Physics Factsheet

September 2000 Number 01

The Quantum Nature of Light

This Factsheet covers one of the fundamental - and hard to grasp - concepts of modern physics; wave-particle duality. To ensure this important topic is clear, the Factsheet is longer than usual.

What is light?

Well, there's no simple answer, because it behaves differently in different situations. Usually it behaves as a wave – it can be diffracted, reflected and refracted – so we consider it to be a wave. However, sometimes this 'wave model' does not explain what we see – for example, when we shine light onto a metal surface, electrons can be released (the photoelectric effect). This requires a new explanation; that light comes in lumps (quanta), or particles called photons. So depending on what experiment we do, light behaves as *either* a 'wave' or a 'particle'. Neither explanation by itself can describe all that we observe.

> ***'Wave-particle duality'*** *means:*
> *the ability of something to show* ***both*** *wave-like and particle-like properties, depending on how we look at it (i.e. what experiment is performed). It is just one aspect of* ***quantum physics****.*

Light is part of the electromagnetic spectrum, which we commonly explain as consisting of waves with different frequencies (e.g. gamma rays, X-rays, radio waves, infra-red radiation and microwaves). We find that all parts of the electromagnetic spectrum show the same 'wave-particle duality' as light, so we commonly speak of '**electromagnetic radiation'** (EM radiation) rather than 'light'.

What is the particle model of EM radiation?

By Plank's theory, EM radiation (e.g. light) is considered to be composed of a stream of small lumps or packets (quanta), which are called **photons**. Each photon travels at the speed of light and has no mass and no charge. Each photon has a fixed amount of energy (E) which depends on the frequency (f) of the EM radiation: the higher the frequency, the higher the energy of each photon:

$$E = hf$$

E: Photon energy (J)
h: Planck's constant (6.63×10^{-34} Js)
f: frequence of EM radiation (Hz)

The more photons (i.e. packets of energy) there are, then the more energy there is arriving at a point each second. Thus, the **power** (defined as energy per second) of the EM radiation depends on the number of photons arriving per second. If the power is measured over an area (e.g. $1m^2$), then we call it **intensity** (Wm^{-2}), which in the case of light is the same as its **brightness**.

> *To summarise the Particle Model of EM radiation:*
> - *EM radiation comes in a stream of packets, known as* ***photons****.*
> - *Each photon has no charge and no mass*
> - *The* ***Energy*** *of each photon depends on frequency only*
> - *The* ***Power*** *or* ***Intensity*** *of EM radiation of a fixed frequency depends on the number of photons arriving each second (where Intensity = Power/area).*

> **Exam Hint :** If you are asked to explain "Wave Particle Duality" with examples, ensure you give examples of light acting both as a particle and as a wave

The differences between the particle and wave views of light

The fundamental differences between the wave and particle views of light are in their explanations of (i) the energy of the light and (ii) how often the 'light' arrives.

The *particle theory* says the energy depends on frequency; and the number of photons arriving per second depends on the power (see above for explanations).

The *wave theory* says the energy depends on the amplitude of the wave, which is related to the power (power ∝ amplitude^2); and the number of waves arriving per second is defined as the frequency.

In summary: Differences between particle & wave views of light

Property of Light	Depends on	
	Particle Theory	Wave Theory
Energy	**Frequency** $E = hf$	**Power** $P \propto A^2$
How often it arrives	**Power** #photons/sec	**Frequency** #waves/sec

The Photoelectric Effect

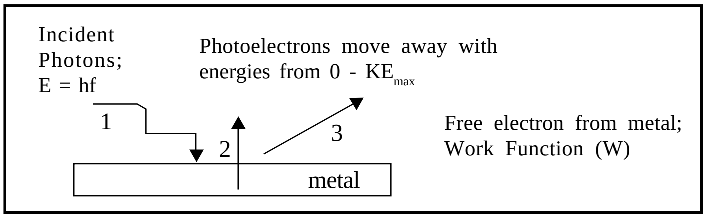
> ***What is the Photoelectric Effect?***
> *When EM radiation falls on a metal surface, electrons are emitted so long as the frequency of the EM radiation is above a certain 'threshold' value. The emitted electrons, called photoelectrons, have kinetic energies ranging from zero to a maximum value.*

How is the Photoelectric Effect explained?

