- ***Candidates should be able to :***
  - *Describe the particulate nature **(PHOTON MODEL)** of electromagnetic radiation.*
  - *State that a photon is a **QUANTUM** of energy of electromagnetic radiation.*
  - ***Select** and **use** the equations for the energy of a photon :*

$$E = hf \quad \text{and} \quad E = \frac{hc}{\lambda}$$

  - *Define and use the **ELECTRONVOLT (eV)** as a unit of energy.*
  - *Use the transfer equation for electrons and other charged particles.*

$$eV = \tfrac{1}{2}mv^2$$

  - *Describe an experiment using LEDs to estimate the **PLANCK CONSTANT (h)** using the equation $eV = hc/\lambda$. (no knowledge of semiconductor theory is expected).*

- ***PHOTON MODEL OF ELECTROMAGNETIC RADIATION***

*Some effects, such as interference, diffraction and polarisation are only explicable by considering light to consist of **waves** (i.e. use a **WAVE MODEL**).*

*Newton's explanations of reflection and refraction, on the other hand, assumed light to have a **particle** nature (i.e. use a **PARTICLE MODEL**).*

*When it comes to explaining the **PHOTOELECTRIC EFFECT** (which we shall be considering shortly) we need to visualise electromagnetic radiation to consist of **particles**.*

*So which is the true model ? Does light and all other electromagnetic radiation have a **wave** nature or does it have a **particle** nature ?*

The answer is that both ideas are simply different ways of explaining how electromagnetic radiation behaves in different circumstances; neither is a perfect or full description.

- ***PLANCK'S QUANTUM THEORY*** *(1900) proposed that electromagnetic radiation is emitted in very small, but separate bundles which he called **QUANTA** (the singular being a **QUANTUM**)*

*Each **PHOTON** is a **QUANTUM** of electromagnetic energy*

***Max Planck** presents **Albert Einstein** with the Nobel Prize for his work on the photoelectric effect.*

*and which we now refer to as **PHOTONS**.*

ESSENTIALS OF QUANTUM THEORY

- *Light and all other forms of electromagnetic radiation is emitted in brief '**bursts**' or '**packets**' of energy.*
- *These packets of electromagnetic energy are now called **PHOTONS** and they travel in a straight line in one direction.*
- *When an atom emits a photon, its energy changes by an amount equal to the energy of the emitted photon.*
- *The **ENERGY (E)** of a photon is directly proportional to the **FREQUENCY (f)** of the radiation and it is given by the equation :*

$$E = hf$$

E (J); h (PLANCK'S CONSTANT = 6.63×10^{-34} J s); f (Hz)

*The unit of '**h**' is really **J Hz^{-1}** which tells us that a photon of radiation of **f = 1 Hz** has **6.63 x 10^{-34} J** of energy.*

- *Since **$c = f\lambda$**, the photon energy equation **E = hf** may be expressed as :*

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

E (J); h (J s); c (speed of e.m. radiation in a vacuum = 3.0×10^{8} m s-1); λ (Photon wavelength in m)

- *Because the energy of a single photon is extremely small (e.g. it is **6.63 x10^{-16} J** for an x-ray photon of frequency **10^{18} Hz**), we often use a smaller, more convenient unit, called the **ELECTRONVOLT (eV)** when dealing with photon energy.*

***1 ELECTRONVOLT (eV)** is the energy gained by an electron when it moves through a potential difference of **1 VOLT**.*

If an electron (charge, $Q = e = 1.6 \times 10^{-19}$ C) moves Through a pd of 1 v, the kinetic energy (E) gained is Given by :

$$E = QV = (1.6 \times 10^{-19}) \times (1)$$

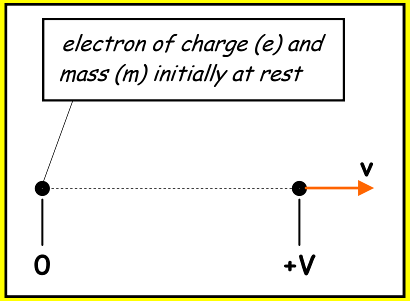
So,

$$1eV = 1.6 \times 10^{-19}\ J$$

To convert eV to J	multiply by	1.6×10^{-19}
To convert J to eV	divide by	1.6×10^{-19}

ENERGY TRANSFER EQUATION

*Consider an electron of charge **(e)** and mass **(m)** which is initially **at rest** and is then accelerated through a pd **(V)** to reach a final speed **(v)**.*



Then :

Kinetic energy gained by the electron = Work done on the electron by the accelerating pd

$$\tfrac{1}{2} mv^2 = eV$$

(kg) (m s^{-1}) (C) (V)

*Rearranging the above gives us an equation for the **electron speed (v)** :*

$$v = \sqrt{(2eV/m)}$$

NOTE

- *These equations can be applied to any type of charged particle.*
- *The equations are **not valid** if the accelerating pd is **large**. This is because the charged particle may then reach speeds approaching the **speed of light (c)** and the relativistic effect of **mass increase** would then have to be taken into account.*

• PRACTICE QUESTIONS (1)

1 Calculate the **energy (in J and eV)** of a single photon of :

(a) Gamma radiation of frequency **3.0×10^{23} Hz.**

(b) Red light of wavelength **680 nm.**

(c) Microwave radiation of frequency **1.2×10^{10} Hz.**

2 Calculate the **wavelength** of the electromagnetic waves having each of the following energies :

(a) **6.25×10^{6} eV**, (b) **10^{-15} J**, (c) **10^{-20} J**, (d) **6.25×10^{-7} eV.**

Use your answers to identify the **type of radiation** which each of these energies is most likely to be associated with.

