# Quantum Physics

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# Introduction

- As far as the area of science is concerned, we have 2 very powerful scientific models – **particles and waves** – to help us to understand more about both light and matter.
- Table below shows how, in particular areas of science, we can use a particle model to interpret and make predictions about macroscopic phenomena.

| Area | Macroscopic phenomena | Particle model is used to explain: |
|---|---|---|
| Electricity | Current | Flow of electrons |
| Gases | Pressure, temperature, volume | Kinetic theory of gases |
| Solids | Mechanical properties (ductile, brittle, polymeric) | Arrangement of the molecules / structure |
| Radioactivity | Radioactive decay, fusion, fission | Nuclear model of atom (protons, neutrons) |
| Chemistry | Chemical reactions | Atomic structure |

**Particle models in science**

# Introduction

- Table below shows some other phenomena that we explain in term of waves.

| Phenomena | Varying quantity |
|---|---|
| Sound | Pressure or density |
| Light (or other EM waves) | Electric and magnetic field strength |
| Waves on strings | Displacement |

**Wave models in science**

- The characteristic properties of waves are that they all show reflection, refraction, diffraction and interference.
- Waves do not have mass or charge unlike particles.
- Since particle models can also explain reflection and refraction, it is diffraction and interference that we regard as the defining characteristics of waves.
- If we can show diffraction and interference, then we know that we are dealing with waves.

# The Particulate Nature of Light

- We expect light to behave as waves, but light can also behave as particles!
- One of the familiar evidence came from the Geiger counter. If you place a Geiger counter next to a source of gamma radiation you will hear an irregular series of clicks. Here are waves giving individual or discrete clicks.
- Thus we can conclude that gamma rays behave like particles when they interact with a Geiger counter. (This effect is most obvious with gamma rays, because they are at the most energetic end of the EM spectrum)
- In one of Einstein's study called the **photoelectric effect**, he convinced physicists that light could behave as a stream of particles.
- The stream of particles which made up light is called **photons** and physicists believe that all EM radiation consists of photons.

# Photons (The Quantum Theory)

- A photon is a "packet of energy" or a quantum of electromagnetic energy.
- Gamma photons are the most energetic.
- According to Einstein, who based his ideas on the work of German Physicist Max Planck, the energy of a photon (in Joules) is related to the frequency (Hz) of the EM radiation by the equation:

$$\boxed{E = hf \quad \text{or} \quad E = {}^{hc}/_{\lambda}}$$

- The constant h is called the Planck constant and has a value of $6.63 \times 10^{-34}$ Js
- From the equation, we can deduce that higher the frequency of radiation will give higher energy photons. Or the shorter wavelength the higher the energy of photons.
- The equation tells us the relationship between a particle property (the photon of energy E) and wave property (the frequency f).
- Do take note that the value of ***E*** calculated is the energy of **one** photon.
- It is called the **Einstein relation** and applies to all EM waves.

# Example 1

1.) Calculate the energy (in Joules & eV) of gamma photon of frequency of $10^{26}$ Hz.

2.) Visible light has wavelengths in the range of 400 nm to 700nm. Calculate the energy of a photon of red light and a photon of violet light.

3.) A 1.0 mW laser produces red light of wavelength $6.48 \times 10^{-7}$ m. Calculate how many photons the laser produces per second.

# Example 2

1.) In a microwave oven photons of energy $1.02 \times 10^{-5}$ eV are used to heat food.

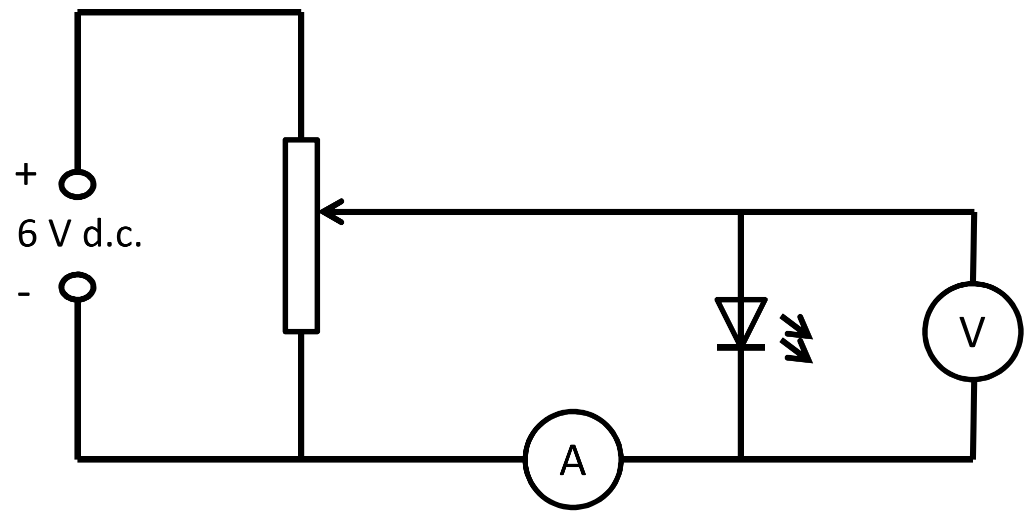
- a.) Express the value in Joules.
- b.) Calculate the frequency of the photons.
- c.) Calculate the wavelength of the photons.

2.) A helium nucleus is accelerated through a potential difference of 7500 V. Calculate

- a.) its kinetic energy in eV and Joules.
- b.) its speed

# Estimating the Planck constant

- This can be done by using LEDs of different colours.




- A LED only conducts in one direction, and that it requires a minimum voltage, the threshold voltage, to be applied in this direction before it allows current to pass through.
- Different colours of LED required different threshold voltages before they conduct and eventually emit light.
- A red LED emits photons that are of low energy. It requires a low threshold voltage to make it conduct.
- A blue LED emits higher energy photons, and requires higher threshold voltage to make it conduct.

