Quantum Physics

A2 Level Physics (9702)

By Sir Pasha

Wave and Particle model

Wave and particle model are the two very powerful scientific models that help us to understand more about both light and matter.

We will take a closer look at each of these models in one by one.

Particle models:

Particles are a macroscopic model.

Our ideas of particles come from what we observe on a macroscopic scale – when we are walking down the street, or observing the motion of stars and planets, or working with trolleys and balls in the laboratory.

Particle models:

The importance of particle models is that we can apply them to the microscopic world, and explain more phenomena.

We can picture gas molecules as small, hard particles, rushing around and bouncing haphazardly off one another and the walls of their container.

This is the kinetic model of a gas.

Particle models:

We can explain the macroscopic (larger scale) phenomena of pressure and temperature in terms of the masses and speeds of the microscopic particles.

K.M.T. a very powerful model, which has been refined to explain many other aspects of the behaviour of gases.

Particle models:

Area	Model	Macroscopic Phenomenon
Electricity	Flow of electrons	Current
Gases	Kinetic theory	Pressure, temperature, volume of a gas
Solids	Crystalline materials	Mechanical properties
Radioactivity	Nuclear model of the atom	Radioactive decay, fission and fusion reactions
Chemistry	Atomic structure	Chemical reactions

Wave model

Physicists have an idealized picture of a wave – it is shaped like a sine graph.

You will not see any waves quite this shape on the sea.

However, it is a useful picture, because it can be used to represent some simple phenomena.

Wave Model

Waves are a way in which energy is transferred from one place to another.

In any wave, something is changing in a regular way, while energy is travelling along.

Wave Model

Phenomenon	Varying quantity
Sound	Pressure
Light (and other electromagnetic waves)	Electric and magnetic field strength
Waves on string	displacement

Wave or particle?

The characteristic properties of waves are that they all show reflection, refraction, diffraction and interference.

Waves themselves do not have mass or charge.

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**, we know that we are dealing with waves

Which of the two models should we use to explain light?

This is the problem that physicists struggled with for over a century, in connection with light.

Both models seem to work when we are trying to explain light.

Light as particle

Newton suggested light as a particle.

He could use this model to explain both reflection and refraction.

His model suggested that light travels faster in water than in air.

Later, experiments on the speed of light showed that light travelled more slowly in water than in air.

Newton's model was in direct contradiction with experimental results.

Light as particle

If you place a Geiger counter next to a source of gamma radiation you will hear an irregular series of clicks.

So, here are waves giving individual or discrete clicks, which are indistinguishable from the clicks given by α-particles (alpha-particles) and β-particles (beta- particles).

Light as particle

We can conclude that γ-rays behave like particles when they interact with a Geiger counter.

This effect is most obvious with γ-rays, because they are at the most energetic end of the electromagnetic spectrum.

It is harder to show the same effect for visible light.

Light as wave:

In 1801 Thomas Young, an English physicist, demonstrated that light showed diffraction and interference effects in his "Double Slit Experiment"

Light as particle (photons)

The photoelectric effect, and Einstein's explanation of it, convinced physicists that light could behave as a stream of particles.

Newton used the word **corpuscle** for the particles which he thought made up light. Nowadays, we call them photons and we believe that all electromagnetic radiation consists of **photons**.

What is a Photon?

A photon is a 'packet of energy' or a quantum of electromagnetic energy.

The energy E of a photon in joules (J) is related to the frequency f in hertz (Hz) of the electromagnetic radiation of which it is part, by the equation:

$$E = hf$$

h = Plank's constant = 6.63×10−34 Js.

Gamma-**photons** (γ-**photons**) are the most energetic.

Relationship of particle property and wave property in photon.

Notice that the equation $E = hf$ tells us the relationship between a particle property (the photon energy E) and a wave property (the frequency f).

It is called the Einstein relation and applies to all electromagnetic waves.

The frequency f and wavelength λ of an electromagnetic wave are related to the wave speed c by the wave equation $c = f\lambda$, so we can also write this equation as:

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

How an atom emits a photon???

Why the energies of photon are quantised???

electronvolt

One electronvolt (1eV) is the energy transferred when an electron travels through a potential difference of one volt.

$W = QV = 1.60\times10-19\times1 = 1.60\times10-19\ J$

$$\mathbf{1\ eV = 1.60\times10-19\ J}$$

Acceleration charged particles

When a charged particle is accelerated through a potential difference V, its kinetic energy increases.

For an electron (charge e), accelerated from rest, we can write:

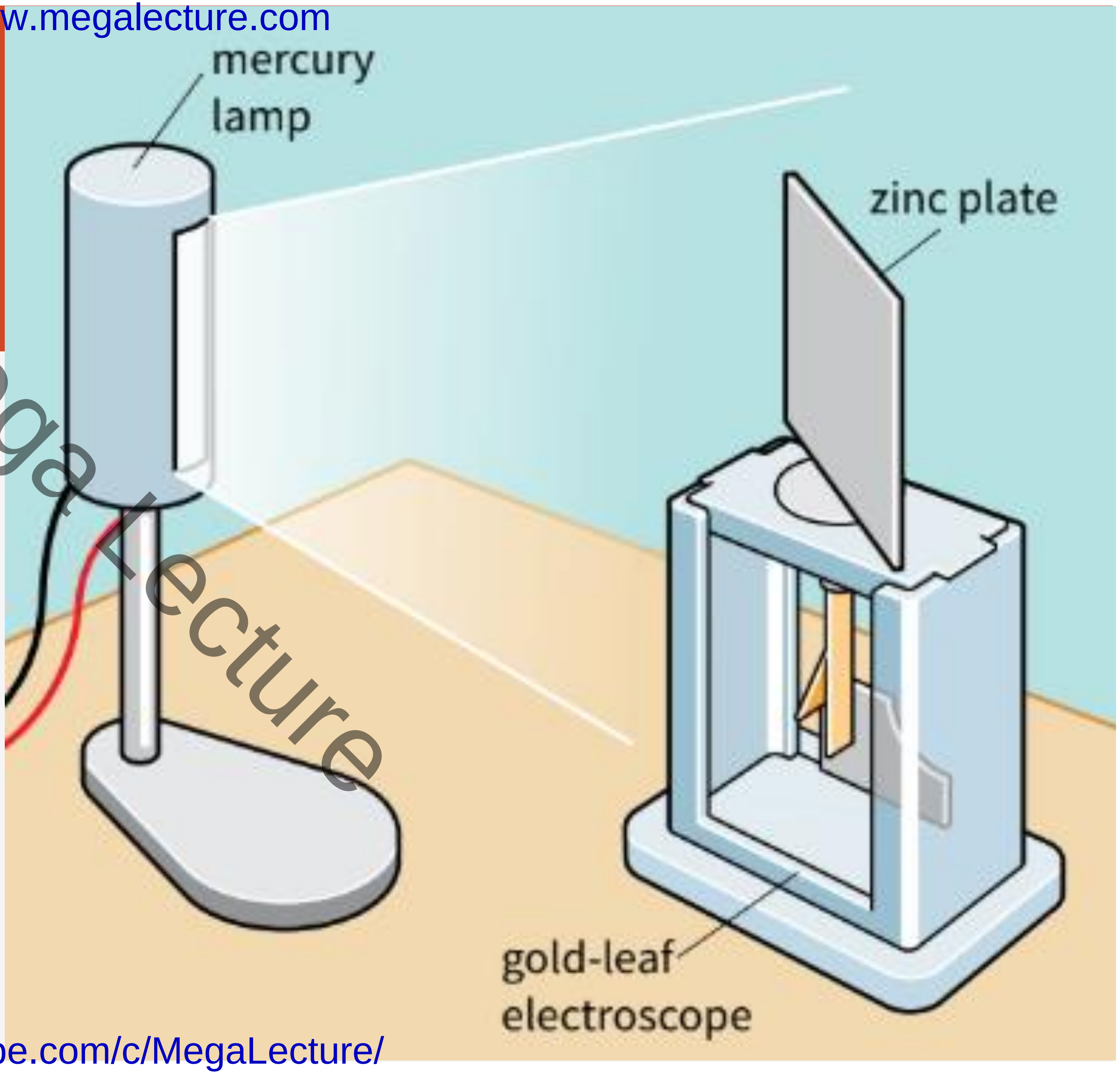
$$eV = \frac{1}{2}mv^2$$

Rearranging the equation gives the electron's speed:

$$v = \sqrt{\frac{2eV}{m}}$$

Photoelectric effect

In the photoelectric effect, light shines on a metal surface and electrons are released from it.



threshold frequency

The threshold frequency is defined as the minimum frequency required to release electrons from the surface of a metal.

Low and high frequency

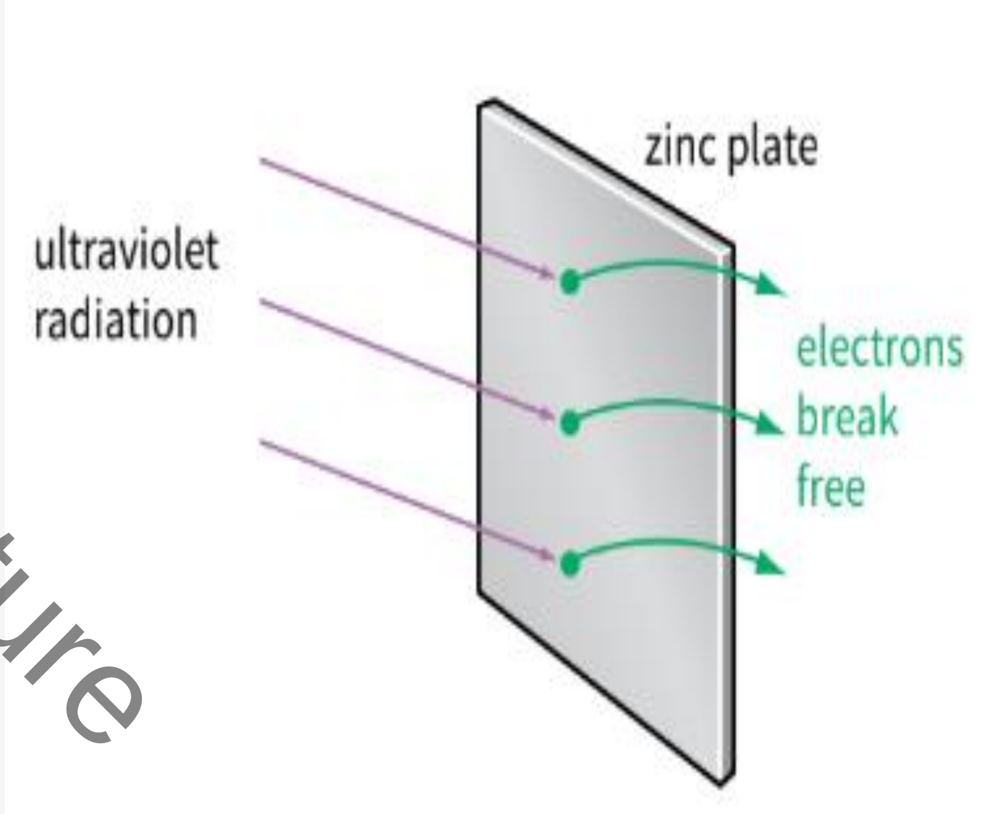
Physicists found it hard to explain why weak ultraviolet radiation could have an immediate effect on the electrons in the metal, but very bright light of lower frequency had no effect.

They imagined light waves arriving at the metal, spread out over its surface, and they could not see how weak ultraviolet waves could be more effective than the intense visible waves.

In 1905, Albert Einstein came up with an explanation based on the idea of photons.

Work function Φ

The **work function energy**, or simply **work function**, of a metal is the minimum amount of energy required by an electron to escape its surface.



Rules for photo electric effect

Electrons from the surface of the metal are removed.

A single photon can only interact, and hence exchange its energy, with a single electron (one-to-one interaction).

A surface electron is removed instantaneously from the metal surface when the energy of the incident photon is greater than, or equal to, the work function Φ of the metal.