- Light consists of *particles* (photons) of energy; the higher the frequency, the higher their energy.
- One ***single*** photon collides with *one* electron and gives all its energy to that electron.
- If this energy is enough to free the electron from the metal surface, then the electron will be released, otherwise it won't be released.
- *The minimum energy required to release an electron from a metal surface* is called the **Work Function (W)**. This differs for different metals, as each metal surface binds the electrons with varying 'strengths'.
- Whether the electron is released or not depends on the energy of the photon (E) in comparison to the metal work function (W):
  - ♦ **Electron just released (E=W).** If the energy of a *single* photon (E) is equal to the work function (W), it can *just* release *one* electron from the *surface* of the metal. We say the photon is at the **threshold frequency, (f_0)**, *the minimum frequency of EM radiation required to just release electrons from a metal surface,* where $E = hf_0 = W$; or rearraged $\mathbf{f_0 = W/h}$.
  - ♦ **Electron not released (E<W).** If the EM radiation is below the threshold frequency, one photon does not have enough energy to release one electron and no electrons are emitted.
  - ♦ **Electron released with energy to spare (E>W).** A photon above the threshold frequency not only has enough energy to free the electron from the metal, but has excess energy which is given to the electron as kinetic energy (KE). The largest value this can take is given by Einstein's Equation (see below).

By using the principle of conservation of energy, we can also write an equation for the transfer of energy from the photon to the electron (pictorially represented in Fig 1).

Fig 1. The Photoelectric Effect



Photon energy → Energy to free electron from metal surface + Electron KE

$$hf = W + KE_{max}$$

Re-arranging this, we obtain;

Einstein's Equation

$$KE_{max} = hf - w$$

KE_{max}: *maximum electron kinetic energy (J)*
hf : *photon energy (J)*
W : *metal work function (J)*

Exam Hints

- **Einstein's Equation** may be written in any of the following forms:

$$KE_{max} = hf - hf_0 \quad (\text{by } f_0 = W/h)$$
$$KE_{max} = hc/\lambda - hc/\lambda_0 \quad (\text{by } c = f\lambda)$$
$$= hc(1/\lambda - 1/\lambda_0)$$

- Often energies are given in electron-volts (eV). To convert eV into joules, multiply by the charge on an electron, 1.6×10^{-19}C, as 1 eV = 1.6×10^{-19}J. *E.g.* $2eV \rightarrow 2 \times (1.6\times10^{-19}) = 3.2\times10^{-19}$ *J.*

Why is the kinetic energy shown as the *maximum* value (KE_{max})? As W is the *minimum* energy required to release an electron from the *surface* of the metal, it follows that the equation gives the largest electron kinetic energy possible, thus it is shown as **KE_{max}**. Electrons that are deeper in the metal will be more strongly bound and so take more energy to be freed, leaving less energy for the electron's KE. Thus a **range** of electron kinetic energies are observed, ranging from zero up to a maximum value given by the above equation.

Typical Exam Question

(a) Explain what each of the terms in Einstein's Equation represents: $hf = KE_{max} + \phi$ [3]

A metal surface of work function 3.0 eV is illuminated with radiation of wavelength 350nm.

(b) Calculate the threshold frequency and wavelength. [3]
(c) Calculate the maximum kinetic energy of the emitted photoelectrons, in Joules. [3]

Answer

(a) *hf – the energy of each light particle or photon* ✓ ; *KE_{max} – the maximum kinetic energy of the emitted photoelectrons* ✓ ; *ϕ - the work function of the metal* ✓

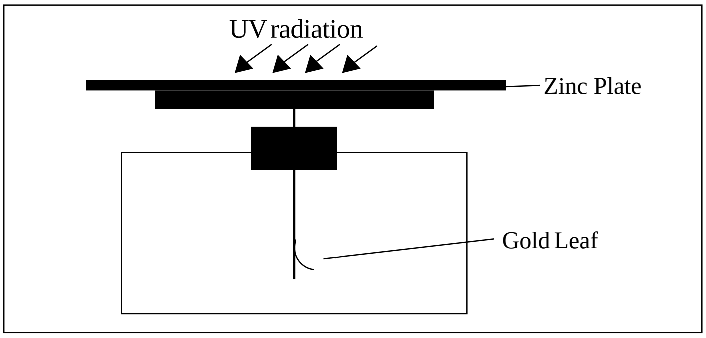
(b) *The work function in joules,* $\phi = 3.0eV \times (1.6\times10^{-19}C) = 4.8\times10^{-19}J$ ✓ ; *The threshold frequency (f_0) is defined as* $f_0 = W/h = 7.2\times10^{14}Hz$ ✓ ; *The threshold wavelength is given by the wave equation* $c = f\lambda$, $\lambda_0 = c/f_0 = (3.0\times10^{8}ms^{-1})/(7.2\times10^{14}Hz) = 4.1\times10^{-7}m$ ✓

(c) *Re-arrange the equation in (a) to give* $KE_{max} = hf - \phi$ ✓ ; *where* $f = c/\lambda = (3.0\times10^{8}ms^{-1})/(350\times10^{-9} m) = 8.6\times10^{14}Hz$ ✓ , *and* $\phi = 4.8\times10^{-19}J$ *(N.B. this must be in joules); Thus* $KE_{max} = 9.0\times10^{-20}J$ ✓

A simple demonstration of the Photoelectric Effect

This uses a **gold leaf electroscope** (Fig 2). The electroscope is initially charged either positively or negatively, so the gold leaf is raised.