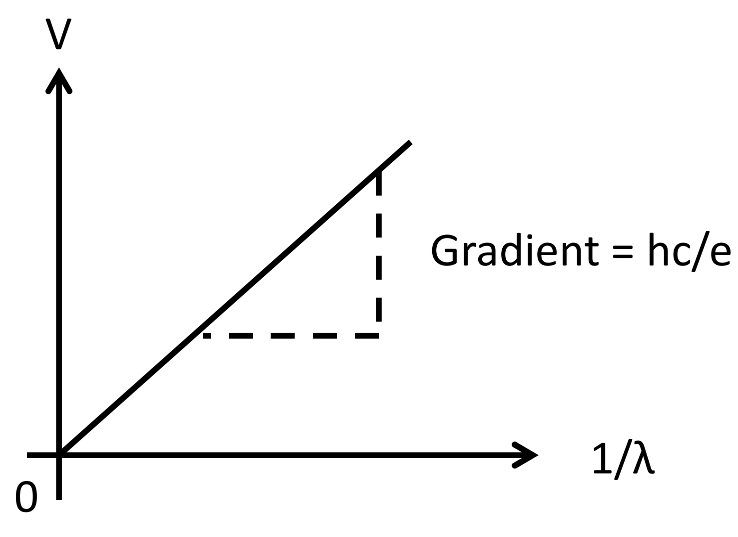
# Estimating the Planck constant

- When a single electron passed through the LED, the electrical energy is lost and is transformed to photons with the same energy.
- We can write the equation as:

energy lost by electron = energy of photon

$eV = hc / \lambda$ , V is the threshold voltage for respective LEDs.
$\lambda$ is the wavelength of each LEDs. (quoted by manufacturer)
The value of e and c are known.

- If several LEDs of different colours are available, V and $\lambda$ can be determined from each and a graph of V versus $1/\lambda$ can be plotted.
- The gradient of this graph would be hc/e , hence value of h can be estimated.



# Photoelectric Effect

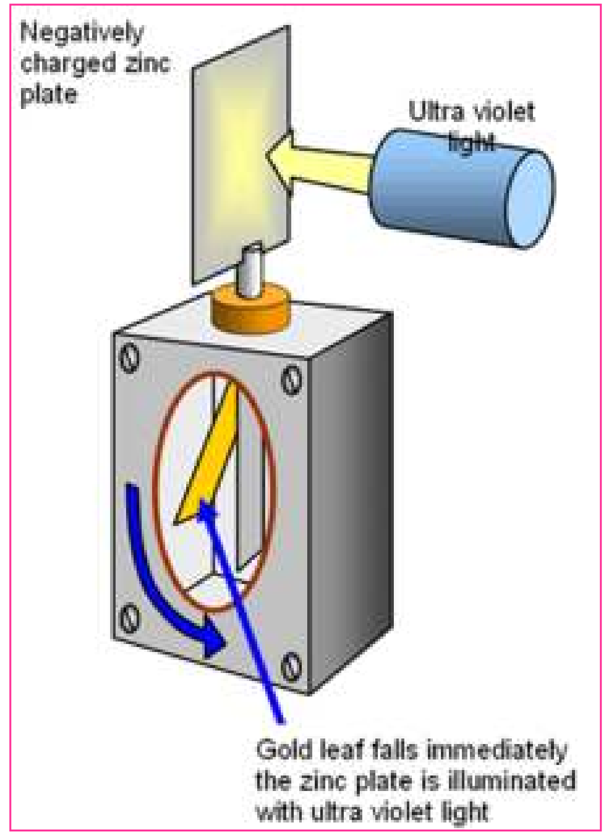
- Any metal will emit electrons if it is given sufficient energy. Heated coils in electron guns produce a large number of electrons. This process is known as thermionic emission. (electrons emitted due to heating)
- In 1902, scientists discovered that electrons can also be emitted from the surface of a metal when it is exposed to electromagnetic radiation of sufficiently high frequency.
- This process is known as photoelectric emission. (electrons emitted due to EM radiation). The emitted electron is also known as photoelectron.
- So photoelectric effect is basically an interaction between a photon and an electron in which the electron is removed from the atom.
- Table below illustrates the response of some metals when exposed to different frequencies of EM radiation.

*Comparison of effects of radiation on metals*

| Metal | X-rays | Ultra-violet | Blue light | Red light |
|---|---|---|---|---|
| zinc | yes | yes | no | no |
| sodium | yes | yes | yes | no |
| caesium | yes | yes | yes | yes |

# Simple demonstration of Photoelectric Effect

- UV radiation (from mercury vapour lamp) is directed onto a freshly cleaned zinc plate connected to an electroscope as shown in figure beside.
- When the initial charge on the electroscope is positive, no effect is observed. If, however, the initial charge is negative, gold leaf rapidly falls, showing that the electroscope is discharging.
- Placing the mercury lamp closer causes the leaf to fall more rapidly. Higher intensity increase the rate of discharge.
- Inserting a sheet of glass between the lamp and the zinc plate stops the discharge. Glass does not transmit UV radiation, thus showing that is it the UV radiation that is causing the discharge of the electroscope.
- If we try the experiment with a very bright filament lamp, we find that it has no effect.
- Thus, we conclude that there must be a minimum frequency that the incident radiation must have in order to release electrons from the metal. This is called threshold frequency, $f_0$.



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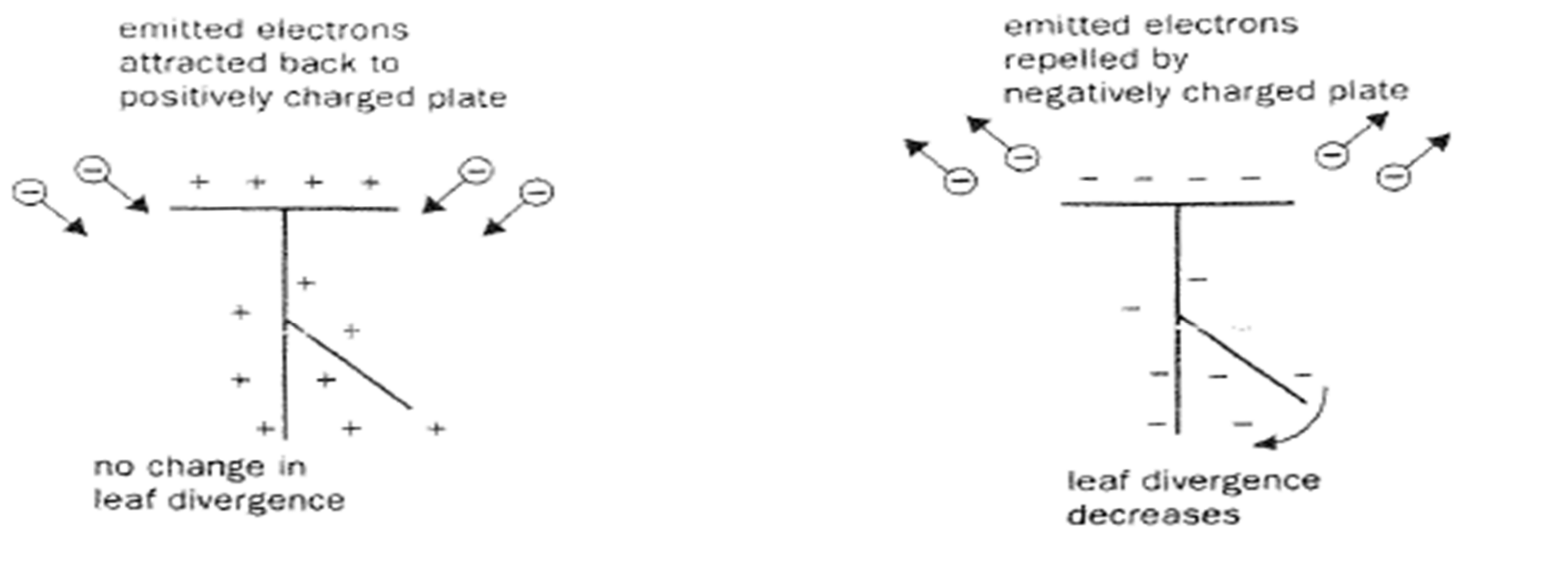