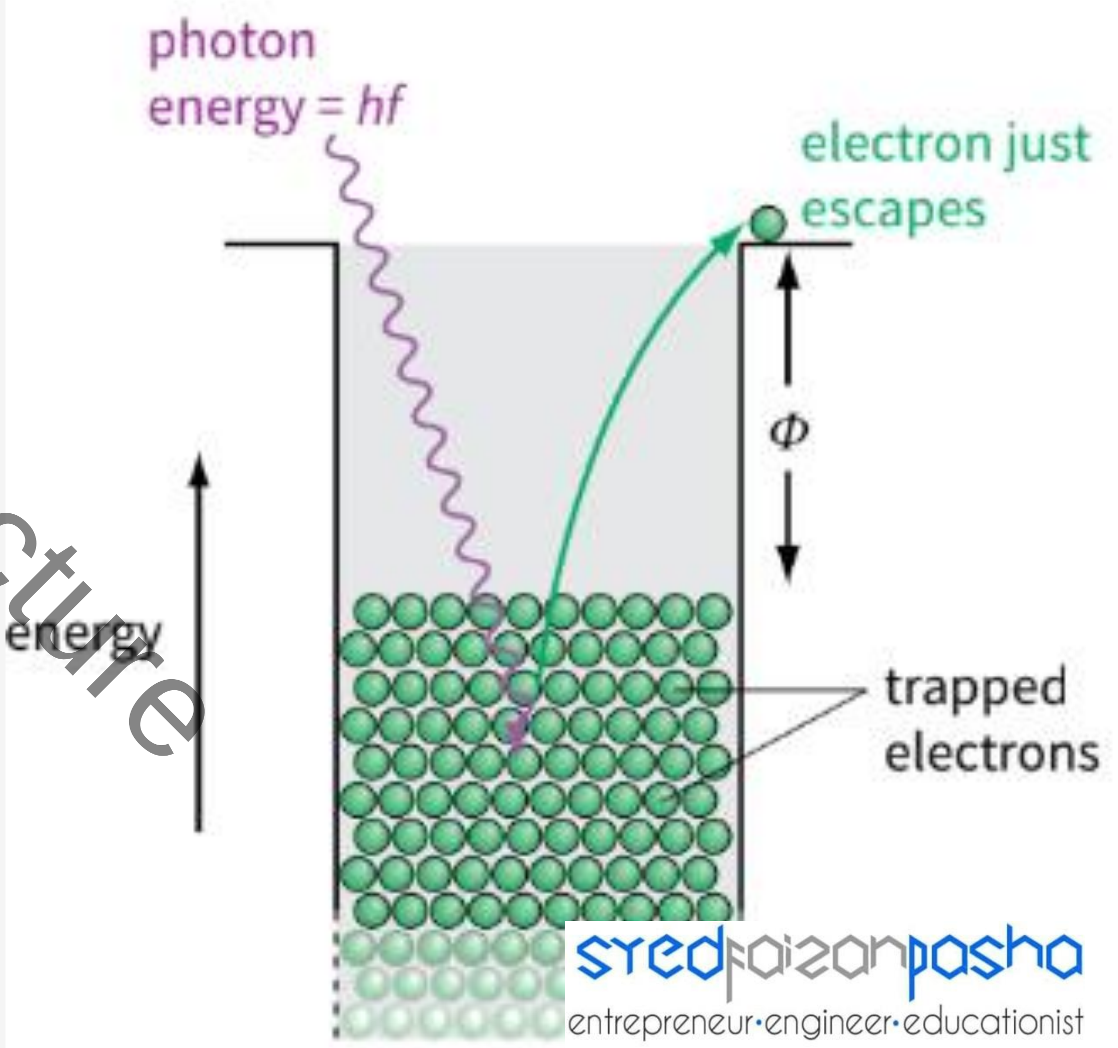
Energy must be conserved when a photon interacts with an electron.

Increasing the intensity of the incident radiation does not release a single electron when its frequency is less than the threshold frequency. The intensity of the incident radiation is proportional to the rate at which photons arrive at the plate. Each photon still has energy which is less than the work function.

Explaining work function

We can picture the electrons as being trapped in an energy 'well'.

A single electron requires a minimum energy Φ to escape the surface of the metal.



Equation for photo electric effect

Imagine a single photon interacting with a single surface electron and freeing it.

According to Einstein:

energy of photon = work function + maximum kinetic energy of electron

$$hf = \Phi + k.e.\ (max)$$

If the photon is absorbed by an electron that is lower in the energy well, the electron will have less kinetic energy than k.e (max).

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

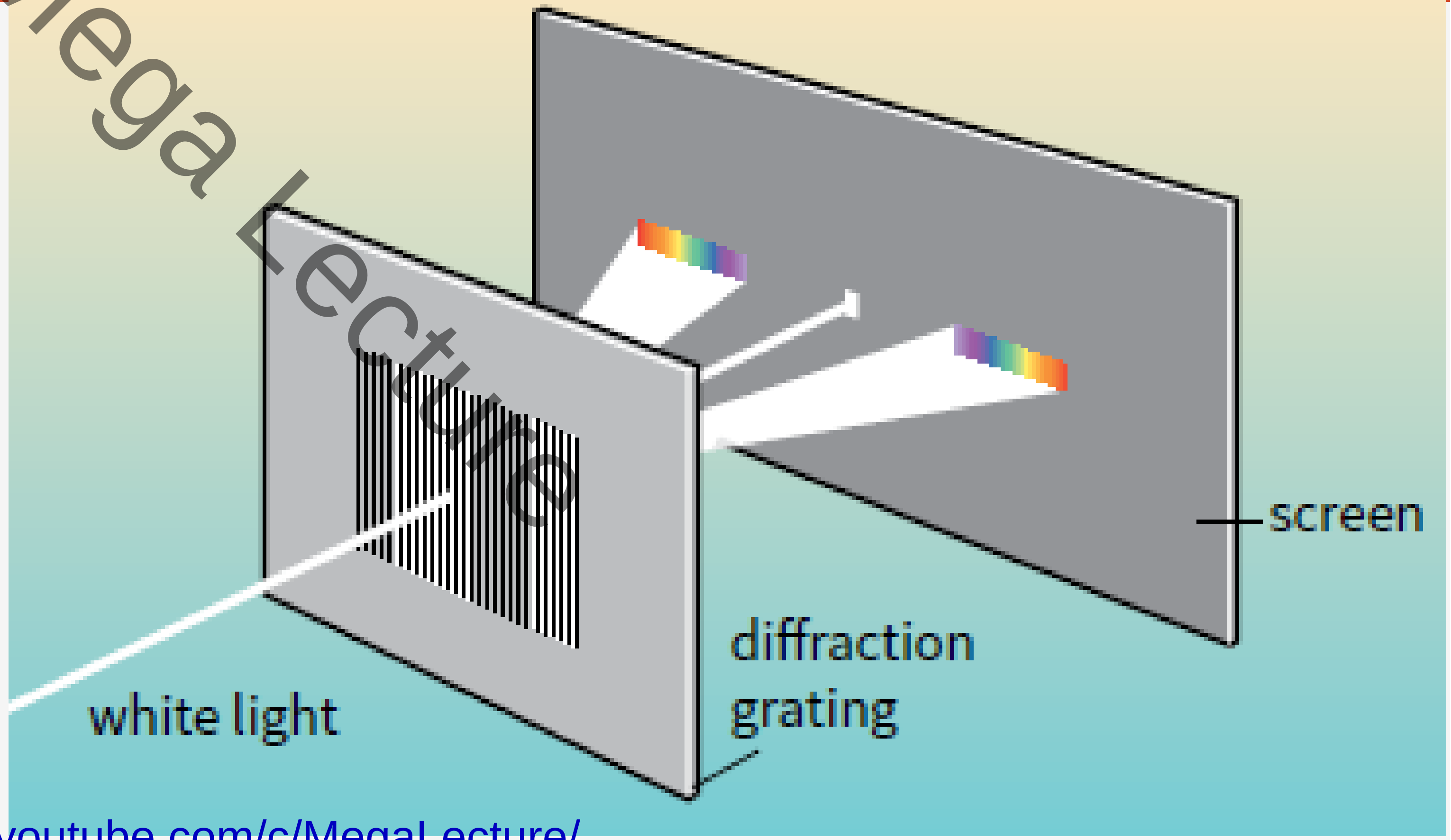
A single photon can still give up its energy to a single electron, but this electron cannot escape from the attractive forces of the positive metal ions.

