3 Quantum Phenomena

3.1 The Photoelectric Effect

Conduction electrons move about freely inside the metal. It was found that sparks produced by a **spark detector** when ultraviolet radiation was directed at the spark gap.

Further investigation showed that electrons are emitted from the surface of a metal when electromagnetic radiation above a certain frequency was direct at the metal. This is known as the **photoelectric effect**.

- Photoelectric emission of electron from a metal surface does not take place if the frequency of the incident electromagnetic radiation is below a certain value known as the **threshold frequency**.
- The number of electron emitted per second is proportional to the intensity of the incident radiation, provided the frequency is greater than the threshold frequency.
- Photoelectric emissions **occur without delay** as soon as the incident radiation is directed at the surface. Provided the frequency exceeds the threshold frequency, and reguardless of the intensity.

Observations from the photoelectric effect could not be explained using the **wave theory** of light.

- The **existence of a threshold frequency** - each conduction electron at the surface of a metal should gain some energy from the incoming waves.
- Why photoelectric emission **occurs without delay**.

The Photon Model of Light

The photon theory of light was put forward to explain the photoelectric effect.

- Light is composed of **wavepackets** or photons.
- Each photon has energy $E = hf = hc/\lambda$.

To explain the photoelectric effect

- When light is incident on a metal surface, an electron at the surface **absorbs a single photon** from the incident light and therefore gains energy equals to hf - the energy of a photon.
- An electron can leave the metal surface if the energy gained from a single photon exceeds the **work function** ϕ of the metal.
  - The **work function** is the minimum energy needed by an electron to escape from the metal surface.
  - Excess energy gained by the photoelectron becomes its kinetic energy.

The maximum kinetic energy is given by

$$E_{\mathrm{Kmax}} = hf - \phi$$

Emissions can take place provided $E_{\text{Kmax}} > 0$, so the threshold frequency of the metal is

$$f_{\text{min}} = \frac{\phi}{h}$$

Stopping Potential

Electrons that escape from the metal plate can be **attracted back** by giving the plate a sufficient positive charge.

- The minimum potential needed to stop photoelectric emission is called the **stopping potential** V_s.
- At this potential, the maximum kinetic energy of the emitted electron is reduced to zero because each electron must do extra work $e \times V_s$ to leave the surface.

Conclusive experimental evidence of the photon theory was obtained by

- Measuring the stopping potential for a range of metals.
- Using light of different frequencies.

The results fitting the photoelectric equation very closely.

3.2 More about Photoelectricity

The energy of each vibrating atom is **quantised** - only certain levels of the energy are allowed, and energy could only be in multiples of a basic amount, or **quantum**.

- If a conduction electron absorbs a photon but does not leave the metal, it **collides repeatedly** with other electrons and positive ions, quickly loses its extra kinetic energy.

The Vacuum Photocell

A vacuum photocell is a glass tube that contains

- A metal plate, referred to as the **photocathode**.
- A smaller metal electrode, referred to as the **anode**.

When light of a frequency greater than the threshold frequency for the metal is directed at the photocathode, electrons are emitted from the cathode and are attracted to the anode. A microammeter can be used to measure the **photoelectric current** proportional to the number of electrons per second that transfer from the cathode to the anode.

- The number of **photoelectrons** transferred per second is given by $n = I/e$.
- The photoelectric current is **proportional to the intensity** of the light incident on the cathode - each electron must have absorbed one photon to escape from the metal surface.
  - **Light intensity** is a measure of energy per second carried by the incident light.
  - Which is proportional to the number of photons per second incident on the cathode.

- The intensity of the incident light does not affect the **maximum kinetic energy** of a photoelectron.
  - No matter how intense the incident light is, the energy gained by a photoelectron is due to the absorption of one photon only.
- The **maximum kinetic energy** of the photoelectrons emitted for a given frequency of light can be measured using a photocell.
- A graph of E_{Kmax} against f
  - The gradient is h
  - The x-intercept is the **threshold frequency**.
  - The y-intercept is the **work function**.

3.3 Collisions of Electrons with Atoms

An **ion** is a charged atom - the number of electrons in an ions is not equal to the number of protons.