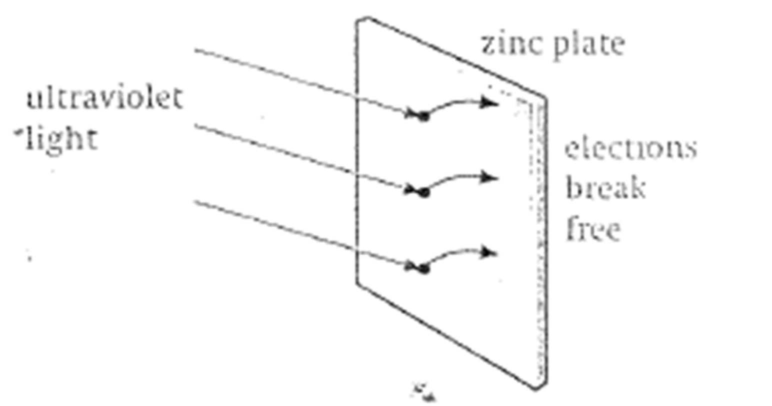

(a) Positively-charged electroscope

(b) Negatively-charged electroscope

- In fig. (a) when the initial charge is positive, the photoelectrons are immediately attracted back to the zinc plate, so although photoemission may occur, the electroscope is not discharged since the electrons are recaptured.
- When initial charge is negative, as in fig (b), the photoelectrons will escape as they are immediately repelled by the electric field surrounding the charged plate. It is this loss of electrons that causes the electroscope to discharge.

# Einstein Photoelectric Equation

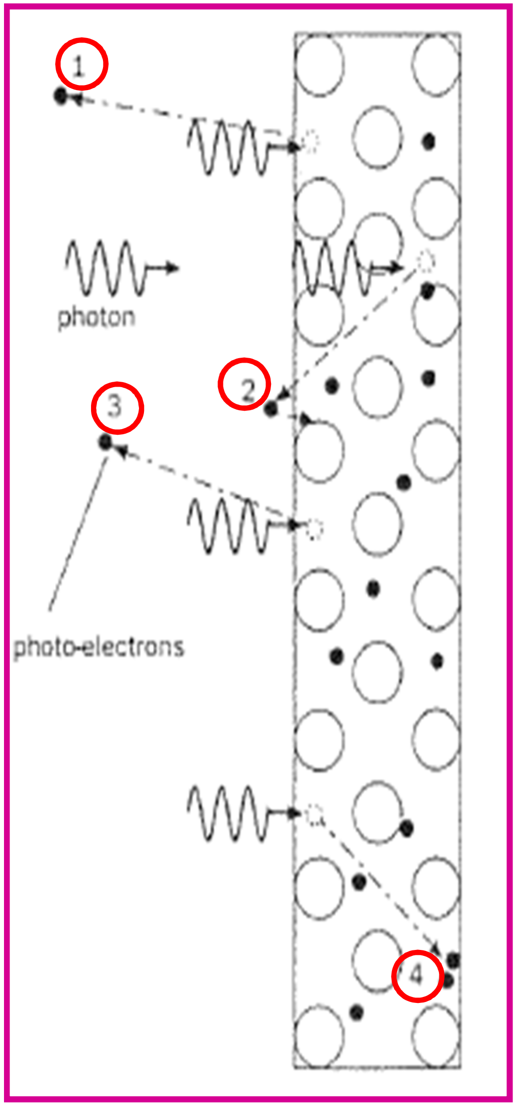
- Physicists can't explain why the weak UV radiation could have an immediate effect on the electrons in the metal, but very bright light of lower frequency has no effect.
- This is because they imagined light waves arriving at the metal, spread out over its surface, and therefore they could not see how weak UV waves could be more effective than intense visible waves.
- In 1905, Einstein came up with an explanation based on the idea of photons.
- Metals (such as zinc) have electrons that are not very tightly held within the metal itself. These are the conduction electrons.
- When photons of certain EM radiation strike the metal, some electrons break free from the surface of the metal. Such electrons only need small amount of energy to escape from the metal surface. (about $10^{-19}$ Joules)
- When a photon arrives at the metal plate, an electron may capture it. The electron gains all of the photon's energy, and the photon no longer exists!
- One photon will interact with one electron only.




The photoelectric effect: when a photon of light strikes the metal plate, its energy may be sufficient to release an electron.

# Einstein Photoelectric Equation

- When the electron gains the energy of the photon, this energy is used by the electron to escape from the attractive forces in the metal; the rest is the electron's kinetic energy.
- When photons arrive at the surface of a metal, figure beside shows some possible results.
- Electron 1 at the surface requires the least possible energy to free itself, so it escape with the maximum possible kinetic energy.
- Electron 2 which is deep in the metal has lost too much kinetic energy by the time it reaches the surface and is therefore attracted back.
- Electron 3 escapes, but has less kinetic energy than electron 1.
- Electron 4 gained enough kinetic energy to escape, but was moving in the wrong direction and is absorbed in the metal.
- This explanation helps us understand the existence of a range of kinetic energies and a maximum kinetic energy of the emitted electrons. Each electrons has to lose some of its kinetic energy in order to overcome the attractive electric fields of the positive ions. Electrons from deep layers lose more energy than those from the surface.