The energy absorbed from the photons appears as kinetic energy of the electrons.

These 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.

Spectrum



Spectrum

The technical term for the splitting of light into its components is dispersion.

The spectrum of white light shows that it consists of a range of wavelengths, from about $4x10^{-7}$ m (violet) to about $7x10^{-7}$ m (red)

This is a continuous spectrum.

Spectrum

It is more interesting to look at the spectrum from a hot gas.

If you look at a lamp that contains a gas such as neon or sodium, you will see that only certain colours are present.

Each colour has a unique wavelength.

If the source is narrow and it is viewed through a diffraction grating, a line spectrum is seen.

Spectra of

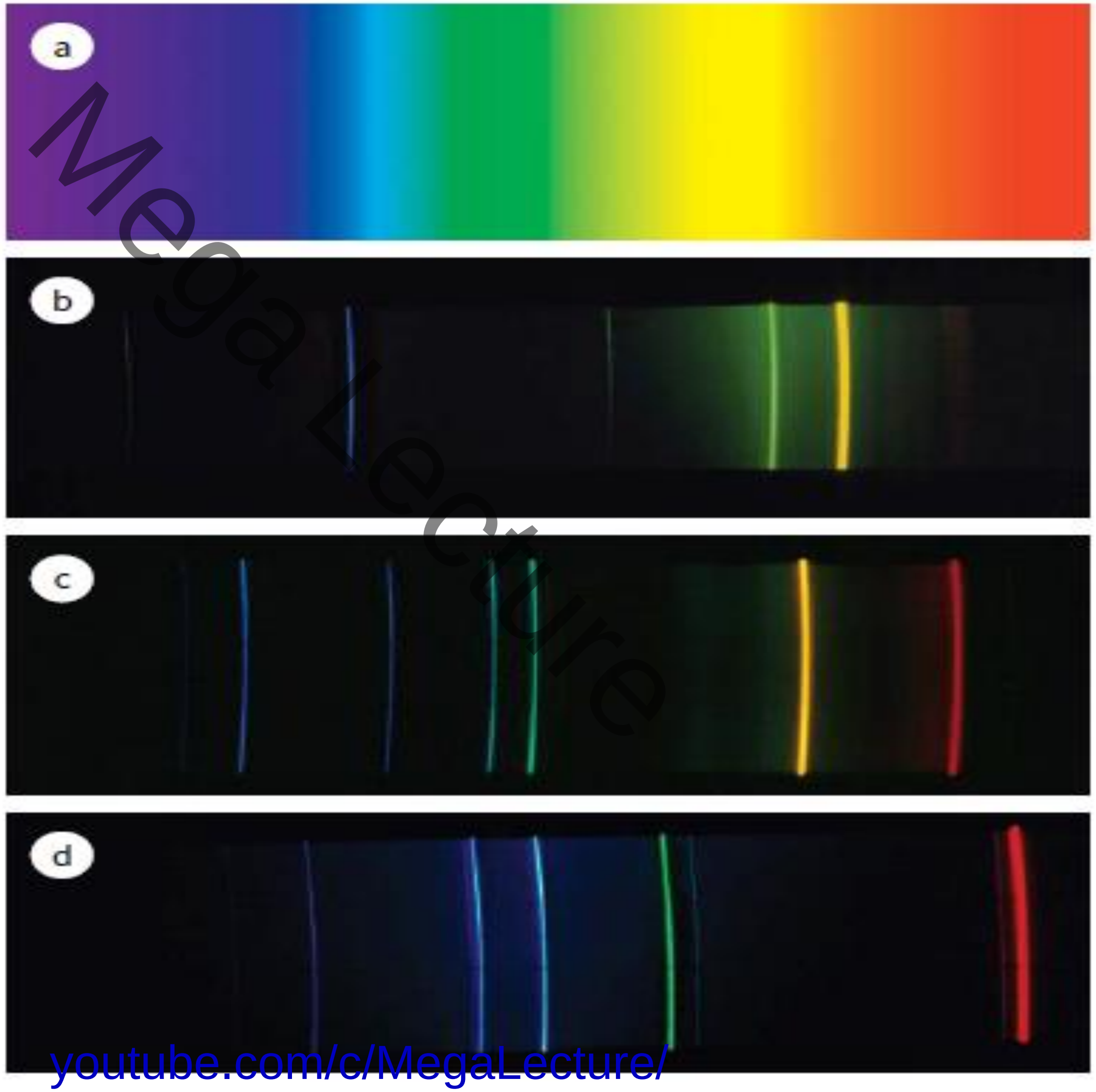
a white light,

and of light from

b mercury

c helium

d cadmium vapour.



Emission spectrum

These line spectra, which show the composition of light emitted by hot gases, are called emission line spectra.