An ion if formed from an **uncharged atom** by adding and removing electrons from the atom. Any process of creating ions is called **ionisation**

- Alpha, beta and gamma radiation create ions when they pass through substances and **collide with atoms** of the substance.
- Electrons passing through a fluorescent tube create ions when they **collide with atoms** of the vapour in the tube.

The **electron volt** is a unit of energy equal to the work done when an electron is moved through a pd of 1V.

Excitation by Collision

Gas atoms can absorb energy from colliding electrons without being ionised, this process is known as **excitation**. It happens at **certain energies**, which are characteristics of the atom.

- If a colliding electron loses all its kinetic energy when it causes excitation, the current due to the flow of electrons through the gas is **reduced**.
- If a colliding electron does not have enough kinetic energy to cause excitation, it is **deflected by the atom** with no overall loss of kinetic energy.

The energy values at which an atom absorbs energy are known as its **excitation energies**.

The excitations energies of atoms in a gas-filled tube can be determined by

1. Increasing the potential difference between the filament and the anode, and
2. Measure the pd when the anode current falls.

When excitation occurs, the colliding electron makes an atomic electron move from an inner shell to an outer shell. Energy is needed to move the atomic electron away from the nucleus.

The excitation energy is always less than the ionisation energy of the atom, because the atomic electron is not removed completely from the atom when excitation occurs.

3.4 Energy Levels in Atoms

Atomic electrons are trapped by the **electrostatic force of attraction** of the nucleus.

They move about the nucleus in allowed orbits, or **shells** surrounding the nucleus.

- The energy of an electron in a shell is constant.
- An electron in a shell near the nucleus has less energy than an electron in a shell further away.
- Each shell can only hold a certain number of electrons.

The lowest energy state of an atom is called its **ground state**. When an atom in ground state absorbs energy, one of its electrons moves to a shell at higher energy, the atom is now in an **excited state**.

An **energy level diagram** for the atom can be constructed using **excitation energy measurements**. The diagram shows the allowed energy values of the atom - each correspondings to a certain **electron configuration** in the atom.

Ionisation energy is used as the **zero reference level** for energy. Energy levels below the ionisation level would need to be shown as negative values.

De-excitation

Gases at low pressure emit light when they are made to conduct electricity. The atoms absorb energy as a result of excitation by collision, but they do not retain the absorbed energy permanently.

- The **electron configuration** in an excited atom is unstable because an electron that moves to an outer shell leaves a vacancy in the shell it moves from.
- Sooner or later, the vacancy is filled by an electron from an outer shell transferring to it.

When this happens, the electron emits a photon, the atom therefore moves to a lower energy level in the process of **de-excitation**. The energy of the photon is equal to the energy lost by the electron and therefore the atom.

$$\text{Energy of the emitted photon } E = hf$$

Excitation by Photons

- An electron in an atom can absorb a photon and move to an outer shell where a vacancy exists.
- But only if the energy of the photon is exactly equal to the gain in the electron's energy.
  - The photon energy must be exactly equal to the difference between the final and initial energy levels of the atom.
  - If the photon's energy is smaller or larger than the difference between two energy levels, it will not be absorbed by the electron.

Fluorescence

An atom in an excited state can de-excite directly or indirectly to the ground state, regardless of how the excitation took place - an atom can absorb photons of certain energies and emit photons of same or lesser energies.

Some substances **fluoresce** (glow with visible light) when they absorb ultraviolet radiation.

- Atoms in the substance **absorb ultraviolet photons** and become excited.
- When the atoms de-excite, they **emit visible photons**.
- When the source of ultraviolet radiation is removed, the substance **stops glowing**.

A **fluorescent tube** is a glass tube with **fluorescent coating** on its inner surface, containing **mercury vapour at low pressure**. It emits visible light when turned on.

1. **Ionisation and excitation** of the mercury atoms occur as they collide with each other and with electrons in the tube.
2. The mercury atoms **emit ultraviolet photons**, as well as photons of less energy when they de-excite.
3. The ultraviolet photons are absorbed by the atoms of the fluorescent coating, causing **excitation of the atoms**.
4. The coating atoms **de-excite in steps** and emit visible photons.

A fluorescent tube much more efficient than a **filament lamp** - it can produce the same light output with less power wasted as heat.