Fig 2. Gold Leaf Electroscope



When ultra-violet (UV) light is shone on the clean zinc plate, then:

- If the electroscope is initially **negatively** charged, the gold leaf rapidly falls, showing the electroscope is discharging.
- If the electroscope is initially **positively** charged, the gold leaf does not move from its raised position: no effect is observed.

These observations are explained by the Photoelectric Effect, as electrons are released from the zinc plate when UV radiation falls on it:

- When the plate is **negatively** charged, any electrons emitted from the zinc plate will be repelled from the plate as 'like charges (negative) repel'. Thus the electroscope 'loses' charge and discharges.
- When the plate is **positively** charged, any emitted electrons are immediately attracted back to the plate as 'unlike charges attract'. So photoemission does occur, but the electroscope does not discharge.

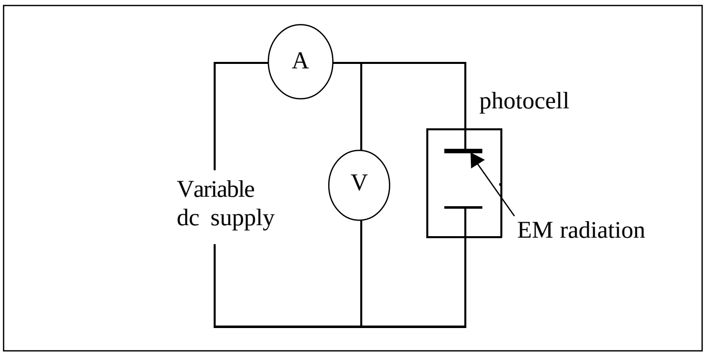
Important points to remember

- The UV light is not charged
- A positively charged plate is one which lacks electrons.
- Only electrons are emitted from the metal surface

Measuring the Photoelectric Effect and checking Einstein's Equation

Experimental measurements can be made to confirm the Photoelectric Effect (or to determine Einstein's Equation) using the apparatus shown in Fig 3.

Fig 3. Photoelectric Effect apparatus



Apparatus

This essentially consists of a photocell and a variable d.c. power supply. The photocell consists of two metal plates sealed in an evacuated quartz container. Quartz is used for the photocell, in preference to glass, as it does not absorb higher frequencies of EM radiation (e.g. ultra violet) that are above the threshold frequencies of common metals. In addition, the photocell is evacuated to prevent the photoemitted electrons colliding with air molecules. The variable d.c. supply is used to alter the voltage across the metal plates in the photocell. Measurements are taken from the ammeter and voltmeter for different supply voltages.