# Einstein Photoelectric Equation

- A single electron requires a minimum energy to escape from the surface of the metal.
- The work function, Φ (Greek letter phi) of a material is the minimum energy needed to remove an electron from the surface of a metal. The rest of the energy becomes electron's kinetic energy. This equation is called Einstein Photoelectric equation and can be written as:
- Energy of incoming photon = work function + kinetic energy of the photoelectron.

$$hf = \Phi + \frac{1}{2} mv^2$$

- If the photoelectron is emitted from the surface with no further interactions with other atoms, then it has maximum kinetic energy corresponding to a speed $v_{max}$. For such an electron:

$$hf = \Phi + \frac{1}{2} mv^2_{max}$$

- The threshold frequency, $f_0$ is given when v is zero, so:

$$hf_0 = \Phi + 0 \text{ , thus } f_0 = \Phi / h$$

# Einstein Photoelectric Equation

- **What happens when the incident radiation has frequency less than the threshold frequency?**

- A single photon can still give up its energy to a single electron, but this electron cannot escape from the attractive forces of the positive metal ions.
- The energy absorbed from the photons appears as kinetic energy of the electrons.
- This electrons lose their kinetic energy to the metal ions when they collide with them. This warms up the metal. This is why a metal plate placed in the vicinity of a table lamp gets hot.

# Conclusion – Photoelectric Emission

- **<u>Conclusion – The Law of Photoelectric Emission</u>**

| OBSERVATION | PHOTON MODEL |
|---|---|
| Emission of electrons happens as soon as light shines on metal | A single photon is enough to release one electron |
| Even weak (low intensity) light is effective | Low-intensity light means fewer photons, not lower-energy photons |
| Increasing intensity of light increases rate at which electrons leave metal | Greater intensity means more photons per second, so more electrons released per second |
| Increasing intensity has no effect on energies of electrons | Greater intensity does not mean more energetic photons, so electrons cannot have more energy |
| A minimum threshold frequency of light is needed | A photon in a low frequency light beam has energy too small to release an electron |
| Increasing frequency of light increases maximum kinetic energy of electrons | Higher frequency means more energetic photons; so electrons gain more energy and can move faster |

# Conclusion – Photoelectric Emission

| FREQUENCY (f) | INTENSITY (I) | ENERGY OF 1 PHOTON (E = hf) | TOTAL ENERGY (I α E) | NUMBER OF INCIDENT PHOTONS (total energy / energy of 1 photon) | NUMBER OF ELECTRONS EMITTED (no. of e α no. of photons) | CURRENT (rate of charge flow) |
|---|---|---|---|---|---|---|
| CONSTANT | INCREASE | CONSTANT | INCREASE | INCREASE | INCREASE | INCREASE |
| CONSTANT | DECREASE | CONSTANT | DECREASE | DECREASE | DECREASE | DECREASE |
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# Example 3

1.) UV light of photon of energy $2.5 \times 10^{-18}$ J is shone onto a zinc plate. The work function of zinc is 4.3 eV. Calculate the maximum energy with which an electron can be emitted from the zinc plate. Give your answer in eV & Joule.

2.) Calculate the minimum frequency of electromagnetic radiation that will cause the emission of photoelectrons form the surface of gold. (work function of gold = 4.9 eV)

# Example 4

The surface of a conductor has a threshold wavelength of 0.85 μm. Calculate

a.) Threshold frequency

b.) its work function in eV.

c.) the maximum speed of the electrons emitted by blue light of wavelength 0.49 μm

# Line Spectra

- We will look at another phenomenon which we can explain in terms of light as photons.
- Scientists used human ability to identify different colour to analyse light, by breaking or splitting it up into a spectrum.
- If a white light is passed through a prism or a diffraction grating, it is split up into a **continuous spectrum** of colours consisting of a range of wavelengths of about 400nm – 700 nm.
- Meanwhile scientist later discovered that a **line spectrum** is observed when atoms in **gas** interact with photons. This can be observed through a spectrometer.
- There are 2 types of line spectra namely emission line spectra and absorption line spectra.

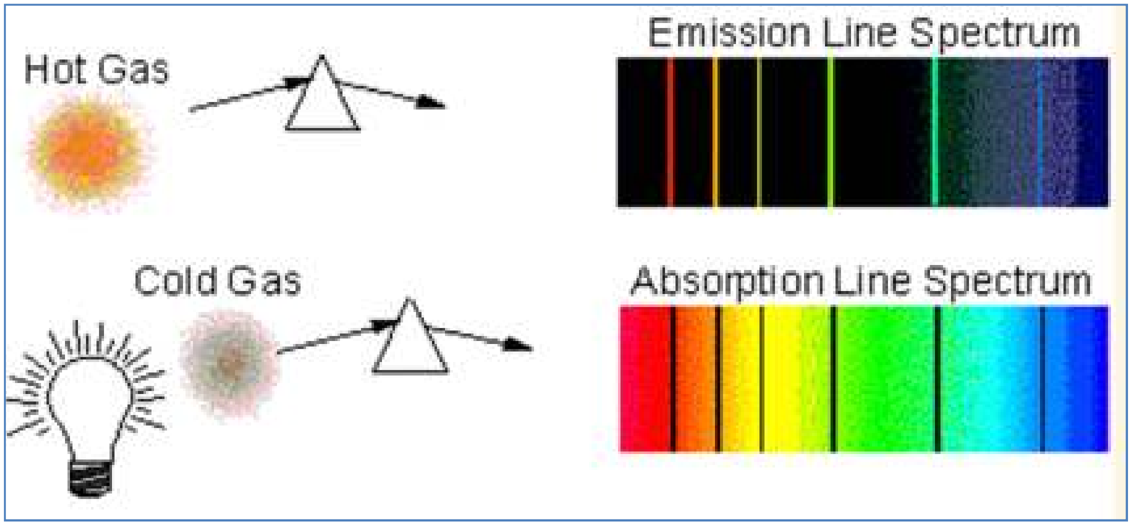
**Emission Line Spectra**

- If you have a lamp that contains hot gas such as neon or sodium, and it is viewed through a prism or a diffraction grating, a line spectrum is seen through spectrometer.
- This line spectra which show the composition of light **emitted** by hot gases are called emission line spectra.
- Each element has a spectrum with a unique collection of wavelengths.