Absorption spectrum

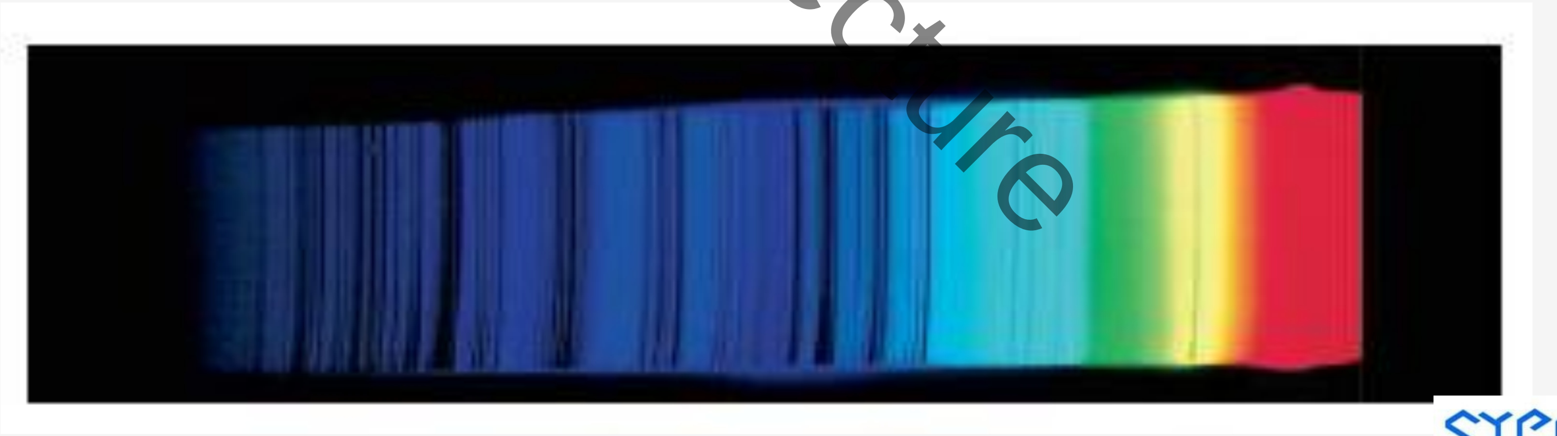
absorption line spectra are observed when white light is passed through cool gases.

Certain wavelengths have been absorbed as the white light passed through the cool gas.

Absorption spectrum

The Sun’s spectrum shows dark lines.

These dark lines arise when light of specific wavelengths coming from the Sun’s hot interior is absorbed by its cooler atmosphere.



Explaining the origin of line spectra

Different elements emit and absorb different wavelengths. How can this be? To understand this, we need to establish two points:

First, as with the photoelectric effect, we are dealing with light (an electromagnetic wave) interacting with matter. Hence we need to consider light as consisting of photons. For light of a single wavelength *λ* and frequency *f*, the energy *E* of each photon is given by the equation

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

Secondly, when light interacts with matter, it is the electrons that absorb the energy from the incoming photons. When the electrons lose energy, light is emitted by matter in the form of photons.

An atom can absorb photons of certain energy

What does the appearance of the line spectra tell us about electrons in atoms?

They can only absorb or emit photons of certain energies.

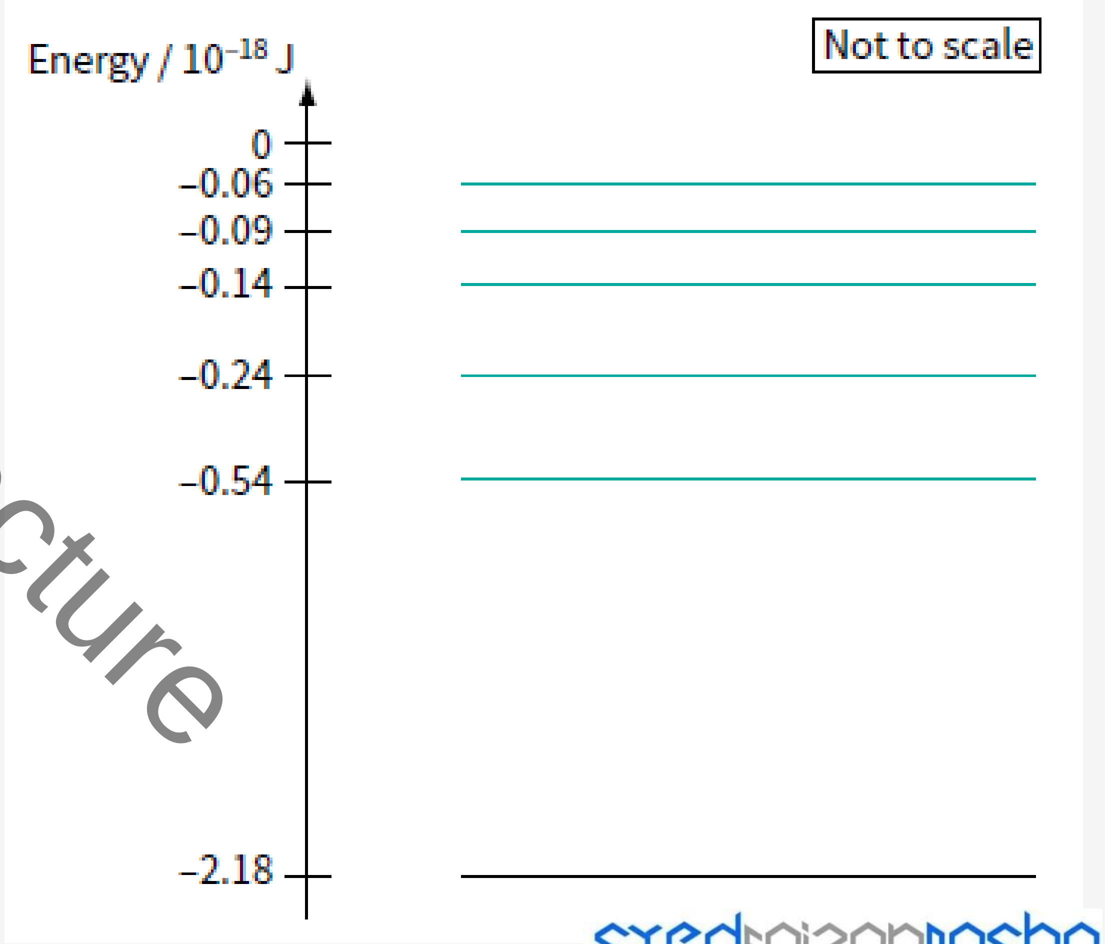
From this we deduce that electrons in atoms can themselves only have certain fixed values of energy.

The permitted energy levels (or energy states) of the electron of a hydrogen atom.

An electron in a 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 of the electron are analogous to the rungs of a ladder.



Why negative values?

The energy levels have negative values because external energy has to be supplied to remove an electron from the atom.