Photoemission

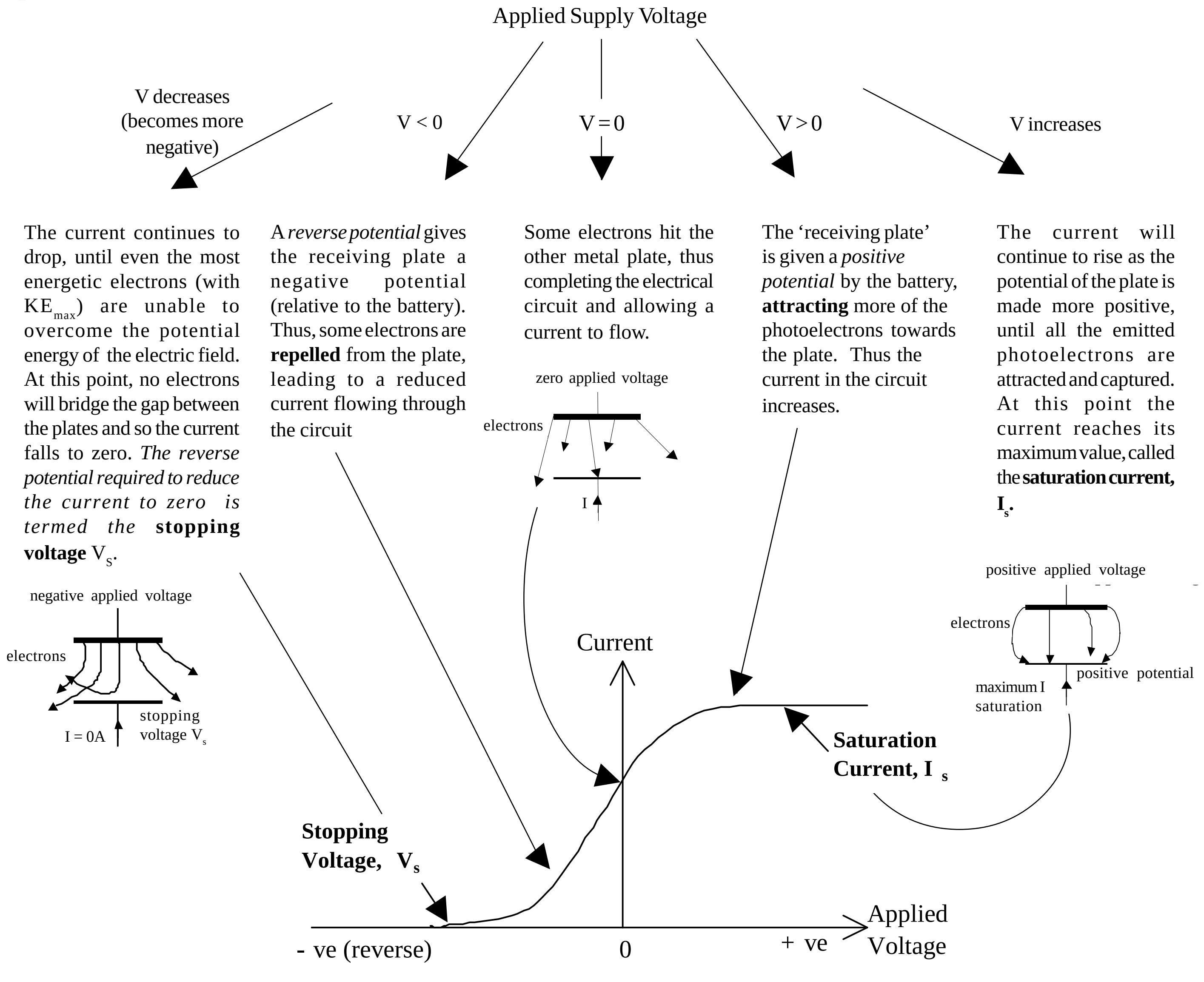
Electromagnetic radiation of a known frequency is directed on to one of the photocell plates.

- If it is above the threshold **frequency** (i.e. if it has sufficient energy), then photoelectrons are emitted.
- The number of photoelectrons emitted per second depends on the number of photons arriving per second, i.e. the Power, or **Intensity**, of the EM radiation.

Electron flow in the circuit

What happens to the electrons after they are emitted from the plate depends on the potential (i.e voltage) of the metal plates in the photocell. This is controlled by the applied voltage (V) from the variable d.c. power supply. Consider the following cases, starting with V = 0:

Effect of Supply Voltage on photocell current.



The current continues to drop, until even the most energetic electrons (with KE_{max}) are unable to overcome the potential energy of the electric field. At this point, no electrons will bridge the gap between the plates and so the current falls to zero. *The reverse potential required to reduce the current to zero is termed the* **stopping voltage** V_S.

A *reverse potential* gives the receiving plate a negative potential (relative to the battery). Thus, some electrons are **repelled** from the plate, leading to a reduced current flowing through the circuit

Some electrons hit the other metal plate, thus completing the electrical circuit and allowing a current to flow.

The 'receiving plate' is given a *positive potential* by the battery, **attracting** more of the photoelectrons towards the plate. Thus the current in the circuit increases.

The current will continue to rise as the potential of the plate is made more positive, until all the emitted photoelectrons are attracted and captured. At this point the current reaches its maximum value, called the **saturation current, I_s.**

↑ EM Energy ⇒ ↑V_S ↑ EM Intensity⇒ ↑I_S

Saturation Current and Stopping Voltage

The **saturation current** depends only on the number of photons arriving per second (i.e **Intensity**), as each photon releases one electron (assuming 100% efficiency).

The **stopping voltage** depends only on the energy of the photoelectrons, which is determined by the photon energy (i.e. **frequency**) for a given metal.

In Summary: **stopping voltage and saturation current**

Photoelectric Effect	Depends on **electron**	Alter by changing **photon**
Stopping Voltage, V_s	*Energy*	*Frequency* *(Photon Energy)*
Saturation Current, I_s	*number emitted per second*	*Intensity* *(number of photons/sec)*

Dependence of Stopping Voltage on Photon Frequency

At the stopping voltage, the most energetic electrons just cannot overcome the potential energy of the electric field between the plates. Thus;

