

Frequency of incident light ($\times 10^{14}$ Hz)	Stopping potential (Volts)	Maximum kinetic energy of an electron (eV)	Maximum kinetic energy of an electron (J)
5.4	0.45	0.45	0.72×10^{-19}
6.8	1.00	1.00	1.60×10^{-19}
7.3	1.15	1.15	1.84×10^{-19}
8.1	1.59	1.59	2.54×10^{-19}
9.4	2.15	2.15	3.44×10^{-19}
11.9	2.91	2.91	4.66×10^{-19}

- The plot of Maximum kinetic energy of an electron vs. Frequency of incident light is shown below.



- This relationship between **maximum kinetic energy and frequency** could not be explained by classical theories and is the most important aspect of the photoelectric effect. You will need to analyse graphs such as these.

☐ Einstein's photoelectric equation

- Use the graph of **Maximum kinetic energy** of an electron (J) **vs. Frequency** of incident light (Hz) to determine:
  - the gradient of the straight line.[16]
  - Can you find a constant in your **data sheet** that is similar in value to the gradient of the line? What is this constant called?[17]
  - the x–intercept (called the **threshold frequency**, f_0).
  - the y–intercept (the negative of the **work function** ϕ).
- The equation of the line is then:[18]
- **Einstein was able to explain the photoelectric effect and this equation.** According to his explanation, the maximum kinetic energy for photoelectrons is:

$$K_{\max} = hf - \phi$$

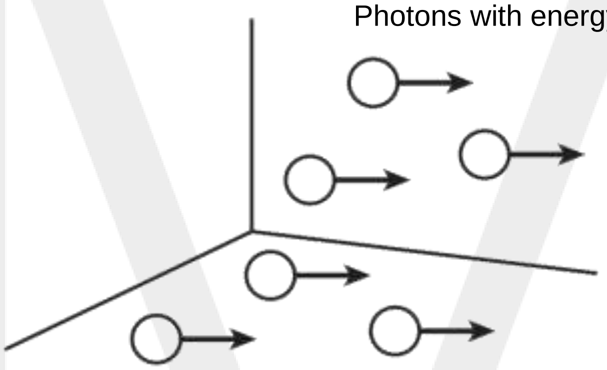
Where: $K_{\max}$ = maximum kinetic energy of the photoelectrons (J)
h = Planck's constant (6.626 x 10^{-34} J.s)
f = frequency of incident light (Hz)
ϕ = the "work function", a constant dependent on the metal used.

- The **work function** represents the minimum energy with which an electron is bound in the metal (usually a few electron volts).

3. Einstein's explanation of the photoelectric effect

☐ **Einstein's** photon theory of light

- Einstein **extended Planck's concept of quantisation to electromagnetic waves** in order to explain the observations of the photoelectric effect. He postulated:
  1. **Light** (or any electromagnetic radiation) **is a stream of particles called photons**.
  2. Energy of the beam of light is localised to each photon, not spread across the wavefront of the light beam.



  3. Each photon has an energy E determined by Planck's equation:

$$\boldsymbol{E = hf}$$

h is Planck's constant

f is the frequency of the radiation

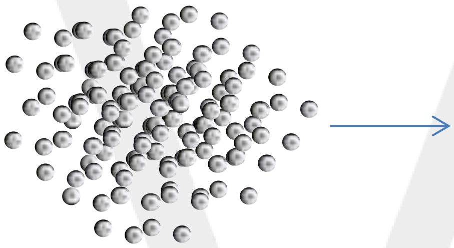
- In a paper published in 1905 Einstein described photons in the following way:

"...the energy [of a light ray] is not continuously distributed over an ever increasing volume, but it consists of a finite number of energy quanta, localized in space, which move without being divided and which can be absorbed or emitted only as a whole."