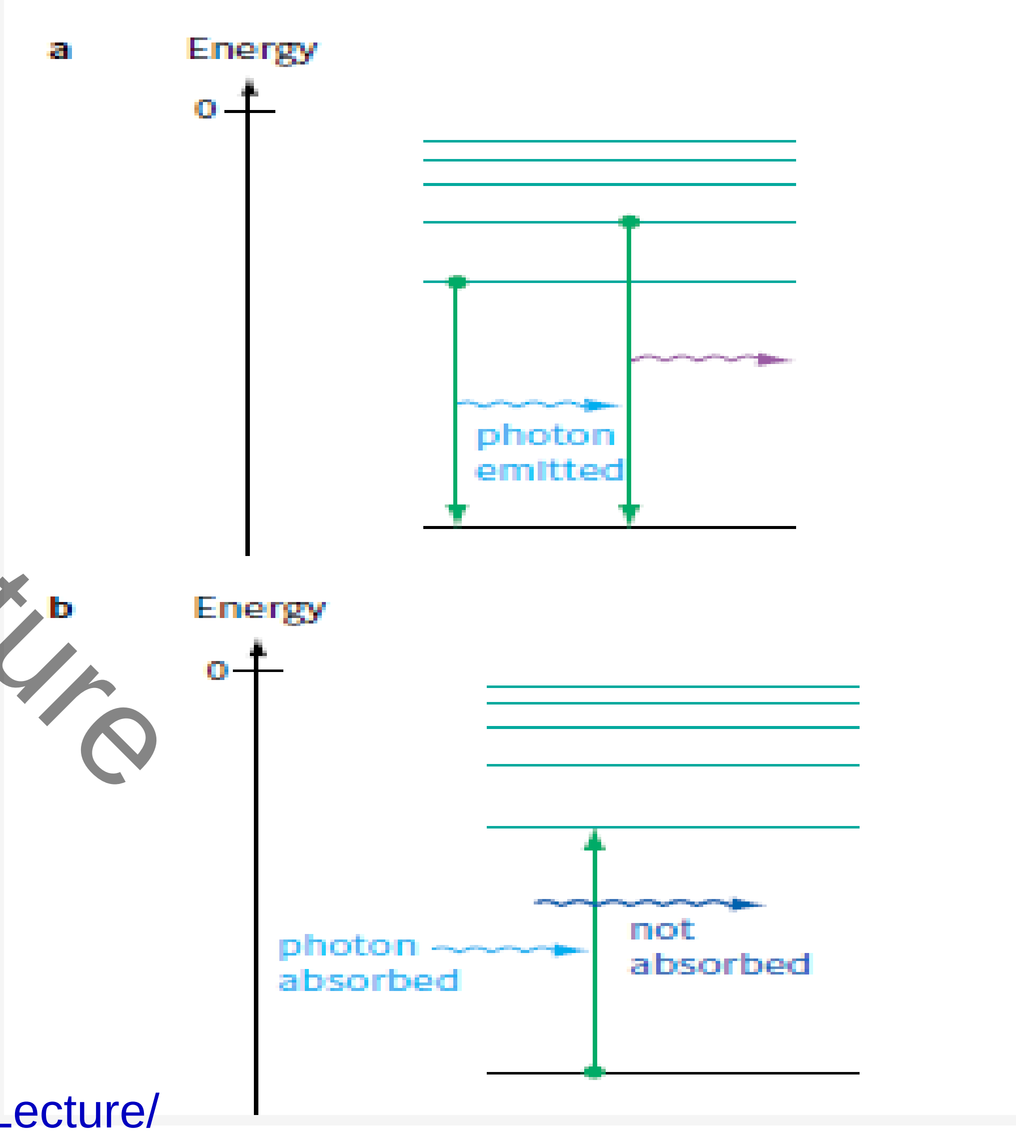
The negative energy shows that the electron is trapped within the atom by the attractive forces of the atomic nucleus.

An electron with zero energy is free from the

Electron transition

a When an electron drops to a lower energy level, it emits a single photon.

b A photon must have just the right energy if it is to be absorbed by an electron.



Photon energy

When an electron changes its energy from one level $E1$ to another $E2$, it either emits or absorbs a single photon.

The energy of the photon hf is simply equal to the difference in energies between the two levels:

photon energy = ΔE

$$hf = E_1 - E_2$$

or

$$\frac{hc}{\lambda} = E_1 - E_2$$

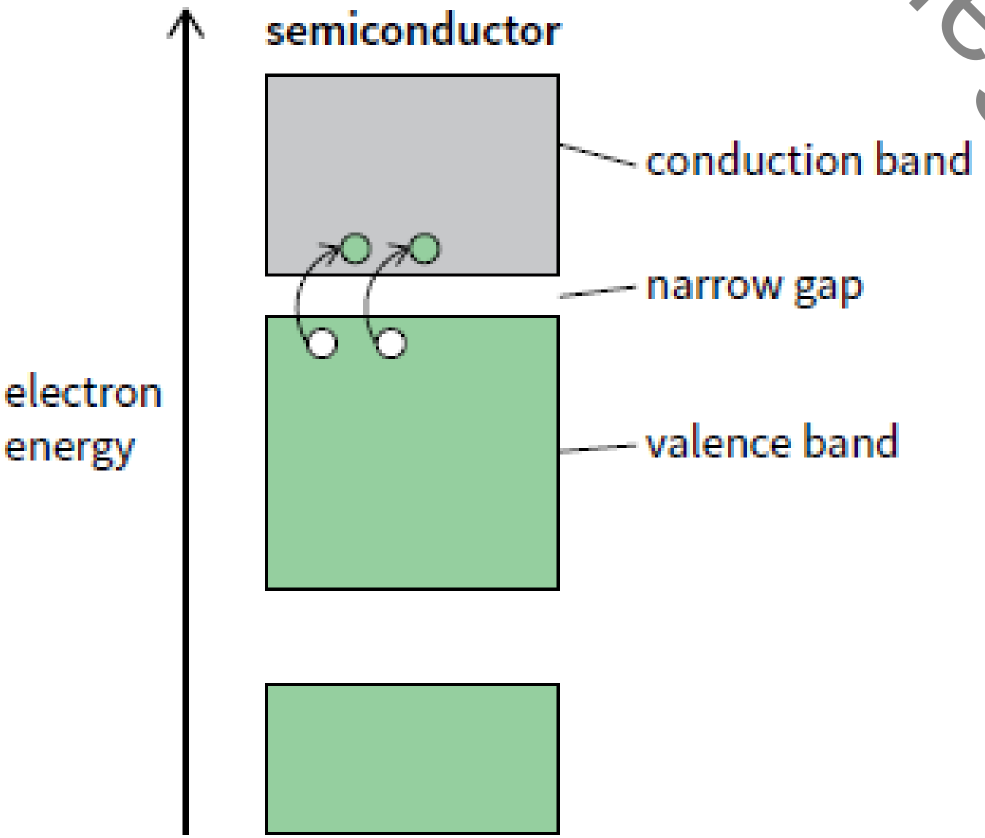
So what is light? Is it a wave or a particle?