Max. Electron energy= Electrical Potential Energy

$$KE_{max} = eV_s$$

Substituting this in Einstein's Equation gives:

$$hf - W = eV_s;$$

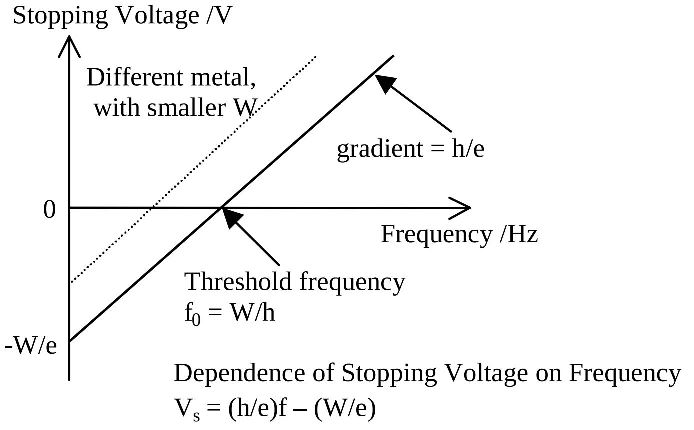
Graphically, this is represented by a straight line if V_s is plotted against f

Dependence of stopping voltage on EM frequency

$$\boxed{V_s = (h/e)f - (W/e)}$$

V_s : *stopping voltage (V)*
h : Plank's constant (6.63×10^{-34}) *Js*
e : charge on an electron (1.6×10^{-19} *C*)
f : EM radiation frequency (Hz)
W : metal work function (J)

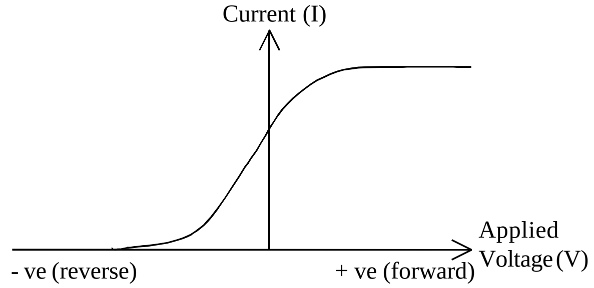
Fig. 4. Dependence of Stopping Voltage on EM frequency



- The gradient is (h/e) regardless of the metal being tested. It can be used to experimentally determine a value for Plank's constant (h) if the charge on an electron (e) is known.
- The y-intercept is (-W/e). It depends on the work function of the metal plate used and is always negative. Thus different metals will have different y-intercepts (work functions), but always the same gradient.
- The frequency axis intercept is equal to the threshold frequency (f_0 = W/h).
- A graph of maximum electron kinetic energy against frequency has exactly the same form, but the gradient becomes h and the y-intercept

Typical Exam Question

A photoelectric cell is illuminated. The graph below shows how the current (I) through the cell varies with the applied voltage (V) across it.



(a) Why does a current flow for positive voltages? [3]
(b) Why does the current reach a constant value for large positive voltages? [2]
(c) Why does the current reach 0A for a large negative voltage? [2]
(d) Add the following to the graph:
  (i) A point, labelled S, to show the stopping potential [1]
  (ii) A curve, labelled F, showing what you would expect if only the frequency of the light illuminating the cell were increased. [1]
  (iii) A curve, labelled I, showing what you would expect if only the intensity of the light illuminating the cell were increased. [1]
  (iv) A curve, labelled W, showing what you would expect if only a metal of a slightly larger work function were used. [1]

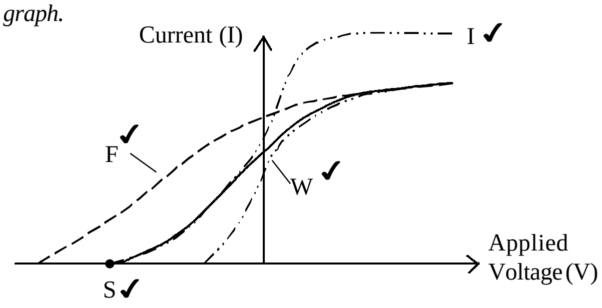
Answer

(a) *Electrons are released from one of the metal plates in the photocell by the photoelectric effect.* ✓ *They are then attracted towards the other metal plate which is positively charged by the battery.* ✓ *Therefore the circuit is completed and a current flows.* ✓

(b) *The current is limited by the number of photoelectrons released each second.* ✓ *Increasing the applied voltage varies how many of the photoelectrons are collected by the positively charged metal plate in the photocell. At large enough potentials, all the electrons are collected* ✓ *and so the current cannot increase further.*

(c) *When the collecting plate is negatively charged, it repels the photoelectrons. At large enough voltages, even the most energetic electrons are repelled.* ✓ *Thus, no electrons 'bridge' the gap between the plates to complete the circuit and no current flows.* ✓