# Line Spectra

**Absorption Line Spectra**

- This kind of spectrum can be observed when white light is passed through cool gas and through the prism or grating.
- On the screen, the continuous white light spectrum is found to have black lines across it; certain wavelengths have been **absorbed** as the white light passed through the gas.
- Absorption line spectra is found when light from stars is analysed. The interior of the star is very hot and emits white light of all wavelengths in the visible range.
- However, this light has to pass through the cooler outer layers of the star.
- As a result, certain wavelengths are absorbed.
- http://jersey.uoregon.edu/vlab/elements/Elements.html



# The Origin of Line Spectra

- The atoms of a given element can only emit or absorb light of certain wavelengths.
- Why is this so?
- Two points we need to establish over here:

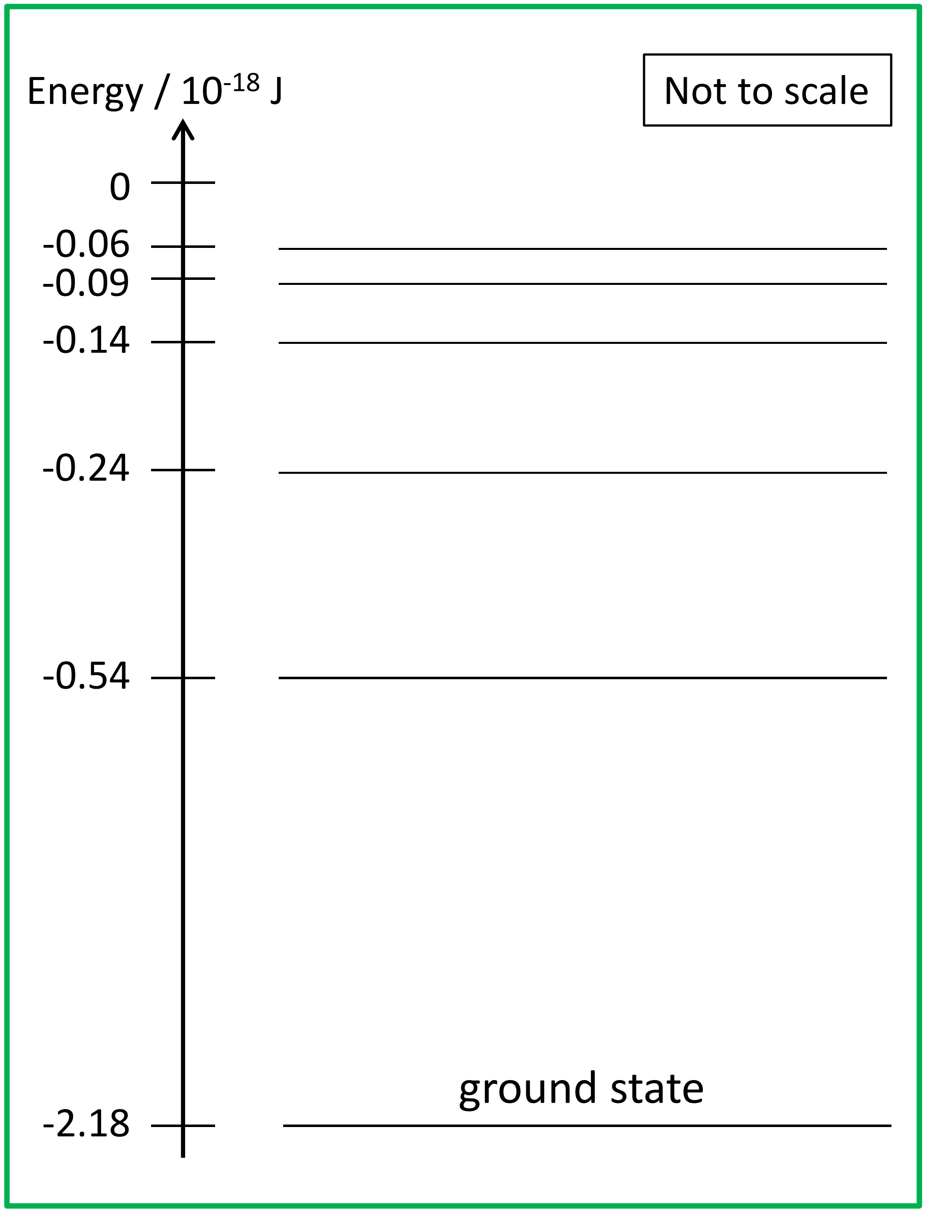
  1.) As with photoelectric effect, we are dealing with light (an EM wave) interacting with matter. Thus, we need to consider light as consisting of photons. For light of single frequency or single wavelength, the energy possess by each photon is $E = hf$.

  2.) As with the concept of energy levels, when light interacts with matter, it is the electrons that absorb the energy from the incoming photons. When electrons lose energy, light will then be emitted by matter in the form of photons.

- The appearance of the line spectra tells us that **electrons in atoms can only absorb or emit photons of certain energies.** From this we deduce that electrons in atoms can only have certain fixed value of energy.
- **Origin of line spectra can be explain by the understanding the concept of energy levels / energy states.**

# Energy Levels / Energy States

- Figure beside shows diagrammatically the permitted energy levels / energy states of electron of a hydrogen atom.
- An electron in hydrogen atom can have only one of these values of energy. It cannot have an energy that is between these energy levels.
- The energy levels have negative values because external energy has to be supplied to remove an electron from the atom.
- The negative energy shows that the electron is trapped within the atom by the attractive forces of the atomic nucleus.
- An electron with zero energy is free from the atom.