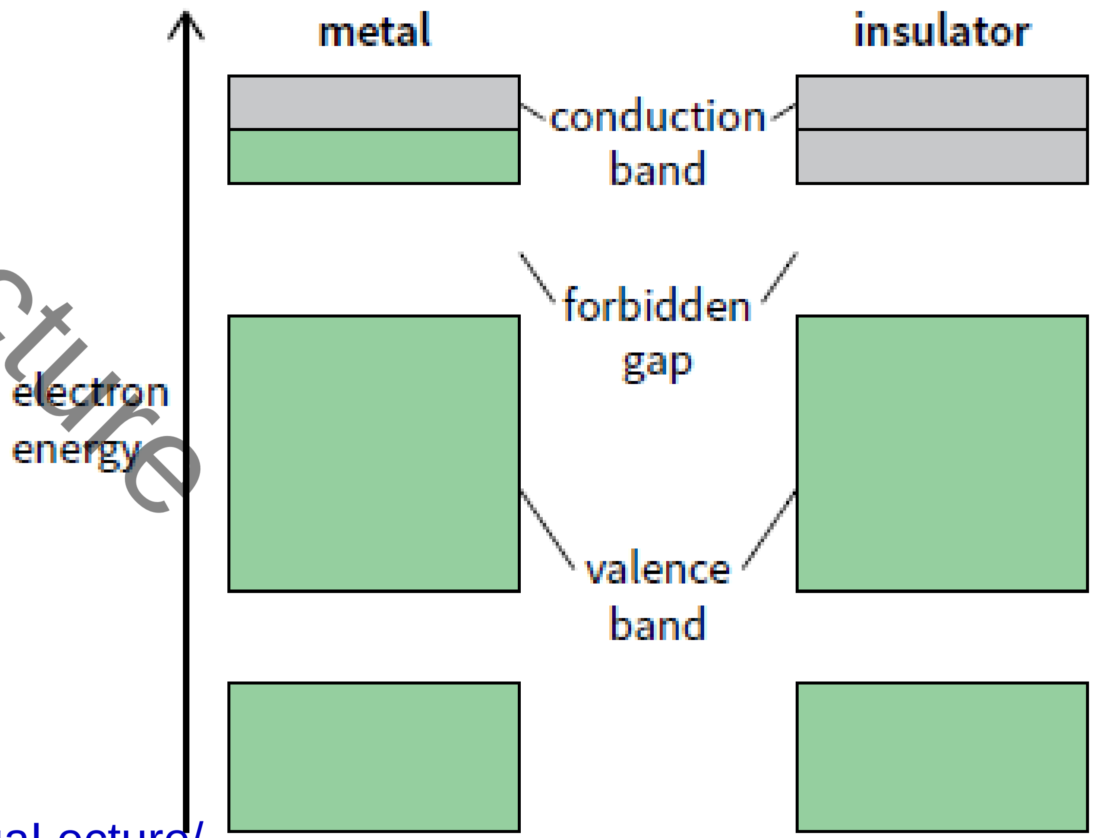
We can conclude **wave particle duality of light** as,

1. Light interacts with matter (e.g. electrons) as a particle – the photon. The evidence for this is provided by the photoelectric effect.

2. Light travels through space as a wave. The evidence for this comes from the diffraction and interference of light using slits.

Band theory of solids





Electron energies in solids

In a solid or liquid, however, the atoms are close together.

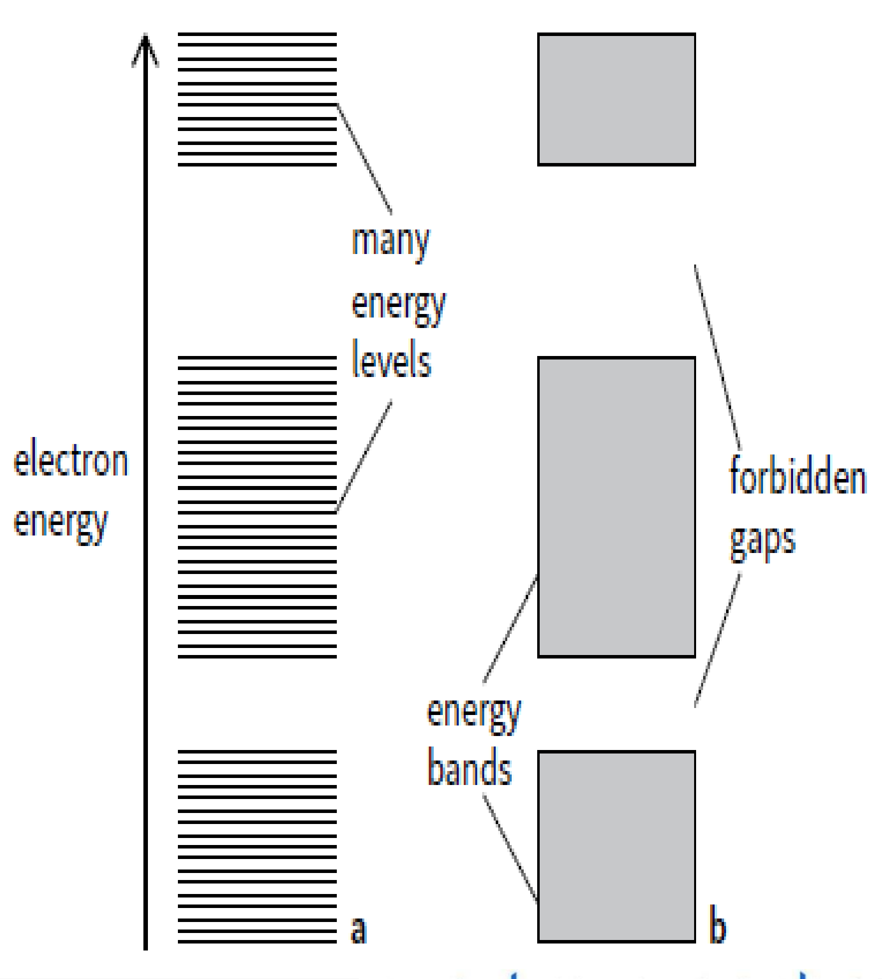
The electrons from one atom interact with those of neighbouring atoms.