(d) *See graph.*



Typical Exam Question

Light of wavelength 420nm with a power of 10mW is incident on a metal. (Charge on an electron is 1.6×10^{-19} C).
(a) Calculate the energy of each photon [3]
(b) Calculate the number of photons arriving per second. [2]
(c) Assuming 50% of the incident photons release electrons, what current is produced? [3]

Answer

(a) $E = hf = hc/\lambda$ ✓ $= (6.63\times10^{-34})(3\times10^{8})/(420\times10^{-9})$ ✓
$= 4.74\times10^{-19}$ J ✓

(b) Number/second = Power/ photon energy $= 0.01/ 4.74\times10^{-19}$ ✓
$= 2.11\times10^{16}\ s^{-1}$ ✓

(c) Number of electrons emitted/sec $= 0.5 \times 2.11\times10^{16} = 1.05\times10^{16} s^{-1}$ ✓
As each electron has charge e, the current produced = (N/s)e ✓
$= (1.05\times10^{16})(1.6\times10^{-19}) = 1.68$ mA ✓

Why does the Photoelectric Effect provide *evidence for particle nature of light*, rather than its wave nature?
Before studying this, make sure that you understand the differences between the wave and particle theories of light (see page 1). Also, remember that intensity is defined as the power per unit area. The observations made in the Photoelectric Effect are unable to be explained using the wave theory of light. Therefore, the particle theory was developed in order to explain what was observed. These are summarised in Table 1.

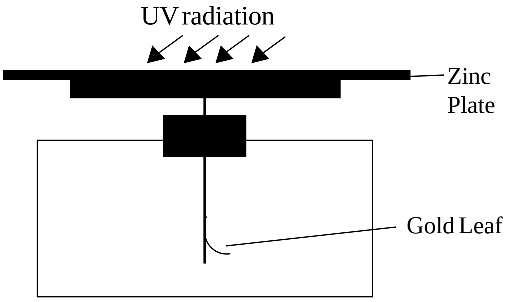
Table 1. Photoelectric Effect - Observations and Explanations

What is Observed?	What does Wave Theory predict?	What does Particle Theory predict?
For a given metal, electrons are only emitted above a certain **threshold frequency** of the EM radiation, irrespective of its intensity.	The greater the intensity (amplitude) of the EM radiation, the greater the energy that arrives at the metal surface. So a high enough intensity should cause electrons to be emitted regardless of the frequency. The frequency should have no effect here.	• Light consists of photons with energy **E = hf** • Minimum energy required to release an electron is the work function (W) • To release electrons, E>W • Threshold frequency (f_0) occurs when E=W; $\mathbf{hf_0 = W}$
The maximum KE of the emitted electrons depends only on **frequency** of the EM radiation.	The greater the intensity (amplitude) of the EM radiation, the greater the energy that arrives at the metal surface. So, more energy is given to each electron. The frequency should have no effect here.	• For frequencies above the threshold frequency ($f>f_0$), Einstein's Equation gives: $\mathbf{KE_{max} = hf - W}$ • Thus KE_{max} depends on the frequency
The **number** of photoelectrons emitted per second depends only on **intensity** of the EM radiation, for a single frequency.	The intensity of the EM radiation relates to energy, not the number of waves arriving per second. So, the number of emitted electrons depends on the number of waves arriving (i.e. the frequency) and not the wave energy (i.e. intensity). The intensity should have no effect here.	• The number of photons arriving per second depends on the intensity of the EM radiation • One photon can release one electron (assuming 100% efficiency) • Thus the number of electrons emitted per second depends on intensity
Low intensity EM radiation (above the threshold frequency) results in **immediate emission** of electrons.	Low intensity EM radiation has low energy. So it will take some time before enough energy builds up on the metal surface to free one electron.	• Intensity only relates to how many photons arrive per second, so few arrive per second for low intensities • But, each photon has enough energy to release an electron ($f>f_0$) so immediate electron emission occurs

Exam Workshop

This is a typical poor student's answer to an exam question. The comments explain what is wrong with the answers and how they can be improved. The examiner's answer is given below.

The photoelectric effect can be simply demonstrated by using an electroscope which is negatively charged, as shown in the diagram.



When ultra violet light is shone on the metal plate, the gold leaf gradually returns to the vertical. However, when red light alone is used, the foil remains displaced and does not return to the vertical.

(a) **Explain why the gold leaf is initially displaced from the vertical [2]**
It's Repelled ✓

- Needs more detail for 2 marks

(b) **Explain why the gold leaf gradually returns to the vertical when UV is shone on to the metal plate? [3]**
It becomes less negatively charged. ✓
The light takes the extra charge away. ✗

- Not enough detail to gain 3 marks.
- Be precise - light does not 'take the extra charge away'.