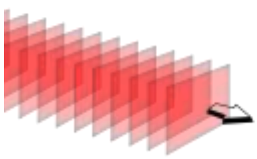
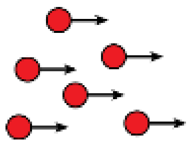
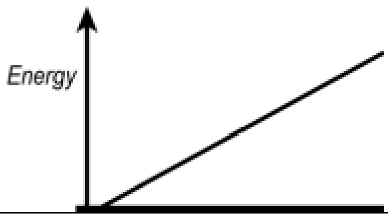
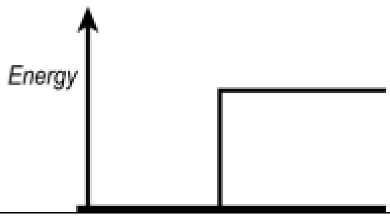
- Using the photon theory of light, we can interpret frequency and intensity of light (or electromagnetic radiation) in the following way:
  1. **Frequency** is related to the **amount of energy each photon carries**.
  2. **Intensity** is related to the **number of photons per second**.

- Consider two lasers. One outputs an intensity of 1 watt (1 joule per second) of red light, the second outputs 1 watt of blue light.

- What can we say about the amount of **energy each photon carries**, and the **number of photons per second**, in each beam?

	Red light	**Blue light**
Power of beam	1 joule per second	1 joule per second
Frequency of light	Lower frequency	Higher frequency
Energy of photons	$E = hf$, low	$E = hf$, high
Number of photons per second to make 1 W beam	Since each photon is low energy, need **larger** number of photons per second	Since each photon is high energy, need **smaller** number of photons per second
Analogy	Throwing 1 kg of ping pong balls  Ping pong ball by Peter Porai-Koshits (Own work) [CC BY-SA 4.], via Wikimedia Commons	Throwing 1 kg of basketballs 

- Because the photon is a particle, it is an **indivisible unit** of energy. This means a photon cannot be partially absorbed or created. This forces absorption and emission of energy to be **discrete**, in terms of integer numbers of photons:

	Wave	**Particle**
Location of energy	Across wavefront 	In photons 
Absorption of energy	Continuous 	Discrete 

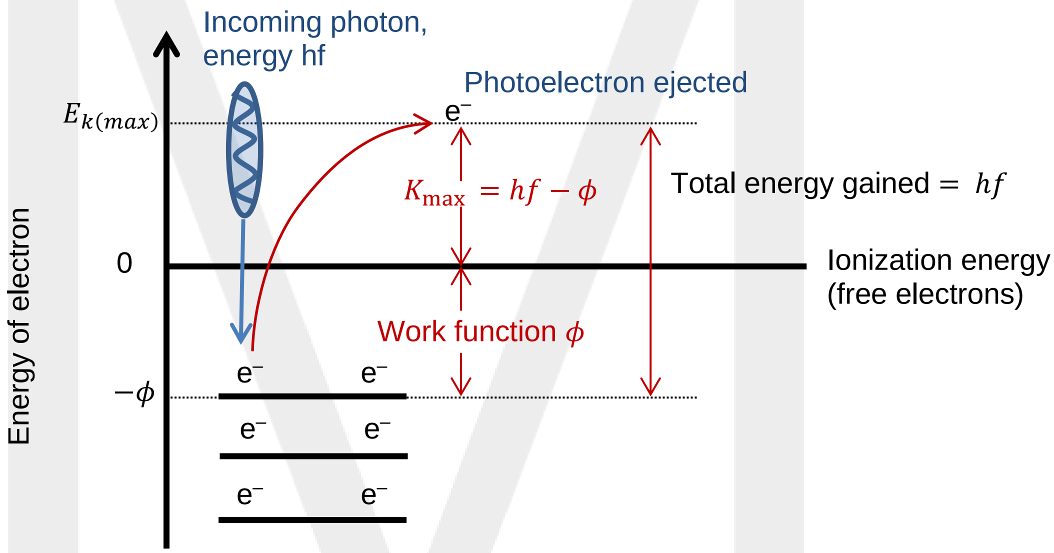
☐ **Einstein's photon** explanation of the photoelectric effect

- Einstein's simple view of the photoelectric effect was that a **single photon** gives **all its energy**, hf, to a **single electron** in the metal. The electron uses some of that energy to escape from the metal, and the remainder becomes the kinetic energy of the electron.

$$hf \rightarrow U + K$$

- This **one-to-one interaction between photon and electron** occurs because the photon is the smallest unit ("quantum") of light and cannot be split up.