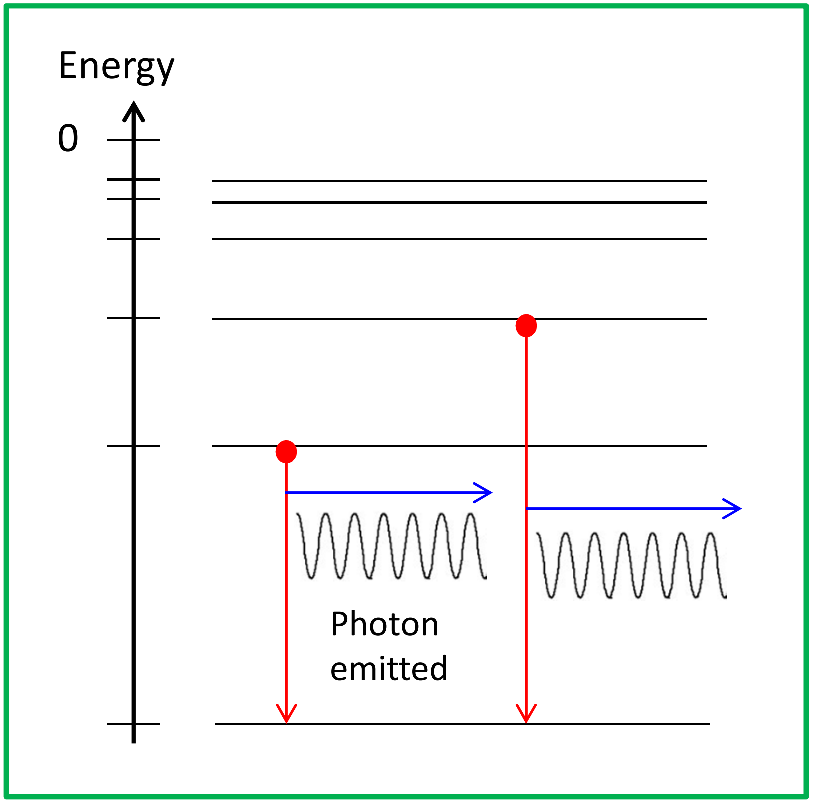
# Energy Levels / Energy States

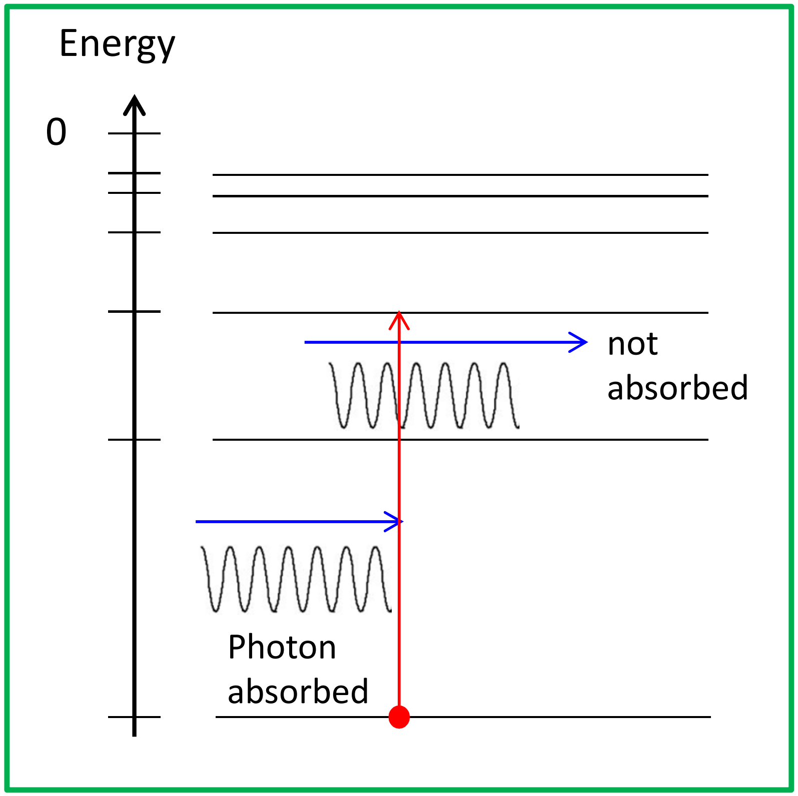
- The energy of the electron in the atom is said to be quantised.
- This is one of the most important statements of quantum physics.
- When an electron of an atom falls from a high energy level to a lower one, the loss of energy leads to the emission of single photon.
- The energy of this photon is equal to the energy difference between the two energy levels.
- If electron makes a transition from a higher energy level, the energy loss is larger and this leads to the emission of more energetic photon.
- The distinctive energy levels of an atom tells us that the energy of photons emitted, and hence the wavelengths emitted will be unique for the atom.
- This explain why only certain wavelengths are present in the emission line spectrum of a hot gas.

# Energy Levels / Energy States

- Similarly, we can explain the origin of absorption line spectra. For photon to be absorbed, it must have exactly the right energy to lift an electron from one energy level to another. The frequency of photon must be such that its energy matches the gap between any two energy levels.
- When the electrons absorbed the photons, it will be brought to an excited state. Being unstable, the electrons will immediately re-radiate photons of same frequency in all directions.
- Very little is emitted in the straight through direction being examined by the spectrometer. Thus we still see dark region.

# Energy Levels / Energy States



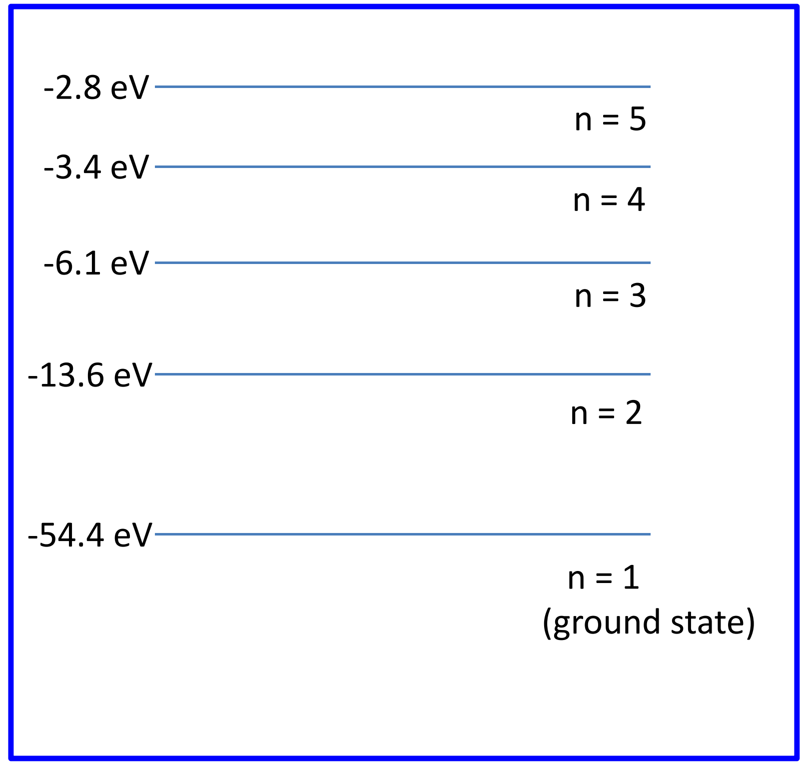

- When electron drops to a lower energy level, it emits a single photon.
- Photon energy, $\Delta E = hf$

  **$(E_{high\ level} - E_{low\ level}) = hf$**

- When a photon has the right energy, it will be absorbed by electron.

# Example 5

a.) Calculate the energy in Joules, that is required to completely remove the remaining electron, originally in its ground state, from the helium nucleus.




b.) Calculate the frequency of the radiation which is emitted when the electron drops form the level n = 3 to n = 2. State the region of the electromagnetic spectrum in which this radiation lies.

c.) Without further calculation, describe qualitatively how the frequency of the radiation emitted when the electron drops from level 2 to 1 compares with the energy of the radiation emitted when it drops from 3 to 2.