(c) **Use the particle theory of light to explain why red light does not have the same effect as ultra-violet light. [5]**
Red light doesn't free electrons as it doesn't have as much energy as UV ✓. *Energy comes in lumps that depends on the frequency* ✓.

- Did not mention what the particle theory of light is (i.e. photons).
- Did not explain why electrons are released when UV light shines on the plate.
- Needs to be specific about red light being below the threshold frequency – too vague here to gain mark.

(d) **If the metal has a work function of 2.3 eV, calculate the maximum kinetic energy of the emitted electrons, in Joules, when light of 200 nm is used. [3]**
$KE_{max} = hf - W = h(200\times10^{-9})/(3.0\times10^{8}) - 2.3 = -2.3eV$ ✗

- Used λ not f in equation
- Calculated energy in eV, not Joules as asked

Examiner's Answers

(a) *Both the foil and rod are negatively charged.* ✓ *Like charges repel, so the foil moves away from the rod.* ✓

(b) *The UV light frees electrons so they can escape from the metal plate (the photoelectric effect)* ✓ *so the negative charge on the metal plate and rod decrease* ✓. *So, the repulsion between the foil and the rod decrease and the foil drops due to gravity.* ✓

(c) *Light consists of packets (quanta) called photons* ✓. *The energy of each photon depends on its frequency, by E = hf* ✓. *As red light has a lower frequency than UV light, it has less energy* ✓. *One photon gives its energy to one electron* ✓. *In order to release an electron, the photon energy must be greater than or equal to the metal work function: red light photons have less energy than this and so do not provide enough energy to free an electron* ✓.

(d) *Use Einstein's Equation:* $KE_{max} = hf - W$,
where $f = c/\lambda = (3.0\times10^{8})/(200\times10^{-9}) = 1.5\times10^{15}Hz$ ✓
and $W = 2.3eV \times (1.6\times10^{-19}C) = 3.7\times10^{-19}J$ ✓.
Substitute in the equation to get $KE_{max} = 6.2\times10^{-19}J$ ✓.

Qualitative (Concept) Test

Look in the text for the answers to the questions and use the hints!

(1) Explain **wave – particle duality**. Include an example in your answer.

(2) What is a **photon**?

(3) Describe the **photoelectric effect**.

(4) How does the photoelectric effect provide evidence for the **particle nature** of electromagnetic radiation?

(5) What is the **work function** of a metal? Explain how this relates to **the threshold frequency** for the metal. (***Hint:*** *See "How is the Photoelectric Effect Explained"*)

(6) What is **Einstein's equation**? What does it describe? Explain all symbols used.

(7) What is the **stopping voltage**? How can it be decreased for a given metal?

(8) Describe an **experiment** to verify Einstein's photoelectric effect. Explain how values for the metal work function and Plank's constant can be determined form this experiment.

(9) If visible light is incident on zinc, no electrons are emitted, irrespective of how intense the light is. Explain this observation.

(10) Monochromatic electromagnetic radiation is incident on a metal surface, resulting in the emission of electrons.
Describe the effect on the maximum kinetic energy and on the number of electrons ejected per second for the following changes:
- (a) increasing/decreasing the frequency of the incident radiation
- (b) increasing/decreasing the intensity of the incident radiation
- (c) changing the metal for one with a greater/smaller work function

(***Hint:*** *See "saturation current and stopping voltage")*

Quantitative (Calculation) Test

Time for test:35 mins Total Marks:34

Data: Plank's Constant $h = 6.63 \times 10^{-34}\ Js$
electron mass $m_e = 9.1 \times 10^{-31}\ kg$
electron charge $e = 1.6 \times 10^{-19}\ C$
Speed of EM in a vacuum $c = 3.0 \times 10^{8}\ ms^{-1}$

(1) Calculate the energy of a photon of:
(i) wavelength 1.2 μm; (ii) frequency 2.0×10^{18}Hz.

(2) Calculate the frequency and wavelength of a photon of energy 60 MeV.

(3) Light of frequency 3×10^{15}Hz is incident on a metal of work function 5.0×10^{-19} J causing electrons to be emitted with maximum kinetic energy 1.46×10^{-18}J.
- (a) Calculate a value for Plank's constant.
- (b) Calculate the threshold frequency for this metal
- (c) Calculate the minimum frequency of radiation required to achieve electron kinetic energies above 4×10^{-18}J.

(4) Laser light of 490nm with a power of 7.5×10^{-2}W is incident on a metal of work function 2 eV.
- (a) Calculate the number of photons emitted per second.
- (b) If 10% of the photons result in an electron being emitted, what current is produced?
- (c) Calculate the energy of each photon in electron volts.
- (d) (i) Calculate the maximum kinetic energy of the photoelectrons in electron volts. (ii) What speed would these electrons have (neglect relativistic effects)?
- (e) If the incident power is doubled, what will be the effect on (i) the maximum energy of the emitted electrons; and (ii) the number of electrons emitted per second
- (f) Calculate the threshold wavelength for the metal.
- (g) Will light of 1.5×10^{15}Hz result in the emission of electrons?