- The process of photoelectron emission is explained below:



1. Light is shone on the metal. Each photon of light carries energy $\boldsymbol{E = hf}$.
2. An electron in the metal absorbs this energy. It requires energy to escape the electrostatic force binding it in the metal. The electrons bound the weakest in the metal require an energy equal to the 'work function' ϕ (any other electrons require more than ϕ).
3. Any leftover energy becomes kinetic energy of the electron as it exits the metal. The electrons bound with energy ϕ have maximum kinetic energy $E_{k(\max)}$ (any electrons bound with more energy than ϕ have less kinetic energy).

- The photoelectric equation is then simply stating that energy from the photon is transferred to the electrons in the metal:

$$\textbf{Energy in from photon} = \boldsymbol{hf} = \boldsymbol{\phi + K_{max}} = \textbf{Energy gained by electron}$$

☐ Solving problems using $K_{\max} = hf - \phi$

Concept Check 3.1

A sodium surface is illuminated with light of wavelength 300 nm.

Data:

$h = 6.626 \times 10^{-34}$ Js

$f_0 = 5.50 \times 10^{14}$ Hz

Determine:

(a) The frequency of the light[19]

(b) The energy absorbed by the electrons[20]

(c) The work function[21]

(d) The kinetic energy of the photoelectrons

(i) In Joules[22]

(ii) In electron volts[23]

Concept Check 3.2 (2011 HSC Q29)

(a) Calculate the number of photons of λ = 450 nm required to transfer 1.0×10^{-3} J of energy.[24]

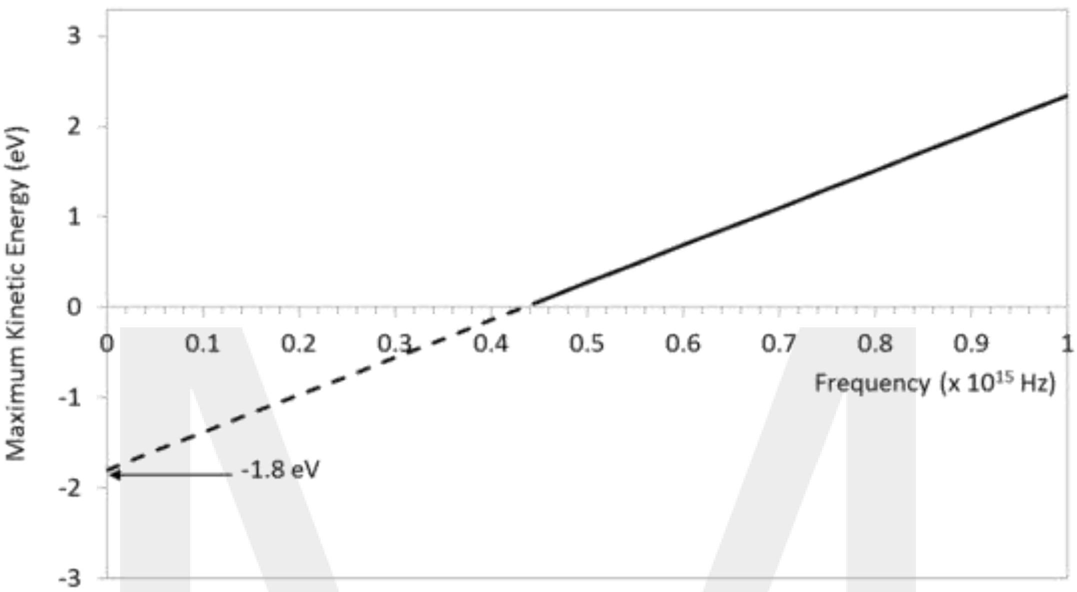
3

(b) A 1 W beam of light transfers 1 J per second from one point to another. With reference to the particle model of light, contrast a 1 W beam of red light and a 1 W beam of blue light.[25]

2

Concept Check 3.3

Data from a photoelectric experiment are shown in the figure below.



(a) Explain why the graph shows a dotted line for frequencies from 0 to 0.44×10^{15} Hz.[26] **2**

(b) What is the minimum frequency that will cause an electron to be ejected from this metal?[27] **1**

(c) What is the minimum photon energy that will cause an electron to be ejected from the metal? Give your answer in eV.[28] **1**

(d) An electron is ejected from the metal with a maximum kinetic energy of 2.0 eV. Assuming all the energy has come from an incident photon, calculate the frequency of light used.[29] **2**