# Example 6

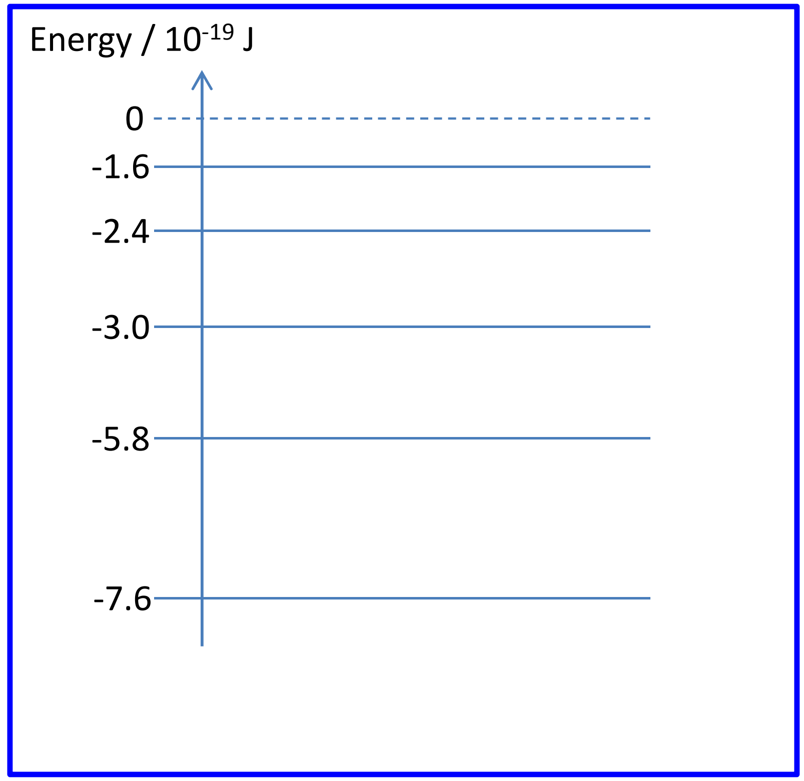
The spectrum of sunlight has dark lines. These are due to the absorption of certain wavelengths by the cooler gases in the atmosphere of the Sun.

a.) Explain the significance of the energy level having negative values.

b.) One particular dark spectral line has a wavelength of 590 nm. Calculate the energy of a photon of it.

c.) With reference to the diagram, which two energy states is an electron involved in the creation of the dark lines.

d.) All light absorbed by the atoms in the Sun's atmosphere is re-emitted. Suggest why a dark spectral line of wavelength of 590 nm is still observed from the Earth.



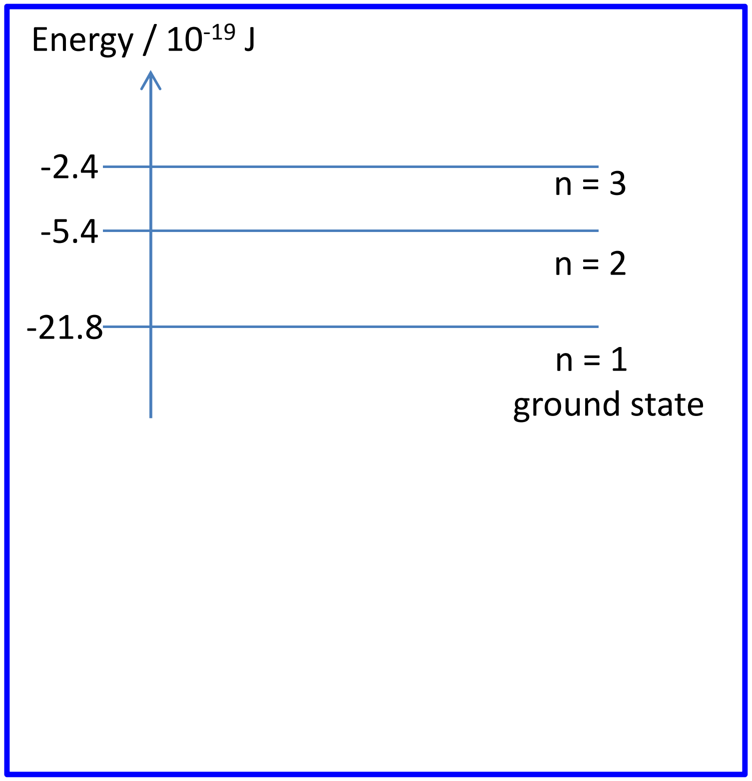
# Example 7

Diagram beside shows the energy level of an isolated hydrogen atom.

a.) Explain what happens to an electron in the ground state when it absorbs the energy from a photon of energy $21.8 \times 10^{-19}$ J

b.) Explain why a photon is emitted when an electron makes a transition between energy level of n = 3 and n = 2.

c.) Calculate the wavelength of an EM radiation emitted when an electron makes a jump between energy levels of 3 and 2.



# Wave-Particle Duality

- Phenomena like refraction, interference, diffraction and polarization provide evidence that light (and all electromagnetic radiation) behaves like a wave.
- Phenomena of photoelectric effect, however, provides evidence that light (and all electromagnetic radiation) behaves like a particle.
- So what is light or EM radiation? Wave or particle?
- The idea of light behaving as wave and the idea of it being a particle are merely two models which help us to explain the behaviour of light. Neither is a complete description.
- Physicists came to terms with the dual nature of light which is the combined approach of the two models.
- This duality is referred to as the **wave-particle duality** of light.

- In simple terms:

  a.) Light interact with matter as a particle (the photon).

  Evidence: the photoelectric effect.

  b.) Light travels through space as a wave.

  Evidence: diffraction and interference of light through a grating.

# Electron Waves (De Broglie's Theory)

- The wave-particle nature of light (EM radiation) led Louis de Broglie to suggest that matter might also exhibit this duality and have wave properties.
- He proposed that the wavelength (λ) associated with a particle is related to its momentum (p) by the equation:

$$\boxed{\lambda = \frac{h}{p} = \frac{h}{mv}}$$

where $\lambda$ = de Broglie wavelength
$m$ = particle mass
$v$ = particle velocity

# Electron Waves (De Broglie's Theory)

- The de Broglie wavelength of an electron which has been accelerated by an electric field can be obtained as follows:
- Consider an electron of mass (m) and charge (e) accelerated from rest to a final velocity (v) by a pd. (V)

K.E. gain by electron = work done by accelerating p.d.

$$\frac{1}{2} mv^2 = eV \Rightarrow v = \sqrt{\frac{2eV}{m}}$$

Momentum (p) is given by p = mv:

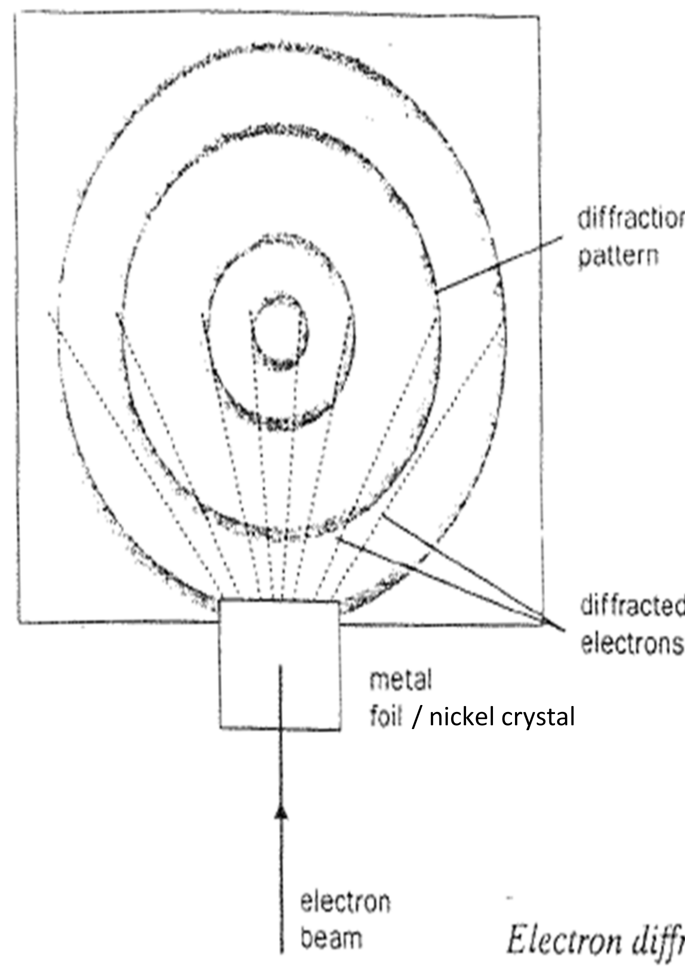
$$p = m\sqrt{\frac{2eV}{m}} = \sqrt{2eVm}$$

De Broglie wavelength (λ) is given by:

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2eVm}}$$

# Electron Waves (De Broglie's Theory)

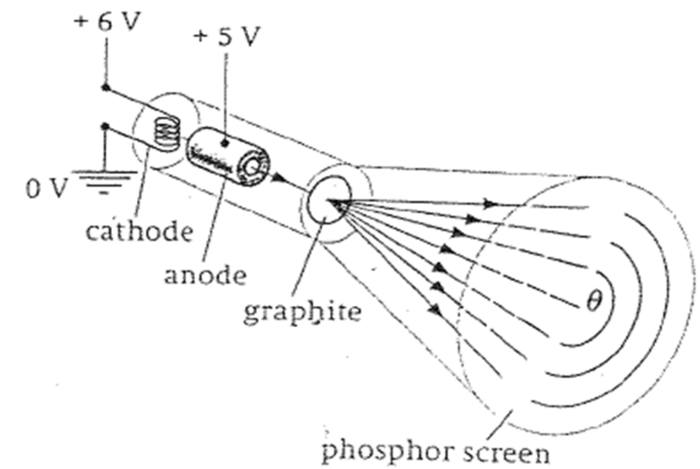
- The wave properties of electron was confirmed by Darison & Germer, who demonstrated diffraction of a beam of electrons by a single crystal of nickel.
- The distance between the planes of atoms in the crystal is of the same order of magnitude as the De Broglie wavelength of the electron beam, thus producing significant diffraction.
- Diffraction effects have since been observed with beams of protons, neutrons, and even alpha particles.
- However, the associated wavelength decreases as mass increases, making diffraction effects more difficult to observe with more massive particles.
- Diffraction of beam of electrons directed at a crystal or a thin metal foil is shown beside.



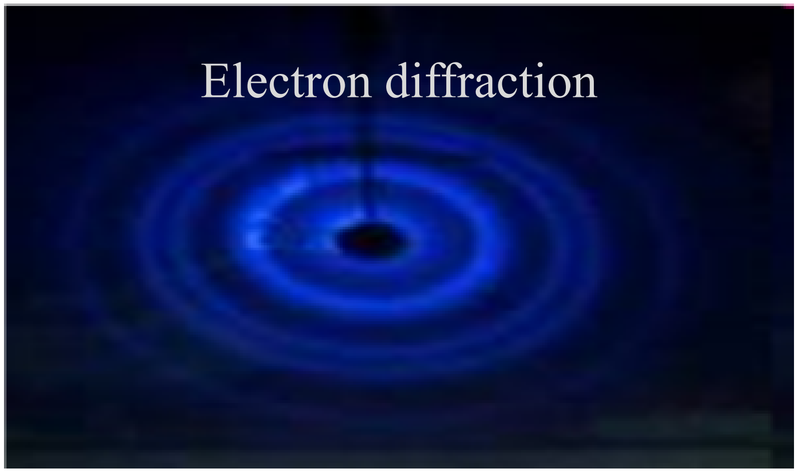

*Electron diffraction*

# Electron Waves (De Broglie's Theory)

- Figure beside is an example of an electron diffraction tube.
- The electron gun at one end of the tube produces a beam of electrons.
- By changing the voltage between anode and cathode, you can change the energy of the electrons, and hence their speed. The beam strikes a graphite target, and diffraction pattern appears on the phosphor screen. The pattern produced is a set of concentric circles.
- Qualitatively, increasing the anode-cathode voltage increases the speed of electrons, thus decreasing its De Broglie's wavelength leading to a shrinkage in the diffraction pattern. (concentric circles)




Electrons are accelerated from the cathode to the anode; they form a beam, which is diffracted as it passes through the graphite.



# Example 8

1.) What is meant by the de Broglie wavelength of an electron.

2.) Calculate the kinetic energy (in Joules) of an electron upon reaching the anode when it is being accelerated through a pd. of 5 kV from the hot cathode in an electron tube used to demonstrate electron diffraction.

3.) Show that the momentum of the electron is equal to $\sqrt{2Ekm}$ and hence calculate the momentum of the electron.

4.) Calculate the de Broglie wavelength of the electrons.

5.) Discuss how the wavelengths of neutrons and electrons moving with the same energy would compare.

# Summary of Wave-Particle Duality

- Over the years, many experiments and discoveries lead scientists to conclude that both light / EM radiation and electron (matter) have dual nature.

| **Exhibition of nature** | **Light / EM radiation** | **Electron (matter)** |
|---|---|---|
| The WAVE nature | Light travels through space as wave. **Evidence: Interference & diffraction of light.** | Electron travels through space as wave. **Evidence: Diffraction of electrons.** |
| The PARTICLE nature | Light interacts with matter as particle. **Evidence: Photoelectric effect.** | Electron interacts with matter as particle. **Evidence: Newtonian mechanics (momentum, kinetic energy)** |