Further Reading

- 'The Quantum World' by J.C. Polkinghorne published by Pelican ISBN 0140226532. A good overview of the subject with minimal mathematical content.

Related Factsheets

- Quantum Nature of Particles
- Basic Wave Properties
- Applied Wave Properties

Quantitative Test Answers

(1) (i) $E = hf = h(c/\lambda)$ ✓ $= (6.63\times10^{-34}Js)(3\times10^{8}ms^{-1})/(1.2\times10^{-6}m)$ ✓
$= \mathbf{1.66\times10^{-19}J}$ ✓;
(ii) $E = hf = (6.63\times10^{-34}Js)(2.0\times10^{18}Hz) = \mathbf{3.14J}$ ✓

(2) $f = E/h = (60\times10^{6})(1.6\times10^{-19}\ J)/(6.63\times10^{-34}Js)$ ✓ $= \mathbf{1.45\times10^{22}Hz}$ ✓;
$\lambda = c/f = (3.0\times10^{8}ms^{-1})/(1.45\times10^{22}Hz)$ ✓ $= \mathbf{2.07\times10^{-14}m}$ ✓

(3) (a) by Einstein's Equation $h = W/f + KE_{max}/f$ ✓
$= (5.0\times10^{-19}J)/(3\times10^{15}Hz) + (1.46\times10^{-18}J)/(3\times10^{15}Hz)$ ✓
$= \mathbf{6.5\times10^{-34}Js}$ ✓.
(b) threshold frequency, $f_o = W/h = (5.0x10^{-19}J)/(6.63x10^{-34}Js)$ ✓
$= \mathbf{7.5\times10^{14}Hz}$ ✓
(c) by Einstein's Equation; $f = W/h + KE_{max}/h$ ✓ $= f_o + KE_{max}/h$ ✓
$= 7.5\times10^{14} + (1.46\times10^{-18}J)/(6.63\times10^{-34}Js) = \mathbf{6.8\times10^{15}Hz}$ ✓

(4) (a) # photons/sec = (emitted power)/(energy per photon)
= Power/(hc/λ) ✓
$=\{(7.5\times10^{-2}W)(490\times10^{-9}m)\}/\{(6.63\times10^{-34}Js)(3.0\times10^{8}ms^{-1})\}$ ✓
$= \mathbf{1.85\times10^{17}\ s^{-1}}$ ✓
(b) Current = (# electrons emitted/sec) × (charge on each electron)
= 0.1×(# photons/sec) x e ✓
$= 0.1(1.85\times10^{17}\ s^{-1})(1.6\times10^{-19}C) = \mathbf{3.0mA}$ ✓
(c) $E = hf = hc/\lambda = (6.63\times10^{-34}Js)(3.0\times10^{8}ms^{-1})/(490\times10^{-9}m)$
$= 4.06\times10^{-19}J$ ✓;
As 1eV= $1.6x10^{-19}$J, this corresponds to $(4.06\times10^{-19}J)/(1.6\times10^{-19}J)$
$= \mathbf{2.54eV}$ ✓
(d) (i) by Einstein's Equation; $KE_{max} = hf - W = E - W$ ✓
$= 2.54 - 2.0 = \mathbf{0.54eV}$ ✓
(ii) $KE = \frac{1}{2} m_e v^2$; $v = \sqrt{\{2(KE_{max})/m_e\}}$
$= \sqrt{\{2(0.54\times1.6\times10^{-19}J)/(9.1\times 10^{-31}kg)\}}$ ✓ $= \mathbf{4.3\times10^{5}ms^{-1}}$ ✓
(e) (i) **no change** as energy is independent of Intensity; ✓
(ii) **doubled, i.e.** $\mathbf{3.7\times10^{16}s^{-1}}$ ✓ as doubling the intensity doubles the number of electrons arriving per second and thus also of the electrons emitted per second.
(f) $W = hf_o = h(c/\lambda_o)$; $\lambda_o = hc/W$ ✓
$= (6.63\times10^{-34}Js)(3\times10^{8}ms^{-1})/(2\times1.6\times10^{-19}J)$ ✓ $= \mathbf{155nm}$ ✓
(g) **No,**✓
as this frequency is below the threshold frequency calculated from part (f);
$f_o = c/\lambda_o = (3.0\times10^{8}ms^{-1})/(155\times10^{-9}m) = 1.9\times10^{15}Hz$ ✓

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