3 An electron is accelerated through a pd of **150 V** in the electron-gun arrangement of a cathode ray tube. Calculate :

(a) The **kinetic energy** gained by the electron **(in J and eV).**

(b) The **final speed** reached by the electron, given that its mass is **9.11×10^{-31} kg.**

4 A laser of power = **15 mW** produces coherent light of frequency **4.62×10^{14} Hz.** Calculate :

(a) The **energy of a single photon** of this laser light.

(b) The **number of photons emitted per second** by the laser.

5 Calculate the energy in **electronvolt (eV)** of :

(a) An x-ray photon of frequency **1.5×10^{17} Hz.**

(b) An infrared photon of wavelength **2.0×10^{-4} m.**

6 (a) Through what **pd** must a proton be accelerated in order to reach a final speed of **5.31×10^{5} m s^{-1} ?** Given that :

proton rest mass = **1.7×10^{-27} kg.**
proton charge = **$+\ 1.60 \times 10^{-19}$ C.**

(b) Assuming that an **alpha particle** (consisting of 2 protons and 2 neutrons) has **twice the charge** and **four times the mass** of a proton, calculate the **final speed** it would reach if it were to be accelerated through the same pd as the proton in (a).

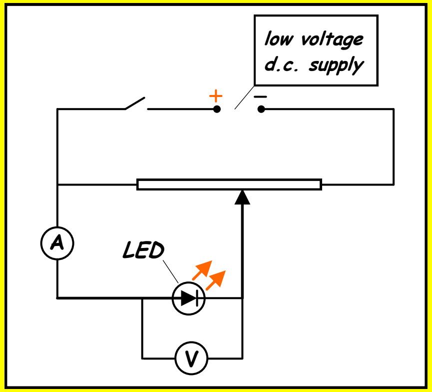
- ***LIGHT-EMITTING DIODE (LED)***

- *An LED will only allow current to pass through it when :*
  - *It is **forward biased** (i.e. when it is connected to a supply as shown in the diagram opposite).*
  - *The applied pd ≥ a minimum value called the **THRESHOLD VOLTAGE (V).***
- ***LEDs of different colours have different threshold voltages** at which they begin to conduct and emit light. A **blue** LED has a **higher** threshold voltage than a **red** one and emits higher energy photons.*
- *When an LED conducts and emits photons, we can say that :*

Energy lost by an electron in passing though the LED = energy of the emitted photon

$$eV = \frac{hc}{\lambda}$$

ESTIMATION OF PLANCK'S CONSTANT (h)



METHOD
The threshold voltage (V) of each of several LEDs of different colour is determined using the circuit shown opposite.

In each case the voltmeter reading is noted when the ammeter reading shows that the LED has just started to conduct.

The wavelength of the light emitted by each LED can be obtained :

- *Directly from the manufacturer's quoted value, or*
- *From actual measurements using a diffraction grating.*

RESULTS

Threshold voltage, V / V	Wavelength, λ / m	1/λ / m-1

ANALYSIS

$$eV = \frac{hc}{\lambda}$$

So, $V = (hc/e) \times 1/\lambda$

Comparing with : $y = mx$ *(the equation of a straight line)*

*It can be seen that a graph of **V against 1/λ** will give a straight line graph whose **gradient (m) = hc/e.***

From which : ***Planck's constant, h = gradient x e/c***

- **PRACTICE QUESTION (2)**

1 The results shown in the table below were obtained in an experiment to estimate the **PLANCK CONSTANT (h)**.

LED Colour	Threshold Voltage, V / V	Emitted light Wavelength, λ / 10^{-7} m	1/λ / 10^{6} m^{-1}
green	2.30	5.60	
amber	2.00	6.10	
red	1.70	6.70	
infrared	1.35	9.10	

(a) Use the relationship ***eV = hc/λ*** to calculate a value for the **PLANCK CONSTANT, h** for each LED and hence obtain an average value for h.
Given that : charge on an electron, **e = 1.6 x 10^{-19} *C***
speed of light in a vacuum, **c = 3.0 x 10^{8} m s^{-1}**

(b) Complete the table of results by calculating **1/λ** for each LED and plot a graph of **V against 1/λ** and use the graph to obtain a value for **h.**