This has the effect of altering the energy level diagram, which becomes much more complicated, with a large number of closely spaced energy levels.

Band theory

Figure 30.19a shows the result. Instead of individual energy levels we have bands of many levels, all close together. In between the bands are gaps with no allowed energy levels.

Figure 30.19b shows a more conventional representation of these energy bands in a solid. An electron can have an energy at any level in one of the bands. However, it cannot have an energy value which lies in the forbidden gap between bands (just as an electron in an isolated atom cannot have an energy which lies between two energy levels).



Band theory and electrical conduction

In a metal, one band, known as the conduction band, is only partially filled. The electrons in the conduction band are the conduction or free electrons which give the metal its conductivity.

In an insulator, the conduction band is unoccupied. The band below this, known as the valence band, is fully occupied. An electron whose energy lies in the valence band is bound to an individual atom.

Band theory and electrical conduction

In semi conductor, valence band is full and its conduction band is empty. However, the gap between the two is very small. At room temperature, a few electrons have enough energy to jump across the gap into the conduction band. These electrons are ‘free’ and can form a current.

Band theory and electrical conduction

If a piece of semiconductor is heated, more electrons will gain the energy needed to jump up into the conduction band and the material will conduct better – its resistance decreases because of the increased number density of electrons in the conduction band.

Band theory and electrical conduction

Silicon and germanium are examples of semiconductor materials like this.

They are described as intrinsic semiconductors because their conductivity is a property of the pure material itself.

Diodes, transistors and computer chips use semiconductors which have small amounts of other elements added to them to increase their conductivity.

Electron waves

De Broglie imagined that electrons would travel through space as a wave

Electron waves

De Broglie proposed that the wave-like property of a particle like the electron can be represented by its wavelength λ, which is related to its momentum p by the equation:

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

where h is the Planck constant.

Electron waves

The wavelength λ is often referred to as the de Broglie wavelength.

The waves associated with the electron are referred to as matter waves.

De Broglie equation

The momentum *p* of a particle is the product of its mass *m* and its velocity *v*.

Therefore, the de Broglie equation may be written as:

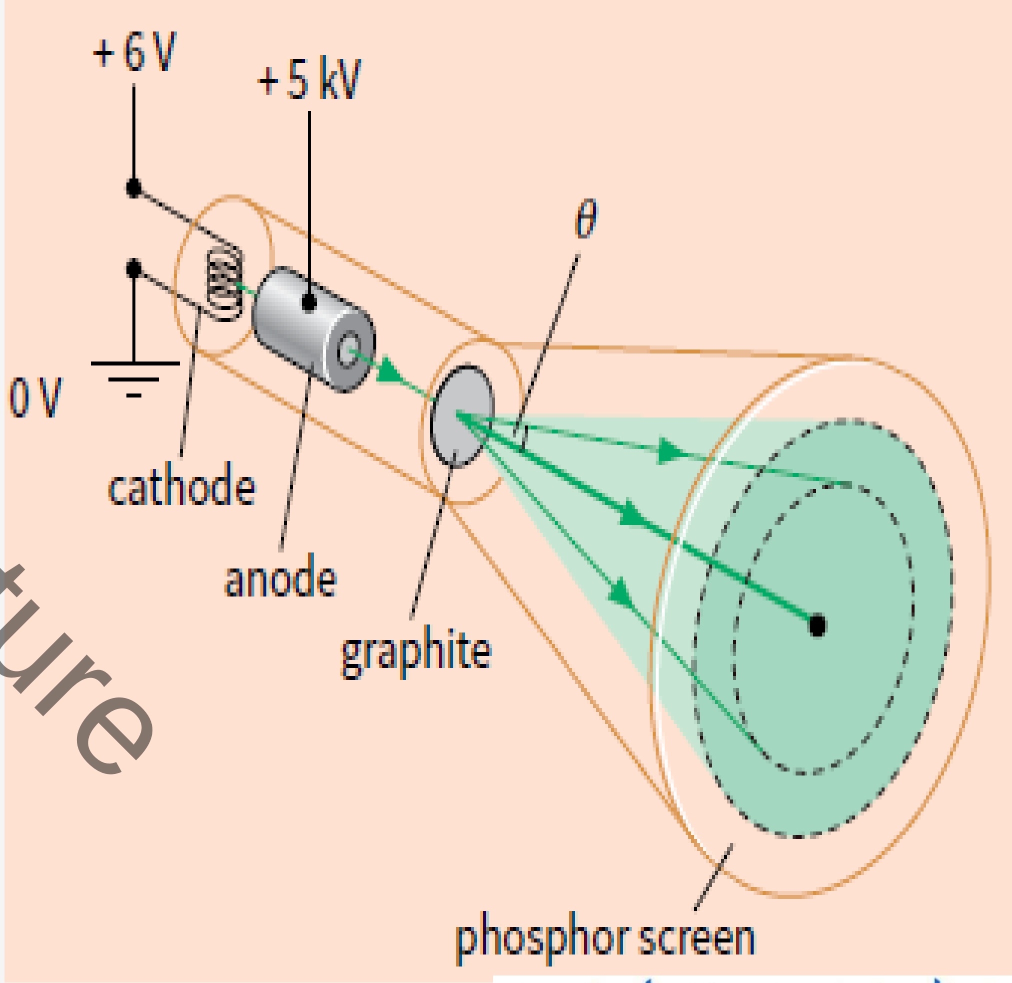
$$\lambda = \frac{h}{mv}$$

Investigating electron diffraction

We can reproduce the same diffraction results in the laboratory using an electron diffraction tube. The electron gun at one end of the tube produces a beam of electrons.

By changing the voltage between the anode and the cathode, you can change the energy of the electrons, and hence their speed.

The beam strikes a graphite target, and a diffraction pattern appears on the screen at the other end of the tube.



Electron diffraction

the wavelength λ of the electrons by measuring the angle θ at which they are diffracted:

$$\lambda = 2d \sin \theta$$

where d is the spacing of the atomic layers of graphite.

You can find the speed of the electrons from the anode–cathode voltage V:

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

Electron diffraction application

Diffraction of slow-moving electrons is used to explore the arrangements of atoms in metals and the structures of complex molecules such as DNA.

It is possible to accelerate electrons to the right speed so that their wavelength is similar to the spacing between atoms, around 10−10 m.

The nature of the electron – wave or particle?

the wave–particle duality of the electron can be concluded in simple terms as:

1. An electron interacts with matter as a particle. The evidence for this is provided by Newtonian mechanics.

2.An electron travels through space as a wave. The evidence for this comes from the diffraction of electrons.

The end