3.5 Energy Levels and Spectra

A **prism** can be used to split a beam of white light from a filament lamp into a **continuous spectrum**. If we replace the light source with a tube of glowing gas, we see a **spectrum of discrete lines** of different colours instead of a continuous spectrum.

- The wavelengths of the lines of a line spectrum of an element are characteristic of the atoms of that element. By measuring the wavelengths of a line spectrum, we can therefore **identify the element** that produced the light.

No two elements produce the same pattern of light wavelengths, because the **energy levels** of each type of atom are unique to that atom, so photons emitted are characteristic of the atom.

1. Each line in a line spectrum is due to light of a certain colour and therefore a **certain wavelength**.
2. The photons that produce each line all have the **same energy**, which is different from the energy of the photon that produce any other line.
3. Each photon is emitted when an atom **de-excites** due to one of its electrons moving to an inner shell.

$$\text{energy of the emitted photon} = E_1 - E_2$$

Given the energy level diagram for the atom, we can identify on the diagram the **transition that caused a photon of that wavelength** to be emitted.

Bohr's Atom

The energy levels of the hydrogen atom, **relative to the ionisation level** are given by formula.

$$E = -\frac{13.6\text{eV}}{n^2}$$

where $n = 1$ for the ground state.

When a hydrogen atom de-excites from energy level n_1 to n_2, the energy of the **emitted photon** is given by.

$$E = \left(\frac{1}{{n_2}^2} - \frac{1}{{n_1}^2}\right) \times 13.6\text{eV}$$

3.6 Wave-particle Duality

Light is part of the **electromagnetic waves**. The **theory of electromagnetic waves** predicted the existence of EM waves beyond the visible spectrum, subsequent discovery of X-rays and radio waves confirmed these predictions.

However, the **photoelectric effect** was not explained until the **photon theory of light**, where light consists of photons, which are particle-like packets of electromagnetic waves.

Light has a **dual-nature**, it can behave as a wave or as a particle, according to circumstances.

- The **wave-like nature** is observed when **diffraction** of light takes place.
    1. Light passes through a **narrow slit**.
    2. Light emerging from the slit **spreads out** in the same way water waves spreads out after passing through a gap.
    3. The <u>narrower the gap</u> or the <u>longer the wavelength</u>, the greater the diffraction.
- The **particle-like nature** is observed in the **photoelectric effect**.

Matter Waves

de Broglie's hypothesis is the idea that matter particles also have a wave-like nature. Extending the idea of duality from photons to **matter particles**.

- Matter particles have **dual wave-particle nature**.
- The wave-like behaviour of a matter particle is <u>characterised by a wavelength</u> - its **de Broglie wavelength**.

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

Electron Diffraction

The wave-like nature of electrons was discovered when it was demonstrated that a **beam of electrons** can be diffracted. Further experimental evidence using other types of particles confirmed the correctness of the theory.

1. A narrow **beam of electrons** in a **vacuum tube** is directed at a thin **metal foil**.
    - A metal is composed of many tiny **crystalline regions**.
    - Each region consists of **positive ions** arranged in rows in a **regular pattern**.
    - The rows of the atoms causes the electrons in the beam to be **diffracted** - just a beam of light is diffracted when it passes through a slit.
2. The electrons in the beam pass through the meal foil and are **diffracted in certain directions only**. Forming a pattern of **concentric rings** on a fluorescent screen at the end of the tube.
    - Each ring is due to electrons **diffracted by the same angle to the incident beam** from regions of different orientations.

The beam of electrons is produced by attracting electrons from a heated filament wire to a positively charged metal plate with a small hole in the centre. Electrons that passes through the hole **forms the beam**.

- The **speed of electrons** can be increased by **increasing the potential difference** between the filament and the metal plate.
- This makes the diffraction rings smaller - increase of speed decreases the **de Broglie wavelength**, so less diffraction occur and the rings become smaller.

Electron Energy Levels

An electron in an atom has a **fixed amount of energy** depending on the shell it occupies.

- Its **de Broglie wavelength** has to fit the shape and size of the shell.
- That's why energy depends on the shell an electron occupies.

The **circumference** of its orbit must be equal to a whole number of de Broglie wavelengths.